Summary

Human-machine interaction (HMI) is a key concept in human factors and ergonomics (HFE), focusing on enabling efficient task performance in complex systems. As HMI expands into domains like Industry 4.0, aviation, and healthcare, the growing complexity of interactions raises mental workload (MWL) and stress, potentially impairing performance and increasing accident risks. This underscores the need for HMI systems capable of real-time monitoring and adaptive response to cognitive states. In aviation, monitoring pilots' psychophysiological conditions has gained importance, particularly with the potential shift toward Single Pilot Operations (SPOs) in civil flights and the necessity of increasing safety in helicopter missions. This shift requires novel approaches to ensure safety levels meet stringent regulatory standards.

This research uses a multi-modal approach to investigate the relationship between stress, MWL, and physiological signals. Six physiological signals—heart activity, skin activity, peripheral temperature, respiration, brain activity, and ocular movements—were analyzed for their connections to stress and MWL demonstrated by the literature. Recent advancements in wearable, unobtrusive devices have enabled precise physiological assessments in dynamic environments, expanding opportunities beyond traditional subjective and behavioral methods.

To address the lack of standardized assessment methods, a tailored "foundation" was developed. This involved cognitive tests—Stroop and Visual, Auditory, and Dual N-Back—designed to elicit targeted cognitive states. Data collected from 99 participants yielded 108 features from physiological signals linked to three levels of perceived stress and MWL. Statistical tests (Kruskal-Wallis, Mann-Whitney) and machine learning algorithms were employed to differentiate and predict cognitive states. Results showed robust differentiation between relaxed and altered states, with multi-class classification achieving up to 85% accuracy and F1 scores for stress and MWL predictions.

Following these preliminary computerized tests, the methodology was tested using a high-fidelity A320 simulator in an aeronautical context. Three pilots conducted missions with varying cognitive demands while physiological data were collected and processed. Perceived MWL was assessed using the NASA TLX subjective questionnaire for each test phase. Signals related to brain activity, skin

conductance, and ocular movements effectively differentiated between MWL levels, showing a strong correlation with the NASA TLX ratings.

The methodology was also applied to a helicopter environment in a roll attitude-tracking task with multiple cueing modalities (visual, degraded visual, haptic, audio, and combinations). Optimal visual conditions yielded the lowest MWL, while degraded or denied visual inputs increased cognitive load. Secondary sensory cues alleviated MWL under poor visual conditions, demonstrating a strategy for cognitive load management. Respiration proved the most reliable MWL indicator, while skin activity and peripheral temperature had limited sensibility in this case. Heart and brain activity showed inconsistent results, requiring additional investigation. Performance and MWL correlations varied across modalities, with stronger relationships observed in non-visual cueing conditions (e.g., audio, audio-haptic, and haptic).

In conclusion, no existing solution comprehensively integrates multimodal physiological signals for cognitive state assessment while being validated in both large populations and high-fidelity aviation environments. This research addresses this gap by exploring the complex relationship between stress, MWL, and physiological signals, leveraging AI-driven analysis to enhance pilot performance and safety. Specifically, this study highlights the potential of a multimodal physiological approach combined with AI algorithms to facilitate the transition toward SPOs and improve safety in helicopter missions. This is particularly relevant as the aviation industry continues to evolve, driven by the rapid advancement of biomedical sensor technology. The increasing availability of smaller, more affordable, and reliable wearable sensors opens new possibilities for real-time cognitive state monitoring, contributing to the development of next-generation aircraft and enhancing overall aviation safety.