A comprehensive data collection and processing protocol for general aviation pilot performance assessment and behaviour research

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Abstract:

The advancement of aviation human factors research and pilot training technology relies heavily on the systematic collection and analysis of flight and pilot performance data. This technical report presents a standardized methodology for data acquisition, processing, and management to support future research in aviation human factors. The methodology ensures consistency and reliability by outlining structured procedures for collecting multimodal data from real aircraft or flight simulator operations.

This report details the design of flight tasks specifically developed to gather comprehensive pilot performance data under controlled and operational conditions. It specifies the types of data collected, including flight telemetry (altitude, speed, heading, and aircraft control inputs if possible), physiological responses (heart rate, eye-tracking, and electrodermal activity), and behavioral indicators (pilot workload, decision-making patterns, and communication). Additionally, it describes the integration of various data acquisition tools, such as flight data recorders, wearable biometric sensors, and eye-tracking devices.

Beyond data collection, this report outlines the protocols for data preprocessing, including synchronization, cleaning, and structuring for analysis. The report also describes best practices for ensuring data integrity, security, and accessibility, detailing how datasets are stored in centralized repositories to support ongoing and future aviation research projects. By establishing a robust and scalable methodological framework, this report provides a foundation for enhancing pilot training, improving aviation safety, and advancing competency-based assessments in general aviation.

Keywords: pilot performance assessment, flight data collection, flight data analysis, data-driven aviation research, aviation human factors, competency-based pilot training.

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1. Introduction

The aviation industry has long recognized the importance of data in enhancing flight safety, pilot training, and operational efficiency. Traditionally, pilot assessment relied heavily on instructor evaluations and subjective performance metrics. While these methods have been effective to an extent, they lack the objectivity and granularity needed to fully understand pilot decision-making, situational awareness, and response to in-flight challenges (Rizvi, Moncion, et al., 2024). As sustainability has become a pressing issue for aviation, there is also the need to improve the value of each training flight and reduce fuel consumption by using more simulation and information technologies (Rizvi, Kearns, et al., 2024). With the integration of advanced data acquisition technologies, aviation researchers now have the capability to collect, analyze, and interpret flight and human performance data in unprecedented detail.

Data-driven research in aviation encompasses various domains, including flight safety, pilot workload analysis, training effectiveness, and human factors. The ability to systematically gather flight telemetry, physiological responses, and behavioral indicators provides researchers with invaluable insights into pilot performance under different conditions. These insights can lead to improvements in pilot training programs, regulatory policies, and aviation safety standards. Additionally, with the increasing adoption of artificial intelligence and machine learning in aviation, access to high-quality, structured datasets is essential for developing predictive models and decision-support systems. For example, recent studies have used such data to examine pilot eye movement patterns (Ayala et al., 2023, 2024), pilot skill models (Wei et al., 2025; Xu et al., 2024), mental workload models (Zhang et al., 2024), simulator training effectiveness (Paul et al., 2025).

Despite significant technological advancements in aviation, there remains a lack of standardized methodologies for collecting and processing flight and human performance data. The aviation research community faces challenges such as inconsistent data formats, fragmented data sources, and the lack of integration across different studies. Without a unified approach, comparing findings across research efforts becomes difficult, limiting the ability to derive meaningful conclusions and best practices for pilot training and flight operations.

A standardized methodology is crucial for ensuring data reliability, consistency, and reproducibility. By establishing a structured approach to data collection, preprocessing, and storage, researchers can create datasets that are suitable for long-term analysis and cross-study comparisons. Moreover, such a framework enables seamless integration of multimodal data sources, including flight telemetry, physiological sensors, and eye-tracking devices, allowing for a more comprehensive analysis of pilot behavior and performance.

This report aims to develop a robust, standardized methodology for acquiring, processing, and managing flight and human performance data. The specific objectives include:

1. Creating a list of structured flight tasks. Select flight maneuvers and operational scenarios that can demonstrate different aspects of pilot competencies.

2. Identifying key data types. Define all different categories of data to be collected, such as flight telemetry, physiological responses, instructor ratings, and pilot self-reported workload.
3. Establishing data acquisition protocols. Outline best practices for integrating and synchronizing multimodal data sources obtained from different devices.
4. Implementing data preprocessing techniques. Develop systematic approaches for cleaning, structuring, and formatting collected data to facilitate efficient analysis.
5. Ensuring data security and accessibility. Establish guidelines for secure storage, controlled access, and long-term usage of research data.

This report serves as a foundational guide for aviation researchers, flight instructors, and industry professionals seeking to implement data-driven approaches in aviation research and training. It is designed to be a practical reference document that outlines standardized methodologies applicable across various aviation studies.

By adhering to this standardized methodology, aviation researchers can improve the quality, consistency, and applicability of their data, facilitating advancements in pilot training, flight safety, and overall aviation research. This report aims to establish a methodological framework that will serve as a reference for ongoing and future studies, ensuring that aviation research continues to evolve in a structured and scientifically rigorous manner.

2. Flight Task and Assessment

To support the needs of general aviation pilot performance assessment and behaviour research, an ideal database should include a wide range of flight tasks with standardised assessment measures. Tasks and assessments should be carefully structured to capture meaningful performance metrics while maintaining operational safety and realism. The key principles guiding flight task selection include:

1. Reproducibility: Flight tasks must be standardized to ensure consistency across different pilots, aircraft, and experimental conditions.
2. Realism: The tasks should reflect real-world operational scenarios to make the collected data applicable to practical pilot training and performance evaluation.
3. Measurability: Each flight task must be designed to generate quantifiable data that can be analyzed systematically.
4. Safety: Given that real aircraft are used for data collection, all tasks must adhere to strict safety protocols to minimize risk to pilots and researchers.
5. Integration with Data Collection Systems: The tasks must align with the capabilities of the data acquisition hardware, ensuring synchronization across different data modalities.

To capture a broad range of pilot performance metrics, carefully selected flight scenarios and maneuvers are incorporated into the flight task design. We recommend the following flight tasks to be included in general aviation pilot performance databases. Takeoff and landing are the most fundamental skills. Steep turn and stall recovery represent relatively advanced skills. And circuit is the most frequently practiced task in general aviation training. These five flight tasks can be included in one flight booking. For example, start with a circuit, then normal takeoff and fly towards an upper air practice area to do the steep turn and stall recovery, and finally fly back to the airport and land. The total flight duration is usually within 50 minutes.

- Normal Takeoff: Pilots perform a standard takeoff, monitoring aircraft acceleration, rotation speed, and initial climb.
- Normal Landing: A standard approach and landing, assessing descent management, flare execution, and touchdown accuracy.
- Steep Turn: Pilots conduct a coordinated turn with a 45-degree bank angle, maintaining altitude and airspeed.
- Stall (Engine On): A controlled stall maneuver with power applied, evaluating stall recognition and recovery techniques.
- Circuit (Traffic Pattern Navigation): A full circuit including takeoff, crosswind, downwind, base, and final approach, requiring precise control and situational awareness.

The flight may be conducted in real aircraft or flight simulators. Each flight should be monitored by a certified flight instructor who provides real-time supervision and ensures adherence to safety protocols. The instructor also rates pilot performance based on standardized assessment criteria (Moncion et al., 2024). These assessments are crucial in complementing objective flight data with expert subjective evaluations.

1. Real-Time Observation: The instructor tracks pilot actions and decision-making throughout the flight.
2. Post-Flight Rating: The instructor provides structured feedback and ratings for each flight maneuver, documenting performance in a standardized format.
3. Integration with Data Collection: Instructor ratings are synchronized with telemetry and biometric data to enhance analysis and provide a holistic view of pilot performance.

To ensure the data collection is ethical, reliable, and comparable across different trials, a standardized data collection protocol should be implemented. This includes:

1. Research Ethics Approval and Informed Consent: The research needs ethics approval from the overseeing research ethics board. Participants must complete informed consent before data collection.
2. Pre-Flight Briefing: Pilots receive instructions on the specific flight tasks, data collection procedures, and safety protocols.
3. Use of Flight Data Recorders: All aircraft or flight simulators should be equipped with data logging systems to capture real-time telemetry.
4. Biometric and Eye-Tracking Integration: Wearable sensors are used to record bio-signals such as heart rate and eye movement.
5. Post-Flight Data Synchronization: All recorded data, including flight telemetry, physiological metrics, and behavioral observations, are time-synchronized for analysis.

The flight task design methodology outlined in this section ensures the structured and systematic collection of aviation data. By incorporating standardized flight scenarios, monitoring pilot performance with expert assessments, and ensuring consistency in data acquisition procedures, this framework provides a reliable foundation for aviation research. The next section will detail the specific types of data collected during these flight tasks and how they contribute to pilot performance analysis.

3. Types of Data Collected

To support various types of data analyses and research questions, we recommend that multiple types of data should be collected, broadly covering study information, demographic information, pilot performance, aircraft telemetry, and physiological responses. We have created a comprehensive but non-exhaustive list of data types grouped in nine categories, as shown Table 1, as a guideline for data standardisation.

Table 1. Types of data recommended for collection in general aviation pilot performance assessment and behaviour research

Data Type	Measure Name	Description	Example and Notes
Research study information	Experiment/study ID	Unique identifier for the study	-
	Year of study	The year the study was conducted	-
	Study name	Title of the research study	-
	Contact person and email	Primary contact for the study	-
	PI name and email	Principal investigator and their contact	-
	Ethics approval ORE#	Ethics review number	-
Flight task information	Date and time	Timestamp when the task started	E.g., yyyy-mm-dd, hh:mm:ss
	Task requirements	Details of the task objective	-
	Instructions to participants	Standardised instructions provided to each participant	-
	Task conditions/configurations	Environmental conditions and configurations	E.g., weather, aircraft model
	Other experiment manipulations	Any additional experimental variations	-
Participant information	Participant unique ID	A unique anonymized identifier linking the same participant across multiple studies in the database if longitudinal comparison is implemented.	-
	Study-specific participant ID	Unique anonymized ID within a specific study	-
	Demographic info	Such as gender, age, flight experience, license, ratings	-
	Health info	Vision and health conditions	-
Aircraft dynamics and physical states	Time (UTC-0)	Timestamp in milliseconds since UNIX epoch	Note that the raw time data from all devices may not follow the same format, and they must be converted into the same format.
	Aircraft dynamics and physics	Altitude, heading, pitch, roll, speed, location	-
	Aircraft system states	Engine RPM, fuel amount, flap states, etc.	-
	Level of automation	Autopilot states	-
	Nearby aircraft dynamics	Locations and movements of nearby aircraft	If available.

Pilot motion and control actions	Time (UTC-0)	Timestamp in milliseconds since UNIX epoch	-
	Hand motion and location	Yoke movement, button presses, checklist interaction	-
	Feet motion and location	Rudder pedal usage	-
Pilot speech and conversation	Time (UTC-0)	Timestamp in milliseconds since UNIX epoch	-
	Audio recordings	Captured audio for later analysis	-
	Think-aloud protocol	Verbalized pilot thoughts (if used)	-
	Conversation with instructors	Dialogue between pilot and instructor	-
	Conversation with ATC	Air traffic control communication (if used)	-
Pilot physiological data	Time (UTC-0)	Timestamp in milliseconds since UNIX epoch	-
	Eye tracking	Measurement of gaze behavior	E.g., AdHawk, Pupil Labs
	EEG	Brain activity monitoring	E.g., Muse S
	Heart rate	Cardiovascular monitoring	E.g., Polar chest strap
	Electrodermal activity	Sweat gland activity indicating stress	E.g., EmbracePlus
Pilot mental state surveys	Mental workload	Self-reported workload assessment	E.g., NASA-TLX or simpler questionnaires
	Stress	Self-reported stress levels	E.g., SSSQ or simpler questionnaires
	Situation awareness	Situational perception assessment	E.g., SAGAT questions or self-report
	Motion sickness	Assessment of motion-induced discomfort	E.g., MSSQ
Instructor assessment	Instructor qualification	Details on the evaluating instructor	E.g., instructor class and years of experience
	Assessment criteria	Items, guidelines, and rubrics used for evaluation	E.g., (Moncion et al., 2024)
	Rating system	Numerical ratings and competency briefing	E.g., 4-point scale used by Transport Canada
	Assessment conditions	Such as traditional in-person observation or video recording evaluation	-

The multimodal data collection framework outlined in this section enables a robust analysis of pilot performance under real-flight conditions. By combining flight telemetry, physiological responses, and expert evaluations, this methodology supports data-driven advancements in aviation research, pilot training, and flight safety analysis. The next section will outline the procedures for collecting these data types in real flight operations.

4. Example Data Collection Procedures Using Real Aircraft

The above protocol could be implemented in either real aircraft or flight simulators. Here we provide an example list of procedures using real aircraft such as Cessna 172. The process of data collection in real aircraft operations involves a structured methodology to ensure consistency, accuracy, and safety. Each step is designed to synchronize multiple data sources and capture pilot performance in real-time flight conditions.

To ensure comprehensive data collection, both aircraft-based and wearable sensors are utilized. The **primary data acquisition systems** include:

1. ForeFlight and SentryPlus: These flight data recorders capture real-time telemetry, including altitude, airspeed, heading, pitch and bank angles, and control inputs.

2. Polar H10 Chest Sensors: Used for measuring heart rate (HR) related data.
3. Pupil Labs Eye-Tracking Device: Tracks eye movements, fixation points, and gaze duration.
4. EmbracePlus Wrist Sensors: Collects electrodermal activity (EDA).
5. Muse EEG Headbands: Captures brain activity data.
6. Instructor Rating Forms: Standardized assessment sheets completed by the flight instructor to evaluate pilot performance by each flight maneuver and competency type (Moncion et al., 2024).
7. Pilot Self-report: A simple and quick one item rating (0-10 scale) for workload, situational awareness, and stress levels.

To ensure data reliability and synchronization, all data collection equipment is properly installed and calibrated before each flight. The **setup process** involves:

1. Aircraft Preparation: Flight data recording systems are tested and synchronized to ensure seamless telemetry capture.
2. Pilot Wearable Setup: Pilots are equipped with biometric sensors, ensuring comfortable and secure attachment to prevent interference with flight operations.
3. Eye-Tracking Calibration: The Pupil Labs eye-tracker is calibrated using a pre-flight gaze test to confirm accurate tracking.
4. EEG and EDA Sensor Check: Signals from the Muse and EmbracePlus devices are validated for proper signal reception and stability.
5. Pre-Flight System Synchronization: A common timestamp is established to align all data sources before takeoff.

The flight tests follow a predefined sequence of maneuvers to ensure consistent data collection across different trials. The **procedure** includes:

1. Pre-Flight Briefing: The pilot and instructor discuss the flight plan, tasks, and safety procedures. The participating pilot completes informed consent and puts on all the wearable devices. The aircraft is Cessna 172.
2. Resting EEG: Before the engine start checklist, the participant sits quietly in the cockpit for about two minutes to record the resting EEG.
3. Instructor Ratings and Observations: Throughout the flight, the instructor records real-time observations and assigns ratings on pilot performance, as well as recording pilot self-reported values. These ratings are completed after each flight maneuver.
4. Taxiing to the Runway: Data recording continues throughout the flight, but data analysis focuses on the following flight maneuvers.
5. Normal Takeoff and Climb: The pilot completes the takeoff roll, lift-off, and initial climb phase. The takeoff and climb part considered from the first-time airplane speeding up on the runway until climb to a certain altitude. It usually takes up to 40 seconds.
6. Steep Turn Execution: The pilot performs a coordinated 45-degree banked turn. In this example we used left side turn. The start point is when the aircraft starts to turn, and the end point is when the aircraft is back to the normal position.

7. Stall (Engine On) Maneuver: A controlled stall (while engine RPM 1500) is induced to assess the pilot’s response and recovery process. When the airplane’s speed starts to decrease and altitude to increase, it is considered as stall start. When speed and altitude come back to normal, it is considered as stall end.
8. Full Traffic Circuit: The pilot executes a complete circuit including takeoff, downwind, base, and landing approach. Note: this circuit may also happen at the beginning before Step 2. It starts from the second speeding up on the runway, until the second landing of the aircraft.
9. Landing and Post-Flight Data Capture: The final approach and landing are logged, followed by a structured debriefing session. The final approach starts with the beginning of the final turn before approaching the runway, ends with the landing of the aircraft and start of taxing.

Following the flight, all recorded data are compiled, synchronized, and validated to ensure consistency and usability for analysis. The **post-flight data processing steps** include:

1. Time Alignment: Data from multiple sources (telemetry, biometric, and instructor ratings) are synchronized using timestamp markers.
2. Quality Assurance Check: Any missing or inconsistent data points are flagged and corrected where possible.
3. Backup and Secure Storage: All raw data files are securely stored in designated research databases for further analysis.

Since human subjects are involved in data collection, all procedures comply with ethical guidelines outlined in the approved research ethics application. The **research ethics considerations** include:

1. Informed Consent: Pilots are briefed on the study objectives, risks, and data handling protocols before participation.
2. Anonymization of Data: All collected data are anonymized to protect pilot identity and confidentiality.
3. Safety Precautions: Data collection does not interfere with normal flight operations or pilot decision-making.

The structured data collection procedures outlined in this section ensure the integrity, consistency, and reliability of flight performance data obtained from real aircraft operations. By combining flight telemetry, biometric sensors, and expert instructor evaluations, this methodology provides a robust dataset to support future aviation research. The next section will cover the data cleaning and processing techniques applied to prepare the collected data for analysis.

5. Data Cleaning and Processing

Data collected during flight tasks require thorough cleaning and preprocessing to ensure accuracy, consistency, and usability for analysis. This section outlines the steps taken to structure and refine the collected telemetry, physiological, and observational data, ensuring seamless integration for research applications.

Since multiple sensors and data collection systems are used, the raw data come in various formats, such as CSV, JSON, and binary logs. **Standardization procedures** include:

1. Converting all timestamps to a uniform UTC format.
2. Resampling data to a common frequency to ensure alignment.
3. Normalizing units (e.g., altitude in feet, speed in knots, heart rate in beats per minute).
4. Assigning consistent labels for different data streams.

To enable accurate cross-referencing, all data sources must be synchronized using a shared timestamp. The **synchronization process** includes:

1. Aligning flight telemetry, physiological, and instructor assessment data based on event markers.
2. To determine the event markers, watch the video recorded during the flight, e.g., from the eye tracker or camera used. Based on the procedure defined in previous section, find out the exact timestamp of the start and end point of each trial.
3. Interpolating missing timestamps where necessary to ensure smooth time-series data.
4. Verifying consistency across different data streams to eliminate timing discrepancies.

Processed data are securely stored in structured repositories, ensuring accessibility for future research. **Data storage protocols** include:

1. Organizing data by trial and participant ID.
2. Maintaining metadata files with sensor calibration details and preprocessing logs.
3. Implementing version control to track updates and modifications to datasets.
4. Encrypting sensitive data and enforcing access control for confidentiality.

The data cleaning and processing methodology ensures that the collected aviation research data are accurate, structured, and ready for analysis. By implementing rigorous standardization, synchronization, and validation procedures, this framework supports high-quality research outputs and fosters reliable insights into pilot performance and aviation safety. The next section will discuss data storage, security, and accessibility for long-term usage.

6. Data Storage and Accessibility

Proper storage and accessibility of collected data are essential for ensuring data integrity, security, and long-term usability. This section outlines the structured approach used for storing flight telemetry, physiological measurements, and instructor assessments while maintaining accessibility for authorized researchers.

All collected data are securely stored in a centralised database that support structured organization and efficient retrieval. The **key elements of data storage** include:

1. Hierarchical Organization: Data are categorized by experiment trials, pilot ID, and data type (telemetry, physiological, instructor ratings).
2. Standardized File Formats: Data are stored in CSV and JSON formats to ensure compatibility with analysis tools.

3. Metadata Documentation: Each dataset includes a metadata file with details such as sensor calibration settings, data collection timestamps, and preprocessing steps.

Ensuring **data security and participant privacy** is a priority. The following measures are implemented:

1. Encryption: All stored data are encrypted to prevent unauthorized access.
2. Anonymization: Personally identifiable information (PII) is removed, and unique participant IDs are assigned.
3. Access Control: Only authorized personnel can access datasets based on research needs and approval protocols.
4. Backup Systems: Redundant copies of datasets are maintained in secure cloud storage and local servers to prevent data loss.

To facilitate collaborative research, structured access protocols are established:

1. Role-Based Access: Researchers are granted tiered access levels based on their project requirements.
2. Request and Approval System: External researchers can request access through a formal application process reviewed by data custodians.
3. API and Web-Based Interfaces: A secure interface allows authorized users to query and download data subsets efficiently.
4. Data Usage Agreements: All users must adhere to ethical and legal agreements outlining data use limitations and citation requirements.

To ensure the longevity and usability of stored data, the following strategies are applied:

1. Periodic Data Integrity Checks: Routine audits verify data consistency and detect potential corruption.
2. Version Control: Any modifications or reprocessing of datasets are logged, ensuring traceability of changes.
3. Archival Storage: Older datasets are archived but remain retrievable for comparative analysis and historical research.
4. Compliance with Regulatory Standards: Data management policies align with institutional and regulatory guidelines for research data retention.

A well-structured data storage and accessibility framework ensures that collected aviation research data remain secure, organized, and readily available for authorized research applications. By implementing rigorous security, access control, and archival procedures, this system facilitates ongoing and future studies in aviation safety, pilot performance, and human factors research. The next section will summarize key findings and outline future research directions.

7. Limitations and Future Improvements

The current data collection methodology has several limitations that may affect data accuracy and completeness. One key challenge is sensor synchronization, as minor discrepancies remain due to variations in sampling rates and hardware synchronization constraints.

Additionally, the dataset primarily reflects controlled flight conditions, limiting the ability to analyze pilot performance under diverse environmental factors such as adverse weather and high-traffic airspace. Another concern is the potential observer effect, where pilots may alter their behavior due to the presence of an instructor or awareness of being monitored. Equipment limitations, particularly for wearable biometric sensors like EEG headbands and wrist-worn electrodermal activity sensors, can also introduce noise due to aircraft vibrations and movement.

Data storage and management present further challenges. The large volume of high-resolution multimodal data requires significant storage capacity, and the current infrastructure may need to scale to support future research. Data security and privacy remain ongoing concerns despite anonymization and encryption protocols, particularly when datasets are shared with external collaborators. Manual intervention in data processing, such as identifying event markers and handling missing data, increases the risk of human error and processing inefficiencies.

Future improvements should focus on enhancing sensor integration and synchronization through more precise time-stamping methods, such as hardware-synchronized clocks or embedded synchronization signals. Expanding data collection to a wider range of flight scenarios, including diverse weather conditions and emergency situations, will improve generalizability. Automating data processing pipelines using AI-driven techniques can reduce manual workload and improve consistency. A transition to scalable cloud-based data storage will enhance data security, accessibility, and long-term usability. Refining biometric data collection by adopting more stable sensors with improved motion compensation algorithms will help mitigate signal noise caused by aircraft vibrations. Additionally, increasing the diversity of participants, including pilots with different levels of experience and backgrounds, will contribute to a more comprehensive understanding of pilot performance.

By addressing these limitations and implementing improvements, the data collection and management framework will evolve into a more accurate, scalable, and efficient system, further supporting advancements in aviation research and pilot training.

8. Conclusion

This report has outlined a comprehensive methodology for collecting, processing, and storing flight performance data using real aircraft operations. By integrating flight telemetry, physiological monitoring, and instructor evaluations, this framework ensures reliable and consistent data for aviation research.

The methodologies presented in this report lay the groundwork for advancements in aviation safety, pilot training, and human factors research. The structured collection and analysis of pilot performance data will support:

1. Competency-Based Training: Development of objective, data-driven pilot evaluation metrics.
2. Human Factors Analysis: Enhanced understanding of workload, situational awareness, and stress management in real-flight conditions.

3. Machine Learning Applications: Use of structured datasets for AI-driven predictive modeling of pilot behavior and decision-making.
4. Flight Safety Enhancements: Data-informed policies and training interventions to mitigate human error risks in aviation.

To maximize the impact of this methodology, the following recommendations are proposed:

1. Integration into Training Programs: Flight schools and training institutions may consider incorporating standardized data collection and analysis frameworks.
2. Collaboration with Industry Stakeholders: Partnerships across regulatory bodies, airlines, and research institutions could enhance data applicability and policy development.
3. Expansion of Data Collection Scope: Future studies may incorporate additional flight phases and environmental conditions for broader analysis.
4. Automation of Data Processing: Implementation of AI-driven data cleaning and analysis pipelines for efficient insights generation.

The structured methodology detailed in this report provides a foundation for ongoing and future research in aviation. By ensuring data integrity, consistency, and accessibility, this framework enables researchers and industry professionals to advance pilot training, human factors analysis, and overall aviation safety. Future work should focus on expanding dataset applications, refining analytical methods, and integrating emerging technologies for enhanced pilot performance assessment.

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