Comprehensive Study on Fighter Pilot Attention and Vigilance Monitoring

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Abstract: Modern air warfare demands a holistic approach to address the evolving complexities of all fighter systems. With a focus on enhancing pilot performance, multi-task automation provides solutions that allow pilots to concentrate on critical aspects of the flight and the mission. Recognizing the need for task automation tailored to individual pilot capabilities, functional state monitoring has become one of the most valuable areas of research. Specifically, monitoring pilot attention and vigilance capacities are pivotal factors in achieving the first layer of situational awareness (perception).

This study explores the adverse effects on pilots' perception of their environment, including issues such as drowsiness, physical and mental fatigue, visual inattention, attentional tunnelling, and attentional entropy. Furthermore, it investigates broader conditions such as stress and workload which have a general influence on pilot attention. Moreover, with the primary objective of providing a comprehensive overview of how the perception of pilots can be effectively evaluated, this work integrates insights from biomedical sensors. By analysing how aviators' perception is impaired because the influence of deleterious factors cited above, this study contributes to the development of tailored solutions aimed at mitigating risks associated with reduced attention and vigilance.

As a conclusion, this paper sketches a conceptual map illustrating the interconnections between perception-related conditions, with the aim of serving as a road map for researchers and practitioners and facilitating a deeper understanding of complex relationships within the proposed framework.

1 INTRODUCTION

The criticality of modern air warfare puts increasing pressure on pilot performance and responsibilities. As a result, higher levels of automation are required to cope with the demands of the mission. However, there have been instances where automation has also proved detrimental to pilot performance (Gouraud et al., 2017).

Therefore, it is essential that this automation can be adaptable, with the pilot as the central axis of regulation. In this way, knowing the functional status of the pilot would allow the system to perform the specific actions and tasks required at each moment. This condition can be altered by various factors, including psychological, cognitive, and behavioural aspects (Martins, 2016; Zhang et al., 2020).

In this context, understanding these alterations is crucial for optimizing pilot well-being and mission outcomes. Specifically, conditions related to perception are intrinsic aspects of pilot performance, as they directly affect their ability to maintain situational awareness and make critical decisions in difficult environments. This situational awareness can be defined based on three different layers that explains how humans handle and process information in dynamic environments (Endsley, 1995):

1. The perception of key information relevant to the current state of the environment;

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2. The understanding of the significance this information has according to the current goals;
3. The projection of the future status to prevent possible situations.

In the aviation context, a paired state of these conditions with environment is crucial to ensure safety, decision-making, performance, risk mitigation and adaptability, among others. This study will focus particularly on the first of them, perception, and how it is computed based on the integration of different systems together with the assessment of pilot's functional state.

To this end, monitoring pilots' health and cognitive conditions is one of the fundamental pillars when designing a user-adapted automation system. In this case, these monitoring techniques require the use of biosensors, which measure human physiology, cognition, and behaviour to perform specific evaluations related to the health or performance of the individual. Some examples used for this purpose are electrocardiograms (ECGs), electroencephalograms (EEGs), or eye-trackers.

The primary objectives of this article are to explore the complexities of pilot condition impairment, focusing specifically on vigilance, attention, and other perception-related factors. By reviewing the latest research findings and theoretical frameworks, this paper aims to provide a comprehensive understanding of the interaction between these conditions and pilot perception, ultimately contributing to the development of effective strategies to improve pilot well-being and performance. Finally, the correlation between the conditions and the way they are measured, through biosensors, will be analysed.

2 THEORETICAL FRAMEWORK

2.1 Hypovigilance

Sustained attention, or vigilance, refers to the state in which attention must be maintained over time (Britannica, nd). A degraded state of this condition could be said to represent a state of hypovigilance (Sahayadhas et al., 2015).

Further conceptualization of this condition is provided in (Abbas and Alsheddy, 2021), emphasizing its association with cognitive and visual inattention, drowsiness and fatigue. The study is framed in the automotive industry, where hypovigilance detection systems use analysis of driver behaviour and physiological measures to identify signs of reduced alertness. Thus, drawing parallels, hypovigilance poses significant challenges to fighter pilot performance as it compromises the ability to maintain perception and respond effectively to dynamic flight conditions. Possible causes of hypovigilance, including distractions, boredom, sleep disturbances, and fatigue, directly affect the alertness and attentional resources of the pilot, and are closely related to other conditions where information processing is involved.

2.2 Fatigue, Drowsiness, and Sleep

Fatigue and hypovigilance contribute to the degradation of pilot alertness and performance in distinct yet interrelated ways. While hypovigilance represents a broader state of reduced vigilance and attentional resources, fatigue manifests as a specific physiological state characterized by decreased mental or physical performance capability due to sleep loss, prolonged wakefulness, circadian rhythm disturbances, or workload (ICAO, nd). This condition, often accompanied by sensations of tiredness and frustration, can arise from prolonged physical exertion or engagement in monotonous tasks, both of which are prevalent in the demanding aviation environment (Hooda et al., 2022).

When pilots experience fatigue, their ability to maintain optimal perception levels is compromised. Both civilian and military pilots are susceptible to the adverse effects of fatigue, which encompass diminished cognitive function, slower reaction times, and higher error rates, compared to a well-rested state (Caldwell et al., 2009). Furthermore, when discussing fatigue among fighter pilots, the risk of fatigue is heightened, given the demanding nature of their tasks and the inherent physiological and psychological stress associated with combat operations, especially on prolonged flights (Ohrui et al., 2008).

On the other hand, distinguishing between task-related and sleep-related fatigue provides valuable insights into the mechanisms underlying pilot fatigue and its impact on performance (May and Baldwin, 2009). Sleep-related fatigue is associated with insufficient sleep or operating during periods of the circadian rhythm when sleep is usually occurring. In contrast, task-related fatigue, resulting from prolonged participation in demanding activities or exposure to monotonous tasks, is tied to the task itself and its associated environmental factors such as temperature or humidity. In addition, it can exacerbate sleep-related fatigue, further compromising alertness and cognitive function of the pilot (Harding et al., 2019; Imtiaz, 2021; Kang et al., 2015).

As each type of fatigue represents a distinct physiological state, with unique implications for pilot performance (Borghini et al., 2014), it has been considered relevant for this study to differentiate it into the following concepts: mental fatigue and drowsiness (or sleepiness). Thus, based on the definition of the International Civil Aviation Organization (ICAO, nd), mental fatigue could be referred to as the reduction in performance capacity resulting from a prolonged workload or high task demands, while drowsiness could be associated with alterations in sleep patterns (Chowdhury et al., 2018; Guede-Fernandez et al., 2019; Rafid et al., 2020).

While mental fatigue is more associated with a decrease in cognitive performance due to sustained mental effort, drowsiness is more related to a physiological drive toward sleep. A person experiencing mental fatigue may be able to maintain concentration and performance for a time through compensatory effort. However, as the state progresses toward drowsiness, this becomes increasingly difficult and performance begins to decline significantly, reflecting the increasing need for sleep and the body's natural preparation for this transition (Borghini et al., 2014). Therefore, the main difference between the two states would be that short rest decreases mental fatigue, while it aggravates drowsiness (Stancin et al., 2021).

Considering the above-mentioned, drowsiness can be described as a physiological state in which the body is in transition from wakefulness to a sleeping state (Ngxande et al., 2017). According to this definition, drowsiness is frequently experienced by pilots during long-duration missions due to circadian rhythm disturbance, loss or interruption of sleep, and prolonged wakefulness; as well as during non-demanding tasks or monotonous activities that could end up in boredom. Performing sophisticated aircraft operations under reduced alertness is primarily associated with severe aircraft accidents (Board, 2018; M. R. Rosekind, K. B. Gregory, E. L. Co, D. L. Miller and Dinges, 2000), and drowsiness has been identified as a contributing factor to such accidents (et Al, 2012).

Another significant aspect of drowsiness is its close relationship with the state of sleep, to such an extent that they can be considered an evolution of states. That is, sleep could be defined as the circadian state that emerges in the final phases of drowsiness, marked by the appearance of partial or total suspension of consciousness, muscular inhibition, and reduced responsiveness to external stimuli. Moreover, the main driver of this continuum can be considered the level of alertness; a decreasing alertness that converges in the final state: sleep (Albadawi et al., 2022). Falling into a sleep state could compromise safety if it occurs at an inappropriate time, such as when piloting an aircraft. Furthermore, in the case of a fighter aircraft, the likelihood of a sleep episode can be influenced by several factors associated with the circadian rhythm disruptions, such as participating in prolonged missions without rest or night missions, and could even result in pilots experiencing what is known as Shift Work Sleep Disorder (Zou et al., 2022).

2.3 Inattention-Related Conditions

Having defined primarily physiological conditions that affect attention and vigilance, the next step will be to analyse inattention as manifested through various cognitive and behavioural processes, illustrating the intricate ways in which attention can be deteriorated in demanding environments. For example, attention may be unintentionally diverted from the task at hand as thoughts wander to unrelated matters. This phenomenon often occurs during periods of monotony or boredom and shows how cognitive resources may inadvertently divert from the demands of the task, what is often referred to as mind wandering (Smallwood and Schooler, 2015). This detour of attention can also be abrupt, due to a sudden, unexpected, overwhelming stimulus. At such moments, a rapid physical and mental response (startle effect) is produced (Deniel et al., 2023), which causes the attention to be momentarily disconnected from the current task (Diarra et al., 2023).

On the other hand, perseveration, another facet of cognitive inattention (Dehais et al., 2019), highlights the challenges in adapting to shifting circumstances. When individuals have difficulty redirecting their attention in response to changes in situations, they may become locked into outdated mental frameworks, impeding their ability to interact effectively with new information (Dehais et al., 2010). Perseveration is intrinsically related to one aspect of behavioural attention, attentional tunnelling. In this state, attentional resources are largely used to select and process subjectively relevant information, and attention is arguably channelled (Baddeley, 1972). In contrast, focusing on many stimuli at once could lead to a failure to focus attention on relevant information. This lack of focus may manifest itself in another behavioural condition known as attentional entropy, due to high entropy in the attentional pathway (Ayala et al., 2023).

2.4 Hypervigilance and Performance-Related Conditions

Hypervigilance is closely related to these attention-related conditions, as it involves an abnormal increase in attention to threat-related stimuli and difficulty disengaging attention from such stimuli (Kimble et al., 2014; Zawilinski, 2020). Thus, in the face of high-priority targets, hypervigilance may lead to amplified attention or increased scanning speed, eliciting atypical alertness. In addition, hypervigilance has been associated with disorders such as depression, anxiety, or post-traumatic stress disorder, among others. The latter is intrinsically related to stress, a common phenomenon among aircraft pilots, who face various sources of physical and psychological demands (stressors) in their work environment, such as persistent noise, uncomfortable temperature, or lighting conditions. In the case of fighter pilots, not only are these stressors exacerbated by the nature of the aircraft, but others are added, such as psychological stress arising from combat and mission-specific operations (Sullivan-Kwantes et al., 2021). Mental workload can act as one of these stressors, but it is a condition in itself derived from high task-related demands compared to available cognitive resources (Gaillard, 1993). Furthermore, sustained stress and mental workload can lead to mental fatigue and decreased performance (Holm et al., 2009; Kunasegaran et al., 2023).

3 HOLISTIC ANALYSIS

3.1 Perception Framework

The previous section has shown that pilot perception is affected by a multifaceted set of conditions and their complex interactions. This section holistically addresses each of these states to understand the factors influencing pilot well-being and operational effectiveness comprehensively.

Figure 1 describes the theoretical framework of the subject of this paper, showing the main factors that alter perception:

- Tiredness may negatively impact pilot attention, leading to decreased alertness and increased risk of errors during flight;
- Boredom could lead to decreased vigilance and reduced focus on the pilot;
- Sleepiness and circadian rhythm alterations require early detection before the mission begins. They may impair pilot attention, resulting in reduced alertness and susceptibility to errors, which can pose significant risks to flight safety;
- Sleepiness and circadian rhythm alterations require early detection before the mission begins. They may impair pilot attention, resulting in reduced alertness and susceptibility to errors, which can pose significant risks to flight safety;
- Inattention could significantly compromise pilot vigilance, potentially leading to missed critical cues or hazards, and increasing the likelihood of errors or accidents during flight. Distractions, surprises, extreme focus, and dispersion are the leading causes of inattention that are unrelated to the other factors;
- Performance refers to the relationships between fatigue, mental workload, and stress, as the continuity of the different demands and stressors that could occur during the mission generates mental fatigue by overloading their mental capabilities. Complex task demands, high-stakes situations, and the need for rapid decision-making can contribute to lapses in attention and vigilance among fighter pilots.

All these factors could potentially compromise the ability of the pilot to maintain perception and respond effectively to critical events during flight, leading to a state of hypo/hyper-vigilance. This could correspond to the expected output that the proposed pilot health monitoring system would be waiting for to assist the pilot, guide their attention, reduce their tasks, or apply the adequate action according to their current attentional capabilities.

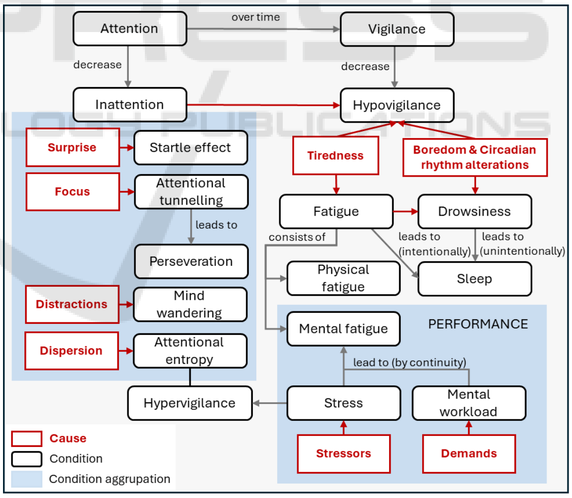

Figure 1: Proposed cognitive model for perception.

On the other hand, there may arise situations where the pilot becomes incapacitated to fulfil his duties appropriately. Fighter cockpits are highly complex and dangerous environments where pilots must specially maintain their orientation, body functions and consciousness, to avoid spatial disorientation and sensory illusions, alterations in respiratory, thermal, glucose or hydration levels, and loss of consciousness. In this extreme case, the aircraft should take control.

Therefore, according to our study, it could be possible to address three levels of perception assessment considering the physiology, behaviour, and cognition of the pilot: alertness, performance, and incapacitation. The next step is to conceptualise the future fighter cockpit pilot monitoring system and how to evaluate the functional state of the pilot based on perception.

3.2 Pilot Monitoring System

In-flight pilot condition monitoring is a significant concern for countries to guide future advances in aerospace engineering and promote flight safety and efficiency (Shaw and Harrell, 2023). To this end, it is necessary to integrate physiological sensors and other devices (such as cameras or microphones) into the aircraft to provide a multi-modal monitoring system. For instance, previous studies have shown that pulse oximetry, respiratory gas exchange, ECG or EEG are among the most promising (Shaw and Harrell, 2023). Following these as baselines, the sensors proposed to compose this monitoring system for the defined pilot perception framework are detailed in the correspondence matrix (Table 1).

By analyzing this matrix, two clusters of sensors can be identified: The first cluster encompasses sensors with broad applicability across various conditions. For example, ocular sensors (eye-trackers), offer versatile implementation across different conditions, enabling assessment of pilot performance in diverse physical and cognitive contexts (Nemcova et al., 2021). Similarly, cardiac technologies, such as ECGs and photoplethysmograms (PPGs), provide biomedical indicators such as heart rate variability, aiding in understanding autonomic nervous system regulation due to varying stress levels, physical fatigue, mental workload, and changes in cognitive demand. These sensors have also proven useful in predicting drowsiness, sleep, vigilance levels and mind wandering (Adão Martins et al., 2021; Burrell et al., 2016; Lohani et al., 2019). Additionally, all these conditions can be detected by recording the electrical activity of the brain, for example through non-invasive sensors such as EEG, and examining its parameters and their variability (Kumar and Bhuvaneswari, 2012; Stancin et al., 2021). Electrodermal activity (EDA) sensors search for a physical response to these states by measuring variances in skin conductance response and conductance levels (Khushaba et al., 2011). Furthermore, respiratory sensors, such as oxygen and carbon dioxide concentration and flow meters, provide different gas exchange metrics, including respiratory rate and volume. These parameters are strongly related to fatigue and monitoring drowsiness (Chowdhury et al., 2018). Motor sensors (electromyograms, cameras, and accelerometers) also contribute to this cluster by detecting body positioning and body segment neuromuscular activities (In-Ho Choi and Yong-Guk Kim, 2014).

The second cluster comprises to sensors tailored to specific conditions. Acoustic sensors (microphones), for instance, capture vigilance or sleep-related states through voice interactions (Kaur and Singh, 2023). On the other hand, thermal activity sensors predict core body temperature, offering insights into emotional states, arousal levels, and stress reactions triggered by cockpit environmental conditions (Shetty et al., 2015; Trujillo, 1998). Lastly, glucometers focus on detecting blood glucose concentration and predicting trends in glucose levels, with implications for assessing physical fatigue (Velasco et al., 2022).

In essence, the true power of pilot monitoring lies not in the capabilities of individual sensors, but in their collective integration. Each sensor brings unique insights, but it's their combined data that offers a comprehensive understanding of pilot states. This comprehensive monitoring approach, facilitated by the collective integration of sensors, is a significant step towards enhancing aviation safety and efficiency, providing reassurance in the thoroughness of our proposed system.

4 DISCUSSION

In the rapidly evolving landscape of modern air warfare, developing automation systems tailored to the functional state of the pilot is urgently necessary. These systems, designed to enhance pilot and mission performance, must address the complex interactions of impairments that deteriorate pilot conditions influenced by psychological, cognitive, and behavioural factors. Understanding these relationships is crucial for developing effective strategies to design pilot monitoring systems that aim to improve pilot well-being and mission outcomes.

This study presents a comprehensive framework that organizes the first layer of situational awareness – perception - within the context of future cockpits. By breaking down perception into three fundamental pillars - alertness, performance, and capability – a structured approach to evaluate and comprehend the factors integral to pilot condition can be provided. As for the level of alertness, given that vigilance is essentially the result of sustained attention, the causes related to its absence have been highlighted as the

Table 1: Relevance matrix between conditions and monitoring system components. X indicates condition measured by sensor.

	CONDITIONS[1]									
SENSORS	**V**	**D**	**SL**	**ST**	**PF**	**MF**	**MWL**	**MW**	**AT**	**AE**
Acoustic	X	X	X							
Cardiac	X	X	X	X	X	X	X	X		
Cerebral	X	X	X	X	X	X	X	X		
Electrodermal	X	X		X	X	X	X	X		
Glucose					X					
Motor	X	X	X		X			X		
Ocular	X	X	X	X	X	X	X	X	X	X
Respiratory	X	X	X	X	X	X	X			
Thermal	X	X			X					

[1] V: Vigilance; D: Drowsiness; SL: Sleep; ST: Stress; PF: Physical Fatigue; MF: Mental Fatigue; MWL: Mental Workload; MW: Mind Wandering; AT: Attentional Tunnelling; AE: Attentional Entropy

first to be monitored. Drawing from the literature, this study has identified and unified attention disorders: surprises and distractions for cognitive conditions; and extreme focus and dispersion for behavioural. As secondary disorders, startle effect and mind wandering have been reported as cognitive conditions; and attentional tunnelling, perseveration, and attentional entropy as behavioural ones. In terms of physiological conditions, drowsiness has been identified as the primary one caused by boredom, circadian rhythm alterations, fatigue, and, in extreme cases, falling asleep. Based on this premise, the leading reported causes of impaired vigilance capabilities are inattention, tiredness, boredom, and circadian rhythm alteration.

Furthermore, a positive balance between stress, mental workload, and fatigue is critical for pilot performance. Such conditions are influenced by complex tasks demands, high-risk situations, and the extended need for rapid decision-making. Therefore, pilot performance is assumed to decrease since the beginning of the mission. Finally, physical disturbances leading to incapacitation (such as loss of consciousness, spatial disorientation, or body malfunctions) are considered within the last pillar of perception.

The primary function of the monitoring system is to track the evolution of pilot state, based on their situational awareness, and to determine the appropriate level of task automation. To achieve this, this study has identified a set of sensors that can cover the conditions related to the first layer of situational awareness. Table 1 outlines the correlation between these conditions and the necessary sensors for their measurement and evaluation. It is important to note the need for a multi-modal approach that can differentiate between conditions and provide a comprehensive assessment of those that occur simultaneously. Through this holistic monitoring approach, while vision is the primary mode of (to evaluate the visual attention and vigilance capabilities of the pilot), other sensory channels are also utilized to address complex and specific cognitive states.

While this study provides valuable insights into pilot cognition and behaviour, it acknowledges its current limitation in not fully exploring the broader context involving a myriad of conditions and possible circumstances. Additionally, the framework is still at a preliminary stage, awaiting experimentation and computation to further refine the proposed perception assessment. This presents an inspiring opportunity for future research and development in this field.

Future research to overcome these limitations will require creating a complete model of the pilot functional state alongside corresponding experimental protocols regarding pilot perception capabilities over a multi-modal approach. It would also be valuable to consider incorporating the other two layers of situational awareness - relevance and anticipation - thereby complementing the scope of this study. In the future, this refined framework may serve as a foundational basis for developing advanced machine and deep learning models aimed at detecting, differentiating, and predicting the various states constituting the situational awareness framework in pilots. Moreover, these models could focus on the interpretation of their results, ensuring clarity on how and why specific states are classified or predicted.

5 CONCLUSIONS

In conclusion, the findings of this study shed light on a holistic approach of pilot's perception of their surroundings. By conducting an integrated analysis of the physiological, cognitive, and behavioural conditions involved, as well as their relationship, this study has built a conceptual framework regarding key factors influencing pilot perception. Furthermore, by examining the correlation between sensors and conditions, the need for a multi-modal approach has been highlighted. This will provide means to quantify the different perception levels identified, improving the ability to effectively address and assess them. Overall, this study contributes to expanding the literature on condition monitoring and underscores its importance in the military aviation field.

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