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Wearable Multimodal Sensing for Pilot Stress and Fatigue Monitoring Across Real-World Flight Phases

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ABSTRACT

This exploratory study looks at patterns of stress and fatigue among four student pilots during flight training, using a mix of physiological recordings and self-reported measures. Physiological data, including heart rate (HR), electrodermal activity (EDA), skin temperature, and acceleration, were collected continuously during flight sessions, while perceived stress and fatigue were also recorded through questionnaires before and after each flight. The signals were then examined across flight phases to identify trends in arousal. EDA and skin temperature were seen to gradually increase across flights. Heart rate responses were more event-specific, with noticeable peaks during more demanding flight segments. Together, these patterns may indicate a gradual buildup of workload-related fatigue, as all four pilots reported greater fatigue post-flight. However, these observations do not establish that the signals specifically measured stress or fatigue; heat, movement, and differences between flights may also have contributed. The findings are exploratory and require confirmation in larger, more controlled studies.

Keywords: Stress, Fatigue, Physiological signals, Aviation safety, Multimodal sensing

INTRODUCTION

Flight operations place pilots under sustained mental and physical demands that can reduce alertness, judgment, and overall performance. Fatigue has been identified as a contributing factor in aviation accidents (Goode, 2003), and these risks are particularly relevant in training settings, where pilots must manage workload, changing conditions and time-sensitive decisions while still gaining operational experience.

Previous work has shown that physiological measures can provide useful real-time information about pilots' mental and physical states during flight (Haarmann et al., 2009). Operational stressors such as workload, poor communication quality, and night flying may further increase cognitive

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load (Socha et al., 2018). Importantly, stress and fatigue are not constant throughout a flight. They shift between phases, which means assessments taken only before or after a session can miss short periods of heightened demand. Continuous monitoring helps capture those changes as they occur. This study examines heart rate, electrodermal activity, skin temperature, and acceleration, along with pre- and post-flight self-reported stress and fatigue and sleep questionnaire. The goal is to characterize within-participant changes across real-world flight phases and explore whether physiological patterns coincide with high-demand events and self-reported stress and fatigue.

RELATED WORK

Research on pilot workload traditionally relied on self-report tools like the NASA Task Load Index (NASA-TLX), the Multidimensional Fatigue Inventory (MFI), and various other questionnaires (Gomez et al., 2024; Pfeifer et al., 2024). While these are valuable, especially for capturing how pilots subjectively experience their workload, they are typically completed before and after the flight. Therefore, they provide limited visibility into changes that occur during the specific phases of flight.

To fill that gap, more recent work has started addressing this by recording physiological signals continuously throughout flight sessions. Heart rate and heart rate variability have been used to track workload and stress, while electrodermal activity has served as a marker of sympathetic arousal (Regula et al., 2014; Setz et al., 2009). Some work has also looked at combining EDA, photoplethysmography, and skin temperature to detect stress and mental workload (Luzzani et al., 2024), and physiological monitoring has shown clear value in examining pilot response during simulated and high-demand flight conditions (Haarmann et al., 2009).

Although these signals provides continuous data, they are often analysed separately from subjective reports. Without bringing them together, it is difficult to understand how what the body is registering relates to how a pilot perceives their stress and fatigue. Most of this work has also been conducted in simulators or controlled settings rather than during actual flights. There remains limited research that combines multiple wearable physiological signals with self-reported measures during real-world student pilot training. That gap is what motivates the multimodal approach in this study, examining both physiological and subjective data together across flight phases.

DATA COLLECTION AND METHODS

Setting and Participants

Four healthy student pilots from Purdue University's flight training program participated in this study. All four were relatively early in their aviation careers, with between 100 and 300 logged flight hours when the data was collected. None of them reported any cardiovascular, neurological, or sleep disorders. Ages ranged from 19 to 20, three males and one female.

Pilots Alpha, Bravo, and Delta flew cross-country training routes with long cruise segments at higher altitudes without a lot of rapid task switching.

Pilot Charlie, on the other hand, had a local training session heavy on performance maneuvers and emergency procedures at lower altitude in warmer weather. These differences were considered when interpreting the physiological responses.

All participation was voluntary, and all participants provided informed consent. The study was approved by Purdue University's Institutional Review Board (IRB).

Preliminaries and Data Collection

Throughout each flight, physiological signals were recorded continuously using an Empatica EmbracePlus, a wrist-worn wearable device with multiple built-in sensors. The device simultaneously captured HR, EDA, temperature (TEMP), and accelerometer (ACC) data. HR, EDA and temperature served as the indicators of physiological arousal, while acceleration was used to identify motion-related artifacts.

Sleep-related variables came from the Karolinska Sleep Questionnaire (KSQ). The KSQ consists of three primary factors: *Sleep Quality*, *Non-Restorative Sleep (NRS)*, and *Sleep Apnea* (Nordin et al., 2013). Only the sleep quality and NRS subscales were analyzed because they were most relevant to stress and fatigue outcomes (Tafoya et al., 2023; Tinajero et al., 2018). Sleep quality captures sleep initiation continuity and disturbance, representing stress-related sleep problems (Tafoya et al., 2023). Non-Restorative Sleep (NRS) captures poor restoration and low energy, which overall inclines towards fatigue-related issues (Tinajero et al., 2018). Subscale scores were calculated as the mean item response and normalized to a 0-1 scale. Higher values mean higher sleep disturbance or poorer restorative sleep depending on the category.

Perceived stress and fatigue were assessed using the 10-item Perceived Stress Scale (PSS-10) (Smith et al., 2014). Flight-related stress and fatigue were assessed immediately before and after each flight using Visual Analog Scale (VAS) ranging from "no stress/fatigue" to "extreme stress/fatigue". The pilots also rated the occurrence of unexpected events, perceived task difficulty, and performance. The responses were then digitized and normalized to a 0-1 scale to calculate pre-to-post changes.

Physiological and survey data were cleaned before analysis. Invalid values, including zeros and NaNs, were removed from HR, EDA, temperature and ACC signals. Accelerometer magnitude was calculated as $\sqrt{\left(x^2 + y^2 + z^2\right)}$ from the three axes. All of these signals were then standardized using minimum and maximum values seen in these pilots.

DATA ANALYSIS AND VISUALIZATION

All physiological measurements (HR, EDA, TEMP, and ACC) were plotted together to visualize the complete dataset across participants. This visualization, shown in Fig. 1, provides a clear overview of how each signal behaves over time and helps identify distinct activity zones corresponding to flight periods. By examining these plots, key segments of interest, such as takeoff or landing, were identified for further detailed analysis. This step

helped narrow the analysis window to segments that reflected meaningful physiological and behavioral changes in the air. To better understand what the overall patterns were showing, each pilot's physiological profile was also examined on its own—looking at how much their signals fluctuated mid-flight, how the dynamics played out across phases, and what stood out about each person's physiological response specifically.



Figure 1: Combined physiological data across all pilots. (Temperature, EDA, HR, and ACC).

Temperature

During analysis, wrist temperature data were averaged across distinct time windows to better isolate physiological changes in response to flight activity. For each pilot, the mean temperature from the 20 minutes before the flight began (0–20 min) was compared with the mean during the active flight window, which is roughly from 20 minutes after the device was put on until about 35 ± 5 minutes before removal. This period corresponded closely with the actual engine start-to-shutdown period, which was cross-checked against flight logs. The resulting averages reflect each pilot's thermal profile pre-flight versus in-flight, making it possible to compare how their temperature fluctuated under similar environmental and workload conditions.

Table 1: Average wrist temperature comparison across pre-flight and in-flight phases.

Pilot	Avg. Temp (0–20 min)	Avg. Temp [20–(tmax–35)]	Δ Temp (°C)
Alpha	31.041	34.856	+3.815
Bravo	29.836	32.712	+2.877
Charlie	30.587	35.390	+4.803
Delta	31.706	33.678	+1.972

All four pilots demonstrated a positive ΔTemp (ranging from +1.97 °C to +4.80 °C), indicating a consistent increase in wrist temperature from the pre-flight baseline. However, the magnitude of the increase varied. Pilot Charlie had the largest shift, which was consistent with the specifics of that flight: lower altitude, warmer temperatures, and a more demanding maneuver profile. The other three pilots showed smaller but still clear increases. Taken together, the pattern potentially suggests that wrist temperature during flight is not driven by any one variable but reflects a combination of environmental exposure, workload, and each pilot's own physiological makeup.

Electrodermal Activity

Electrodermal activity (EDA) was examined to track sympathetic arousal patterns across the flight for each pilot. Pilot Alpha's data was excluded due to signal dropout. Among the remaining three pilots with usable EDA data, EDA increased over the recorded session, although the magnitude and timing differed across individuals.

Pilot Bravo showed a modest but steady rise (slope = 0.0109 μS/min, Δ EDA = 1.236 μS), increasing from a pre-flight mean of 0.304 μS to 1.540 μS post-flight. Pilot Charlie experienced the strongest response (slope = 0.0654 μS/min, ΔEDA = 5.276 μS), with sharp peaks corresponding to high-workload phases such as simulated engine failures. Pilot Delta also showed a moderate but clear upward trend throughout (slope = 0.0056 μS/min, ΔEDA = 1.561 μS). Positive EDA slopes were observed in all three usable recordings, consistent with increasing arousal but not specific to stress or fatigue.

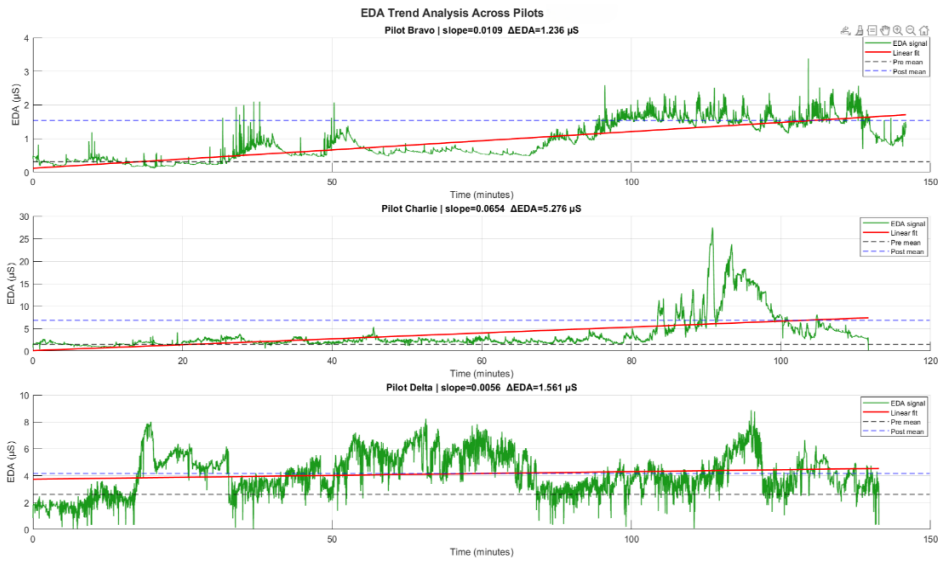


Figure 2: EDA activity trends across pilots (Bravo, Charlie, Delta).

This rise could partly reflect sympathetic arousal tied to flight-related stress and task demand. However, EDA is also sensitive to environmental heat, skin conductivity, and movement, all of which may have contributed to

the increases observed here. Notably, post flight EDA peaks in Charlie and Delta matches with the increased ACC activity. Both pilots had to manually reposition the aircraft after landing, which suggests that the physical exertion may have influenced the signal. Therefore, the EDA changes are consistent with increased arousal, but they cannot be attributed specifically to psychological stress.

Heart Rate Baseline Analysis

The score was calculated as $\frac{(T_{above} - T_{below})}{(T_{above} + T_{below})}$, relative to each pilot's overall flight mean HR. Scores ranged from –1 to +1; positive values indicate more time above individual mean and negative values indicate more time below it. HR responses varied noticeably across different flight phases. Before takeoff, Alpha, Bravo, and Delta were above their mean HR, while Charlie remained below baseline. During takeoff, Charlie and Delta showed the strongest increases; Bravo dropped below baseline and Alpha showed a smaller change. During landing, Alpha and Charlie showed the largest decreases, with the other two pilots showing smaller shifts. During the main in-flight segment, all four pilots spent more time slightly below their individual mean heart rate. After landing all pilots except Delta stayed below baseline.

Table 2: Normalized HR time-balance score relative to each pilot's overall HR across flight phases.

Pilot	Pre-Flight	Takeoff	Landing	In-Flight	Post-Flight
Alpha	0.3604	0.1096	–0.9800	–0.2770	–0.5868
Bravo	0.3804	–0.4552	0.04983	–0.0574	–0.2037
Charlie	–0.7482	0.8738	–1.0000	–0.0465	–0.6685
Delta	0.0500	0.4419	–0.3667	–0.0813	0.2603

Perceived Stress and Fatigue

Pre- and post-flight VAS responses were used to quantify subjective stress and fatigue levels for each participant. All pilots reported higher fatigue levels post-flight. In contrast, stress scores remained relatively stable, showing minimal variation among participants. This suggests that while pilots reported greater fatigue post-flight, their perceived stress levels showed only small decreases and did not change in any substantial way.

Karolinska Sleep Questionnaire

The sleep questionnaire results were analyzed to make sure underlying sleep issues are not influencing the pilots' stress or fatigue responses. Overall, the mean scores across the group were within a good range. This suggests that, for this sample, long-term sleep behavior was unlikely to be a major confounding factor because of satisfactory sleeping patterns and habits.

However, because the questionnaire only captures general patterns rather than sleep quality the night before each flight, short-term sleep variability cannot be ruled out.

Focused Analysis – Pilot Charlie

A detailed case analysis was conducted on Pilot Charlie's data as the flight had clearly defined phases and distinct physiological changes. HR was examined across the full flight, with focus on the in-flight window (20-68 minutes). Simulated engine failures and landing events were identified through flight logs and follow-up discussions with the pilot. EDA was reviewed alongside HR to check whether these events also aligned with sympathetic arousal spikes. This pilot-specific analysis examined how physiological changes occurred around identified high-demand flight events.

Table 3: Identified HR peaks during Pilot Charlie's flight.

Time From Start (min)	Time From Flight Start (min)	Heart Rate (bpm)	ΔHR From Mean (bpm)
29.2	9.2	149.3	+57.4
36.7	16.7	116.7	+24.7
41.7	21.7	128.7	+36.7
46.0	26.0	114.2	+22.2
62.5	42.5	118.8	+26.9

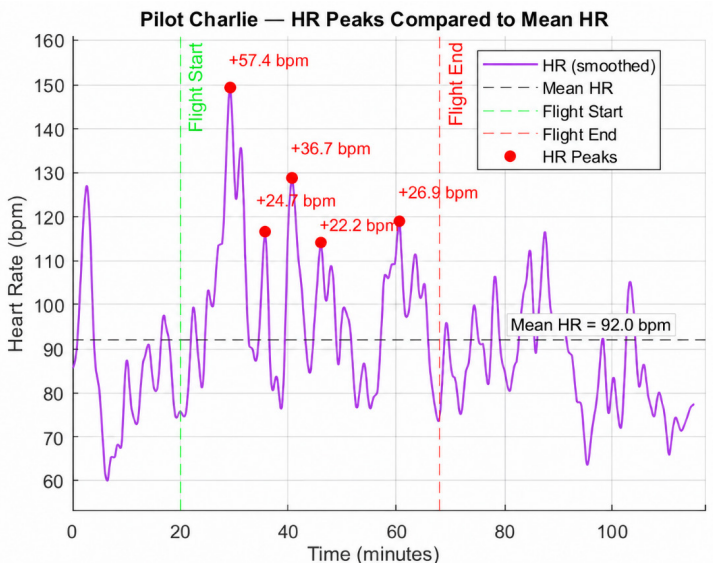


Figure 3: Pilot Charlie's heart rate profile with identified peaks relative to the mean HR.

The HR peaks align closely with key in-flight events confirmed by the pilot. The flight session took place in warm conditions (85°F) and included three simulated engine failures: during the takeoff roll, at 400 ft AGL, and

on the downwind leg. Each high-demand event produced a clear HR spike shown in Table 3. Because some event times were based on the pilot's later recollection, these alignments should be considered approximate. Between events, HR generally returned towards the participant's mean level, which could be an indication of quick physiological recovery once immediate demand had passed. EDA and temperature, by contrast, rose gradually across the flight instead of spiking at individual moments. This distinction suggests that HR may be more sensitive to acute, event-related responses, while EDA and temperature may reflect slower changes in physiological arousal over time.

DISCUSSION

Examining the signals together allows comparison of temporal patterns within each pilot's flight. Wrist temperature increased across all four cases, which may reflect a combination of environmental heat exposure and physiological activation, although their individual contributions could not be separated. In contrast, EDA tends to rise more gradually and becomes most noticeable towards the tail end of each flight, during periods when workload and task engagement were likely higher at their highest.

A noticeable pattern also appears between ACC and EDA observed during post-flight recordings. For pilots Charlie and Delta, noticeable EDA increases appeared shortly after flight ended, coinciding with elevated ACC activity. This pattern is not seen in Alpha and Bravo, as neither had similar physical task after shutdown. This overlap suggests that observed EDA changes may reflect a combination of physical activity and cognitive demand.

The self-reported data help connect these physiological changes to subjective experience. Fatigue VAS scores increased from pre- to post-flight across pilots. Temperature and EDA also increased in pilots with usable data. While the limited sample size prevents definitive conclusions, the similar direction of change across flight ratings, EDA, and temperature may be relevant to understanding the fatigue-related patterns.

HR appeared to have captured a different dimension of the pilot's response. Rather than rising gradually, HR showed sharp, prominent increases during specific high-demand flight segments and consistently returned toward baseline once those moments passed. This is most evident in Pilot Charlie's Data, where HR peaks corresponded directly with simulated engine failures and other demanding phases. This can potentially suggest that heart rate might be responsive to short-duration changes during demanding flight phases (Fauquet-Alekhine et al., 2016).

Across these individual cases, EDA and temperature showed more gradual changes over time, while HR showed greater short-term variations around some flight events. These differences may reflect distinct aspects of the pilots' physiological responses, but they should be interpreted cautiously. Taken together, the combined signals may provide a more complete picture of pilot response than any single physiological measure considered alone. This observed pattern may reflect a combination of workload, heat exposure, movement, and the general toll of time spent flying, all of which may contribute to stress and fatigue related changes.

LIMITATIONS

The primary limitation of this study is the small sample size of four pilots. With only four participants, meaningful statistical analysis is difficult, and the findings cannot be generalized broadly. Operator experience has been shown to influence workload and fatigue patterns (Li et al., 2017). Differences in training progress and procedural familiarity may also have shaped physiological responses in ways that could not be fully accounted for. EDA was analyzed for only three pilots because Alpha's recording was incomplete. In addition, the sleep questionnaire only captured general sleep habits rather than sleep quality the night before each flight. This means short-term sleep variability that could affect stress, alertness, and physiological responses was not measured (Dawson and McCulloch, 2005). Cabin air temperature was also not included in the analysis, which may have influenced EDA measurements.

FUTURE WORK

Future work should include a larger, more diverse group of pilots to enable meaningful statistical analysis and capture how experience level affects stress and fatigue responses. Adding independent cognitive measures, like reaction-time tests, would help validate physiological changes against stress and fatigue outcomes. Collecting direct environmental measurements such as noise, vibration, and thermal stress would also help separate workload-driven responses from environmental ones. With richer multimodal data, building both general and personalized stress and fatigue models becomes feasible. Automated event-recording systems or cockpit-based time markers would further improve the alignment between physiological signals and specific flight events.

CONCLUSION

This exploratory study examined physiological and self-reported measures across four individual real-world student-pilot flights. HR, EDA, temperature, and survey responses were all considered together to better understand how pilots responded as flight demands changed and to identify patterns across both physiological and subjective data. In practice, this kind of monitoring could give pilots a clearer picture of their own stress and fatigue and help training programs spot when a student might benefit from targeted support. Real-world recordings may complement simulator-based studies by capturing physiological patterns under operational flight conditions. Larger studies with independent validation are needed before these measures can support real-time stress or fatigue monitoring.

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