

Creating a Framework for the Collection of Biometric and Environmental Data During Collegiate Flight Training

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ABSTRACT

The aviation industry has long recognized fatigue as a critical safety hazard, yet fatigue management strategies have predominantly focused on long-haul commercial operations (Olaganathan et al., 2021). This focus leaves significant gaps in General Aviation (GA) specifically the collegiate flight training sectors (Mendonca et al., 2021). The purpose of this ongoing research project is to investigate the psychophysiological experiences of flight students and certified flight instructors who operate within a rigorous academic environment that also includes high-stakes flight training. To advance our understanding of pilot performance, the researchers are collecting and analyzing high fidelity multimodal data. The current study employs a comprehensive sensor suite to capture the interaction between a pilot's internal state and the physical environment of the training aircraft. The research utilizes biometric data such as heart rate (HR), electrocardiography (ECG), electrodermal activity (EDA), heart rate variability (HRV), and other data to monitor physiological responses. Concurrently, the team measures environmental factors such as noise, vibration, and temperature. This objective data is paired with subjective pre-flight and post-flight surveys to provide a more complete context for each training event. By integrating these distinct data streams, the research team can identify trends and patterns. The analysis further explores how physiological metrics fluctuate during various flight training activities. This paper will discuss how multimodal monitoring can be incorporated into flight training activities, lessons learned, and future research opportunities. Ultimately, the progression of this type of research will support the development of next-generation flight risk assessment, including Fatigue Risk Management Systems (FRMS) that are specifically tailored to the unique flying of collegiate aviation pilots.

Keywords: Aviation fatigue, Stress, Heart rate variability, Whole-body vibration, Cockpit noise, Multimodal sensor fusion, Machine learning

INTRODUCTION

NASA research suggests human error contributes to ~70% of aviation accidents (Helmreich, 2000). NTSB summaries indicate roughly 1,400 U.S. civil aviation accidents occurred in 2024, with most in general aviation, including many training aircraft (NTSB, n.d.). Fatigue is implicated in about 20–23% of accident investigations (Caldwell, 2012; NTSB, 2016).

Fatigue is commonly defined as a physiological state that reduces mental or physical performance and impairs alertness (IATA et al., 2015; ICAO, 2020). Guidance attributes impairment primarily to sleep loss, extended wakefulness, circadian timing, and workload; U.S. regulations similarly define fatigue as reduced performance from insufficient sleep or increased physical activity that diminishes alertness (14 C.F.R. § 117.3, 2026; FAA, 2012). Collectively, these frameworks treat fatigue as a systems risk arising from the interaction of scheduling, sleep opportunity, circadian phase, and the operational environment (FAA, 2013; ICAO, n.d.).

Collegiate flight training is a high-risk testbed: students fly unpressurized aircraft with limited environmental control while performing repetitive takeoffs/landings and demanding instrument tasks under sustained attention, with persistent noise and vibration exposure (GAO, 2017; Mansfield & Aggarwal, 2022). Evidence suggests fatigue in collegiate populations is multifactorial and may not be fully captured by standard safety management practices (Keller et al., 2022). Because self-reports, duty limits, and post-incident analyses can miss within-flight, short-window cognitive degradation, research has shifted toward continuous objective monitoring (Wingelaar-Jagt et al., 2021). Wearable physiology and data-driven models increasingly enable real-time inference of fatigue- and stress-related risk states (Martins et al., 2021). This paper reviews multimodal monitoring evidence in collegiate operations and describes ongoing collection of synchronized environmental and physiological data to characterize these risks.

LITERATURE REVIEW

Environmental Stressors and Human Performance

Work in occupational and transportation settings indicates that environmental stressors relevant to reciprocating aircraft operations often co-occur and can jointly degrade cognitive and motor performance. In controlled exposure research manipulating air temperature and noise, increasing noise significantly impaired working memory, sustained attention, and reaction time; in several task configurations, combined exposures produced larger effects than single stressors (Sepehri et al., 2019). Recent experimental work similarly suggests that simultaneous thermal stress and noise can amplify physiological strain and cognitive impairment relative to single-stressor exposure (Yousefinezhad et al., 2026). Although these studies were not conducted in aviation, they are consistent with broader evidence that persistent environmental noise can elevate cognitive load and reduce performance on complex tasks, particularly when combined with other stressors.

In aviation contexts, the value of environmental measurement is also supported by research on cockpit air quality variables. In flight simulation work with commercial airline pilots, both CO₂ exposure and heart rate variability (HRV) were independently associated with performance differences, suggesting that environmental telemetry can explain variance in outcomes beyond task difficulty alone (Cao et al., 2019). While piston aircraft differ from transport-category aircraft in ventilation and operational profiles, the broader implication is that cockpit environmental conditions can contribute to performance variability and should be measured rather than assumed.

Whole-body vibration is another exposure relevant to reciprocating aircraft. A state-of-the-science review of whole-body vibration in fixed-wing aircraft concluded that, despite aviation's scale, reported vibration exposure data remain limited and measurement practices are not consistently standardized (Mansfield & Aggarwal, 2022). Cross-sector experimental evidence further suggests that vibration can interact with thermal stress to degrade objective motor performance. For example, a simulator-based study of city taxi drivers found that combined heat and whole-body vibration degraded balance and grip strength more than heat alone (Aghamiri et al., 2022). Although cockpit tasks differ from driving, these findings support the plausibility that combined vibration and heat can reduce functional reserve in operators who must maintain postural stability and fine motor control over extended periods, such as during multiple training flights in a single day.

Biometric Indicators of Workload, Stress, and Fatigue

To connect external exposures and task demands to internal state, aviation human factors research increasingly relies on continuous physiological monitoring. HRV is a widely used index of autonomic regulation and is often applied as an objective marker of workload and psychophysiological strain. In an aviation workload study combining HRV metrics with the NASA Task Load Index (NASA-TLX), HRV was used to complement subjective workload reporting and to examine associations between perceived and physiological workload during flight-related tasks (Alaimo et al., 2020). These approaches are relevant to collegiate training because perceived fatigue and workload may not reliably reflect short-duration performance degradation under sustained demand.

Device validity is central to applying HRV in operational settings. Chest-strap electrocardiography (ECG) devices are commonly selected for field studies because they provide higher-fidelity interbeat interval data than wrist-based photoplethysmography under movement. Validation research comparing the Polar H10 chest strap with clinical ECG reported strong agreement for R–R intervals and several linear HRV metrics, while also noting that some non-linear indices may be more sensitive to measurement conditions (Schaffarczyk et al., 2022). This evidence supports the use of chest-strap ECG for collegiate flight monitoring, where vibration and control inputs may introduce artifacts.

Electrodermal activity (EDA) provides a proxy for sympathetic arousal and can capture acute stress responses. However, EDA and other wrist-worn

wearable signals are susceptible to motion artifacts, particularly in contexts requiring sustained hand and arm movement. In a stress-inducing driving study, wrist-worn device accuracy for HRV and EDA was evaluated under realistic movement and stress conditions, reinforcing the need for signal-quality assessment and artifact handling in field deployments (Costantini et al., 2023). In flight training environments, EDA may therefore be most informative for detecting acute arousal during discrete events, with interpretation conditioned on movement and vibration levels.

Because individual physiological signals are rarely specific to fatigue alone, researchers increasingly advocate multimodal monitoring approaches that integrate multiple physiological and environmental streams to improve inference about fatigue- and stress-related states.

Multimodal Fusion and Predictive Modeling

Unimodal fatigue markers are rarely fatigue-specific. HR and HRV also reflect stress, workload, hydration, thermal strain, and exertion, while EDA primarily indexes arousal that may not track cognitive decline. As a result, transportation safety research increasingly favors multimodal fusion, synchronizing physiology with environmental telemetry and, when feasible, neurocognitive measures.

Recent aviation work supports this approach. Chen (2026) fused short-term electroencephalogram (EEG) and ECG features and reported 88.42% cross-subject accuracy using XGBoost, suggesting multimodal features can generalize across individuals. Related EEG-based studies also show interpretable pipelines can classify attention- and workload-relevant states (Alreshidi et al., 2023). While not specific to collegiate pilots, these findings motivate synchronized multimodal monitoring with supervised learning.

For deployment, confounding by phase of flight and task difficulty is central: takeoff, landing, and emergency drills can elicit fatigue-like physiological spikes in rested pilots. Cross-subject validation and phase-of-flight modeling are therefore essential for translating models from controlled datasets to training flights, consistent with guidance to integrate multiple data streams rather than rely on a single indicator (ICAO, 2020).

Synthesis and Implications for Collegiate Reciprocating Aircraft Research

Evidence from aviation and related transportation domains suggests three points motivating this study. First, stressors in light, unpressurized aircraft noise, heat, and vibration co-occur and can jointly degrade cognitive and motor performance. Second, wearables can support objective workload assessment, but training cockpits require motion-robust devices; validation studies indicate chest-strap ECG provides HRV fidelity in high-movement conditions, whereas wrist-worn sensors are more artifact-prone. Third, single physiological signals (e.g., heart rate, EDA) are not fatigue-specific, so multimodal fusion is preferred for reliable state inference. Despite fatigue-related risk in general aviation, this approach has not been systematically

applied to collegiate flight training. Accordingly, we treat fatigue as a time-varying state shaped by sleep, scheduling, task demand, and cockpit conditions, and integrate environmental telemetry with validated physiology to support risk assessment tools tailored to collegiate pilots.

METHODOLOGY

This study employed a naturalistic observational design to collect synchronized physiological and environmental data during collegiate flight training operations. The research team consists of faculty members from aviation, health sciences, and applied and creative computing. Prior to commencement of the study, the team received Institutional Review Board (IRB) approval for their proposed work with human subjects. Additionally, the aviation faculty coordinated with various stakeholders within their department, including the school head, chief flight instructor, safety team, and maintenance personnel. Conversations also took place with representatives from the FAA, and their feedback was considered in the study design.

As part of the IRB approval process, biometric and environmental monitoring equipment was selected. The health sciences faculty member already had a strong working knowledge of devices available and their applicability to this research. The devices were tested for suitability within the collegiate flight training program, and the research team decided which equipment was most appropriate. The selection of wrist-worn devices presented a challenge due to various manufacturers, sunseting and competing models, and the quantity and quality of data derived from the devices.

Much of the equipment used in the study was already owned by the university. Additional and updated equipment was procured through support from the research team's discretionary accounts and an internal grant received from the university. As the study expands both in scope and number of participants, additional funding has been sought from external organizations.

Consistent with the IRB protocol, participants were recruited from aviation classes. These courses aligned with students working towards their instrument, commercial, and multi-engine certifications. These stages of flight training are particularly rigorous, demanding students balance their academic courseload requirements with flight training schedules, along with extracurricular, personal, and work obligations. These concurrent commitments render this population of flight students particularly vulnerable to fatigue. This creates an opportunity for the researchers to measure and analyze fatigue before, during, and after flights. Further, the participants may reflect on this information and how fatigue may have impacted their performance. In the long term, participants can use this information to inform their decision making on fitness for flight and health implications.

More flight students than could be accommodated expressed an interest in participating in this study. Limiting factors included the availability of research team members with participant flight schedules, the number of sensors accessible for a flight, the battery life and data storage capacity of sensors, and inclement weather or maintenance issues disrupting scheduled

flights. The research team endeavored to select flights that represented varying lengths and missions.

The day before each proposed flight, a member of the research team distributed intake forms to the participant. These included informed consent, demographic and health information, the Karolinska Sleep Questionnaire, and the Perceived Stress Scale. On the day of the flight, participants met with a member of the research team approximately 30 minutes prior to their lesson. At that time, students were outfitted with the sensors, performed a Psychomotor Vigilance Test (PVT) and hand grip test, and completed an immediate state form, which asked for their fatigue and stress levels.

After completion of the flight lesson and debriefing with their instructor, participants returned to the research team member for approximately 15 minutes. At that time, the participant performed another PVT and hand grip test and completed another form asking participants to rate their post-flight fatigue and stress levels. Sensors were returned to the research team at that time.

One limitation of this study design is that participants cannot return to the research team member immediately following their flight. A critical element of training is a debrief with the instructor immediately following the lesson. The research team strove to disrupt the training process as little as possible. Data collection was secondary to the lesson requirements.

Upon completion of data collection, all forms and test results were uploaded to a secure shared folder among the research team. The hard copies of the forms were maintained in a locked office. Data analysis was then initiated by the health sciences and applied and creative computing research team members. They were assisted by undergraduate students in their respective fields who demonstrated interest in this research project. The next section will discuss lessons learned throughout the ongoing project.

DISCUSSION

Lessons Learned

Deploying biometric and environmental monitoring equipment in a collegiate flight training environment yielded several practical insights for future field research. Substantial lead time was needed to coordinate with institutional and operational stakeholders (e.g., flight operations leadership, safety and maintenance personnel, certified flight instructors, the Federal Aviation Administration, and the university's Institutional Review Board) to ensure compliance with operational safety requirements. To prioritize flight safety, the team evaluated equipment weight, lithium-ion battery constraints, and mounting security. These requirements led to the development of custom 3D-printed holders for specific devices, such as the heat stress meter. Repeated ground testing in an operational aircraft ensured that sensor placement did not obstruct normal, abnormal, or emergency flight procedures.

Field deployment also introduced challenges related to sensor reliability and data management. Ensuring that each device was initialized and recording before flight required standardized preflight checks, particularly after instances in which devices stopped recording unexpectedly. Early testing revealed that an incompatible SD card prevented environmental data from being recorded

on the heat stress meter, underscoring the importance of validating storage media and device settings before each sortie. Time alignment across devices required additional attention: although sensors were configured to local time, flights that crossed time zones required post hoc time conversions. Event marking across data streams was also difficult because participants could not record timestamps during flight without distraction. Instead, operational milestones (e.g., engine start/shutdown and departure/arrival times) served as reference points for aligning physiological and environmental data. Post-flight debrief procedures were refined to capture additional events needed for synchronization during analysis.

Wearable sensor performance presented further technical constraints. Motion artifacts occasionally degraded data quality, particularly for wrist-worn devices. Electrodermal activity signals collected with Empatica sensors sometimes showed brief gaps or irregular values associated with arm movement and cockpit vibration, requiring additional post-processing and highlighting the importance of selecting devices that maintain signal integrity in dynamic operational environments.

Operational logistics within flight training also affected data collection. Scheduling research flights was frequently constrained by weather variability, aircraft availability, and competing student and instructor schedules, often requiring multiple attempts to complete a single flight. Participant availability further shaped data collection timing because instructional debriefs occur immediately after lessons. As a result, study procedures—including fitting sensors, administering baseline assessments, retrieving equipment, and completing post-flight surveys and performance tasks could require up to 35 minutes both before and after flight. Recruiting participants without conflicting obligations was therefore important for maintaining consistent data collection.

Future work will expand the dataset to support more comprehensive analyses of physiological responses, environmental stressors, and operational workload during flight training. As additional flights are collected across aircraft types, lesson profiles, and instructor–student pairings, the research team will examine how multimodal biometric signals (e.g., heart rate variability, electrodermal activity, and electrocardiographic measures) vary across phases of flight and under cockpit environmental conditions such as vibration, noise, and temperature. A larger dataset will also strengthen alignment among physiological data, environmental exposures, and operational events. Over time, these data may support fatigue monitoring approaches and mitigation strategies tailored to collegiate flight training and contribute to fatigue risk management practices that incorporate objective physiological and environmental measurement.

CONCLUSION

This paper presents a practical framework for collecting synchronized biometric and cockpit environmental data during collegiate flight training. The approach integrates physiological measures (heart rate, heart rate variability, electrocardiography, and electrodermal activity) with environmental

indicators (cockpit noise, vibration, and temperature). Structured pre- and post-flight surveys and performance tasks provide additional context for interpreting physiological responses during training flights. Collectively, these methods complement fatigue assessment approaches that rely primarily on scheduling models or subjective self-report. They also enable more temporally specific characterization of fatigue- and stress-related states.

Collegiate aviation training offers a valuable naturalistic setting for advancing multimodal human performance monitoring. As additional data are collected, the framework can support these analyses. Specifically, it can examine how physiological markers and performance outcomes vary with environmental stressors and operational demands across training missions. Insights from this work may inform fatigue risk assessment and mitigation strategies better aligned with the irregular schedules, constrained cockpit environments, and high instructional workload typical of flight training operations.

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