# Predicting Workload Experienced in a Flight Test by Measuring Workload in a Flight Simulator

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**BACKGROUND:** In order to determine the minimum flight crew number and show compliance with airworthiness regulations, the workload of flight crew should be measured in various flight scenarios both in a simulator and in flight tests demonstrating compliance. However, the complexity, environment, and safety considerations of flight tests require pilots to take more responsibility and be more careful with decisions and actions with higher stress, and it might be inappropriate to carry out flight tests in a high-risk abnormal situation. Therefore, it is necessary to assess workload measures in a simulator to predict workload experienced during a flight test.

**METHODS:** Two subjective workload measurements and three psychophysiological measurements were compared both in a simulator and in a flight test among three flight scenarios. The scenarios were carried out in an ARJ21-700 full-flight simulator and a corresponding aircraft, and a total of 17 pilots participated.

**RESULTS:** Both flight scenarios and flight environment had a significant influence on NASA-TLX, eye blink rate, and heart rate. Additionally, the NASA-TLX ($R = 0.864$) and heart rate differences ($R = 0.840$) presented strong correlations between the simulator and flight test.

**DISCUSSION:** NASA-TLX and heart rate could be used in simulators and flight tests as consistent measures of workload. Furthermore, in order to reduce the quantity and risk of compliance during a flight test, the best strategy is to combine the results of the NASA-TLX scales and HR-D together in a flight simulator to predict workload experienced in a flight test.

**KEYWORDS:** airworthiness, workload, flight test, flight simulator.

**Zheng Y, Lu Y, Jie Y, Fu S. *Predicting workload experienced in a flight test by measuring workload in a flight simulator*. Aerosp Med Hum Perform. 2019; 90(7):618–623.**

Airworthiness is certification and supervision of the design, manufacture, implementation, and maintenance of aircraft based on the airworthiness regulations and materials on behalf of public safety.[8] The aim of airworthiness is to ensure the aircraft can achieve the safety level that authority requires. Typically, the design of commercial aircraft should comply with Federal Aviation Regulations Part 25—Airworthiness Standards: Transport category airplanes, and Certification Specifications for Large Aeroplanes CS-25, which is issued by the European Aviation Safety Agency, respectively.

Since inappropriate human factors considerations could threaten aviation safety, there are several airworthiness regulations that concern human factors issues in FAR/CS-25. Among them FAR/CS25.1523—Minimum Flight Crew is one of the most important and stipulates the number of flight crew who should rely on the workload of individual pilots.[10] In other words, in order to show compliance with FAR/CS25.1523, the workload of each flight crewmember should be measured. According to the Advisory Circuit of FAR/CS 25.1523, workload can be defined as a term used to describe the relationship between an individual's capacity to perform a task (mental and/or physical), the level of system and situational demands associated with the performance of that task, and the recommended means of compliance (MOC) to satisfy the regulation, including a flight test (MOC6) and a simulator test (MOC8).[11]

Flight testing is a branch of aeronautical engineering that develops and gathers data during the flight of an aircraft. It can

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This manuscript was received for review in February 2019. It was accepted for publication in March 2019.

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DOI: https://doi.org/10.3357/AMHP.5350.2019

determine and modify any design problems and verify and document the aircraft capabilities for government certification or customer acceptance. The flight test phase can range from the test of a single new system for an existing aircraft to the complete development and certification of a new aircraft.[6] Although flight testing is the most direct means of compliance in aircraft human factors airworthiness certification, it is not the preferred approach due to the following three aspects. Firstly, it might not be appropriate to test an abnormal situation due to safety considerations. Flight crew, who have both tremendous capabilities and finite limitations, need to take more responsibility and be more careful with decisions and actions with higher stress.[17] Secondly, in the flight environment, it is normally difficult to manipulate the operational environment, which might be required to apply the scenario-based approach. Last but not least, human factors scenarios performed during a flight test are not easy to duplicate due to the lack of controllability of the operational context.[21] Since excessive workload should not be experienced in flight as part of the airworthiness certification process, it may be unsuitable to perform the flight test in all kinds of high-risk abnormal situations; thus, a simulator test is a more recommended means of compliance for aircraft manufacturers.

Traditionally, studies of flight crew workload have been carried out either in commercial aircraft flight simulators or military aircraft flight simulators. Lahtinen et al. found heart rate increased during interceptions and decreased during the return to base and slightly increased during the instrument landing system approach and landing in a Weapons Tactics Trainer simulator of an F-18 Hornet.[15] Similarly, in a Boeing 747-400 flight simulator experiment, peak heart rate was observed during takeoff and landing, and incremental heart rate was also greatest.[16] Besides, in the same study, the NASA-Task Load Index (TLX) scale revealed that mental and performance demands were essential components of workload during simulator flight.[16] Furthermore, Karavidas et al. stated the respiratory system is very reactive to high workload conditions in a Boeing 737-800 simulator.[14] On the other hand, some studies were performed during real flight of twin-engine propeller aircrafts or military aircrafts and the corresponding flight simulators. Dahlstrom and Nahlinder indicated there was a high degree of correspondence not only in psychophysiological reaction, but for subjective ratings of mental workload between a Piper Arrow Navajo simulator and real flight.[7] Moreover, Magnusson suggested that the reaction patterns in the psychophysiological variables between a simulated JA37 Viggen and real flight were analogous, but the levels were significantly different.[18] Nevertheless, most of the available measuring procedures are laboratory-oriented and their applicability under field conditions is limited, and their validity is often a matter of controversy. Furthermore, few studies concentrated on comparing workload between flight simulators and real flight, especially an in-flight test.

In order not to induce over-tasking or excessive workload during a flight test, we intended to measure workload in a simulator to be able to predict workload experienced in flight. So as to determine the desirable workload measurements, subjective rating scale measures and physiological measures were selected, as these two types of measures are most commonly used in aviation.[4] Among them, the NASA-TLX and Bedford scales were representative subjective measures, and eye blink rate, heart rate, and respiration rate were physiological measures selected for this study. Furthermore, three different flight scenarios, standard instrument departure, standard instrument approach, and direct mode approach, were carried out both in the flight simulator and during an in-flight test. According to the Task Complexity in Flight method (TCIF), the complexity difference of the three flight scenarios are significant.[26] There were 12 flight crews composed of 17 pilots based on their various flight hours who participated in this study.

## METHODS

### Subjects

Seventeen Chinese male pilots ranging in age from 30 to 53 (Mean = 39.1 ± 7.75) were invited to participate in this experiment. These pilots included 12 commercial airline pilots and 3 flight instructors from China Eastern Airlines, and 2 test pilots from the Civil Aviation Administration of China. The average total flight hours of these pilots were 7173.2 ± 5270.9 (range from 1000 to 18,000), and their mean flight hours in the last 2 wk before the experiment were 10.82 (SD = 7.66, median hours = 8.83). Furthermore, the median age of the subjects was 36 and the median flight hours were 6000. Each pilot had been either captain or co-captain of an ARJ21-700 for more than 1 yr (mean = 2.46, SD = 1.22). Simultaneously, they had all been recruited as captains or co-captains for some types of aircraft (seven for B737, five for A320, three for A330, and two for B747). Furthermore, these pilots were paired into 12 flight crews. Among them, seven pilots were assigned with different flight responsibilities in different crews, i.e., as pilot flying in one crew and as pilot monitoring in the other. Before the experiment, all subjects signed the consent form, which was approved by the Institutional Review Board of Shanghai Jiao Tong University.

### Equipment

The experiment was carried out in an ARJ21-700 aircraft and one corresponding full-flight simulator, which is a qualified flight simulator (level D) conforming to the guidance presented in Federal Aviation Administration Advisory Circular AC 120-40B—Airplane Simulator Qualification.[12] All the configurations in the flight simulator were identical with the real aircraft. Except for this experiment, this flight simulator has been used with pilots training for commercial airlines. Simultaneously, the flight test was conducted in a real ARJ21-700 aircraft, which was coded as 104, undertaking systems testing in the aircraft airworthiness process.

Besides the flight simulator and the aircraft, two kinds of physiological measurement devices were used in this experiment. A head-mounted eye tracker (Tobii AB, Stockholm, Sweden) with a sample rate of 30 Hz was used to determine the eye blink rate of the subjects during the experiment. Moreover, the heart rate and respiration rate of each subject were recorded with physiological parameter monitoring equipment (Bio Harness, Zephyr Technology, Annapolis, MD, USA).

**Procedure**

For the purpose of comparing the workload measurements in the simulator and during the flight test, three flight scenarios were designed, including standard instrument departure (SID), standard instrument approach (SIA), and direct mode approach (DMA). Each of the flight scenarios was carried out in the simulator and during the flight test, respectively. The configurations and operating procedures for the flight scenarios were the same in the two flight apparatus as follows.

***Standard instrument departure.*** The flight scenario was conducted at Chengdu Shuangliu International Airport. The task was started when the pilot flying pressed the TOGA (Takeoff/Go-around) button. Then he pushed the throttle and kept accelerating. When the aircraft reached rotation speed ($V_R$), the pilot needed to rotate and maintained a 3° climbing angle, approximately. When the aircraft reached 1500 ft (457 m), he was required to connect the autopilot system and keep supervising the essential flight parameters until 10,000 ft (3048 m).

***Standard instrument approach.*** The flight scenario was conducted at Chengdu Shuangliu International Airport. The task was started at 40 nmi away from the descent point. After slowing down to 145 knots and descending to 1500 ft, the aircraft was in a landing pattern. The pilot flying needed to execute a CAT I standard instrument approach procedure and land on the runway.

***Direct mode approach.*** This flight scenario was also conducted at Chengdu Shuangliu International Airport. The task was started at a height of 8000 ft (2438 m), where the display of altitude and airspeed failed. Subsequently, the flight crew needed to perform the corresponding quick checklist and select heading and compass mode on MFD. After that, the flight crew executed a nonprecision approach procedure and landed on the runway.

The simulator test was carried out prior to the flight test and the interval between those two tests was 2 d. Before the experiment, each subject was trained in the same flight simulator for 2 h to be familiar with the aircraft configurations and the procedures of the tasks. Also, they were taught how to implement the subjective measures before the experiment. In the simulator phase, each flight crew performed takeoff and landing twice. In the first flight, they performed a standard instrument departure and a standard instrument approach. In the second flight, they performed a standard instrument departure and a direct mode approach. The interval between those two flights was 15 min.

Simultaneously, one flight instructor, who was responsible for task configuring, stayed with the flight crew in the simulator and acted in the role of air traffic controller (ATC) if necessary. Bedford scales were asked when subjects accomplished a task (SID, SIA, or DMA) during each flight, and NASA-TLX scales were fulfilled after each flight. The results of the SIA were only recorded in the first flight. During the flight test, the procedures were the same as in the flight simulator. In addition, in order to eliminate the individual variation of heart rate (HR), HR-D was recorded. HR-D is equal to the difference between the real-time HR and baseline HR of the pilot, where the real-time HR was the value recorded during the experiment and the baseline HR was the mean value recorded when each pilot performed a cruise task about 5 min before the experiment in the same flight simulator. Only the data of pilots flying were recorded in this study.

**Statistical Analysis**

SPSS 17.0 for Windows was used to process the experiment data, and ANOVA analysis and correlation analysis were implemented in this study. When $P < 0.05$, the results were considered statistically significant.

## RESULTS

For each measurement, the results were evaluated from two aspects. Firstly, the workload difference of the three flight scenarios were analyzed in the simulator environment and flight test environment separately. Secondly, the correlation of each scenario and the overall correlation of each measurement between simulator and flight test were analyzed.

According to the subjects' judgments on six rating subscales of the NASA-TLX scales, in all three flight scenarios, mental demand had highest weight and temporal demand was the second most important. In the SID and SIA scenarios, effort was the third essential element, then performance, physical demand, and frustration. Nevertheless, in the DMA scenario, physical demand was the third critical factor, then effort, performance, and frustration. Furthermore, both scenarios [$F(2,24) = 31.968$, $P < 0.001$] and flight environment [$F(1,36) = 9.842$, $P = 0.002$] had a significant influence on workload, but the interaction of these two factors was insignificant [$F(2,24) = 0.074$, $P = 0.929$]. On the other hand, in the SID scenario, the correlation of workload in the flight simulator and during the flight test was moderate ($R = 0.529$, $P = 0.077$). However, the greatest correlations were found in the SIA scenario ($R = 0.808$, $P = 0.001$) and DMA scenario ($R = 0.815$, $P = 0.001$), and the overall correlation was also significant ($R = 0.864$, $P < 0.001$), as shown as **Fig. 1**.

Considering the results of the Bedford scales, unlike the NASA-TLX, neither flight scenario [$F(2,24) = 0.619$, $P = 0.542$] nor flight environment [$F(1,36) = 0.048$, $P = 0.828$] exhibited significant influence on workload. The overall correlation of workload in the flight simulator and during the flight test was weak ($R = -0.151$, $P = 0.379$).

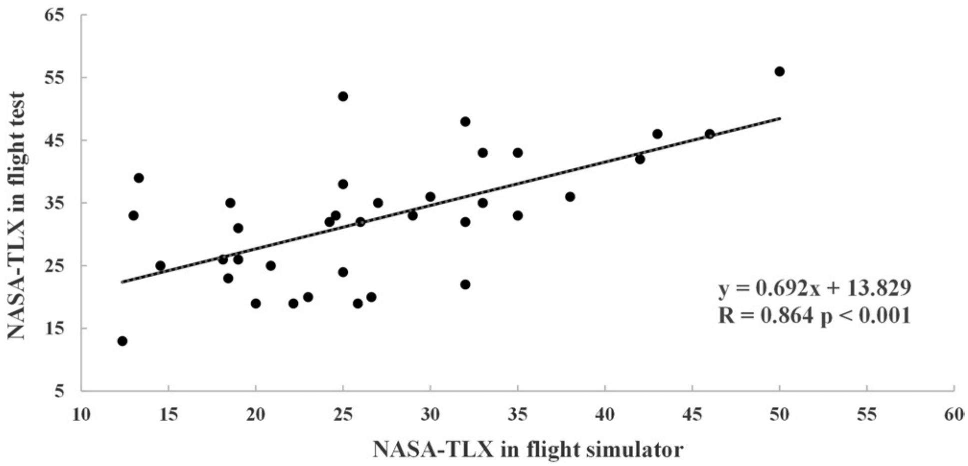


**Fig. 1.** The linear regression results of the NASA-TLX scales for the flight simulator and in-flight test.

0.840, $P < 0.001$), as shown as in **Fig. 3**.

Respiration rate uniformly increased in flight but not significantly, which is depicted in **Fig. 4**; only flight environment [$F(1,36) = 31.349$, $P < 0.001$] manifested a significant effect on workload, but flight scenario [$F(2,4) = 2.949$, $P = 0.059$] and the interaction of these two factors were insignificant [$F(2,24) = 2.161$, $P = 0.123$]. In addition, both in the SID (R = 0.550, $P = 0.064$) and the SIA (R = 0.633, $P = 0.027$), the correlation of workload in the flight simulator and flight test was moderate. Nevertheless, in the DMA, the correlation was weak (R = 0.105, $P = 0.746$) and the overall correlation of respiration rate was also weak (R = 0.392, $P = 0.018$).

Considering the results of eye blink rate, as shown in **Fig. 2**, both flight scenario [$F(2,24) = 4.877$, $P = 0.011$] and flight environment [$F(1,36) = 7.730$, $P = 0.007$] caused a significant effect on workload, but interaction of these two factors was insignificant [$F(2,24) = 1.191$, $P = 0.310$]. Furthermore, in the SID, the correlation of workload in the flight simulator and during the flight test was moderate (R = 0.571, $P = 0.052$). In the SIA, the correlation was strong (R = 0.762, $P = 0.004$) but in the DMA the correlation was weak (R = 0.334, $P = 0.288$). The overall correlation of eye blink rate was moderate for the flight simulator and flight test (R = 0.545, $P = 0.001$). Therefore, although eye blinks were uniformly decreased in flight, there was no significant decrease.

Similar to the NASA-TLX scale and eye blink rate, in the results of HR-D, both flight scenario [$F(2,24) = 17.720$, $P < 0.001$] and flight environment [$F(1,36) = 12.182$, $P = 0.001$] presented a significant influence on workload, but interaction of these two factors was insignificant [$F(2,24) = 0.065$, $P = 0.938$]. Otherwise, both in the SID (R = 0.813, $P = 0.001$) and in the SIA (R = 0.786, $P = 0.002$), the correlation of workload in the flight simulator and flight test was great, and in the DMA, the correlation was moderate (R = 0.718, $P = 0.009$). Moreover, the overall correlation of HR-D was conspicuous (R =

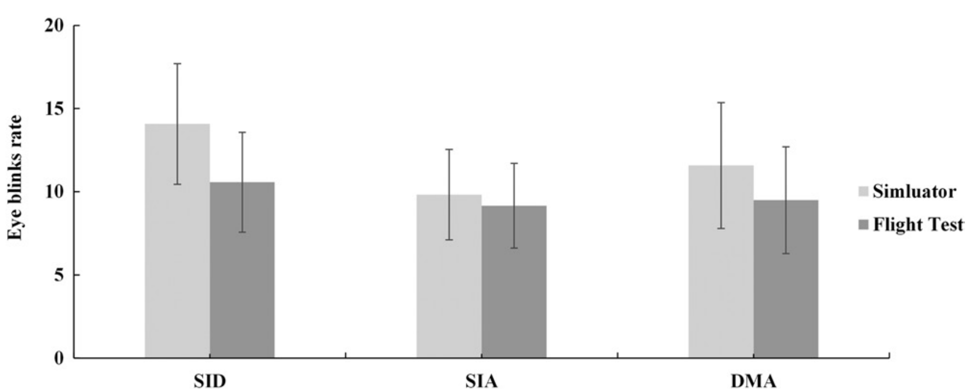


**Fig. 2.** The results of eye blink rate for the three flight scenarios, which were standard instrument departure (SID), standard instrument approach (SIA), and direct mode approach (DMA), in the flight simulator and in-flight test. The error bars stand for the standard deviation of eye blink rate of the subjects either in the simulator or in-flight test.

## DISCUSSION

According to the statistics, over 70% of flight accidents were attributed to human factors.[23] Therefore, the certification of human factors issues, especially flight crew workload, during the design phase of aircraft is of vital importance for further safety. Although the recommended means of compliance include a flight simulator test and flight test, the complexity, environment, and safety considerations of the compliance activities of a flight test require flight crew to take more responsibility and be more careful with decisions and actions with higher pressure. The actual danger of flight would also cause more anxiety than in the flight simulator. In consequence, the workload in the flight test was, on average, higher than in the simulator; for instance, increased heart rate and respiration rate, and decreased eye blink rate. Therefore, a simulator experiment might be more appropriate than a flight test, especially in high risk flight scenarios.

In this study, we were trying to measure workload subjectively and objectively in a flight simulator to be able to predict workload experienced during a flight test. In the subjective measures of this study, the correlation of the Bedford scale results was weak between the simulator and flight test. This was primarily due to the following two reasons. Firstly, the Bedford method only has 10 scales that assesses 4 levels, and scores of 1 through 3 were in the same range as that of satisfactorily perceived workload of the task.[22]

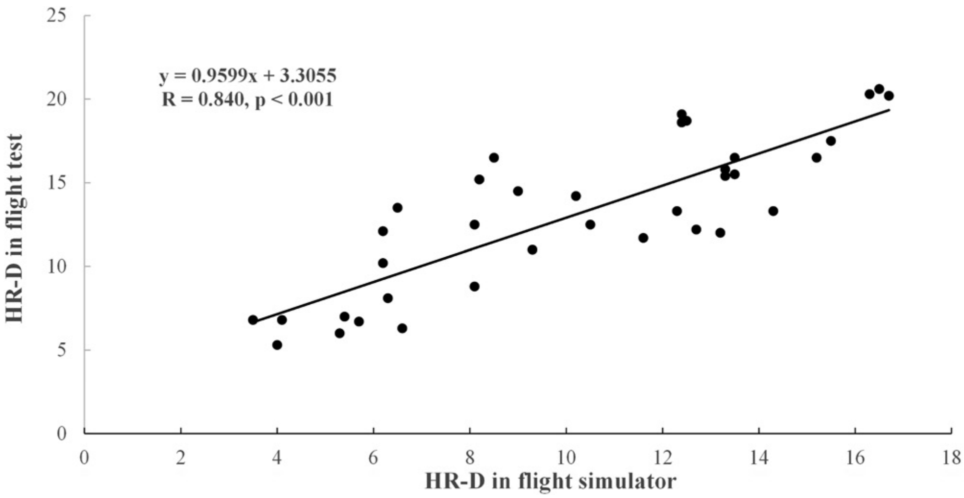


**Fig. 3.** The linear regression results of HR-D in the flight simulator and in-flight test.

It is difficult to distinguish the different workloads within the same range. Secondly, it is a kind of in-process questionnaire which might interfere with flight performance and affect subject's judgments. In contrast, the NASA-TLX is a post hoc multidimensional rating scale that assesses a subject's subjective workload on six 100-point scales related to a different aspect of workload.[13] It is more precise and comprehensive in workload evaluation. From the analysis of six rating subscales, mental demand and temporal demand were two primary causes of workload in all three scenarios. As more advanced high-tech applications are implemented on the flight deck, the role of pilot transforms from operator to supervisor; currently, even necessary physical demands of manual manipulations are decreased dramatically.[20] Besides, takeoff and landing are the most crucial flight phases, which require pilots to place emphasis on changes of airspeed, attitude, and altitude; that is, time pressure is relatively high during these two flight phases. Furthermore, the satisfactory discriminability of flight scenarios and flight environment and an overall strong correlation between flight simulator and flight test shows that the NASA-TLX could be considered a consistent measure of workload both in the simulator and flight test.

In the psychophysiological measures, the correlation of eye blink rate was moderate for the flight simulator and flight test. This was owing to the ambient light conditions in the flight test, which were brighter than in the simulator. In real flight, pilots are normally exposed to natural light and the majority of them choose to wear sunglasses to reduce the adverse impact of intense light. Nonetheless, some studies suppose that eye movement activity measures can provide a more sensitive measure of visual workload in real flight. For instance, Wilson suggested blink rates decreased during the more highly visually demanding segments of flights.[24] It is worth noting that different tasks can generate different patterns, depending on the type of index employed. Some indexes can be sensitive to visual demands but insensitive to cognitive demands. Similarly, respiration is influenced by some other factors, such as changes in the function of the central and autonomic nervous system.[25] The main problem with using respiration rate as an indicator of workload is the difficulty of separating the effects of workload from those of stress, particularly related to emotion.[19] Therefore, respiration rate would not be a reliable and long term predictor of workload.

On the other hand, HR-D represented great flexibility and a great correlation between simulator and flight test. The physiological effects of tasks cause an increase in heart rate. This result was similar to several other studies. Bonner and Wilson assumed heart rate would be used as the workload indication of airline pilots from preflight to landing in real flight.[3] De Rivecourt et al. noted that heart rate measures were sensitive to task complexity and compensatory effort resulting from stressors.[9] Thus, HR-D could also be regarded as a consistent measure of workload both in the simulator and flight test.

Currently, most workload evaluations of airworthiness certification are based on pilots' comments, especially from the in-flight test phase, and psychophysiological approaches are sometimes used in a simulator test phase. Nevertheless, both these two measures have their own limitations. Subjective rating scale measures are sometimes uncertain on the repeatability and validity, and data manipulations are often questioned as being inappropriate.[2] Psychophysiological measures are influenced by ambient

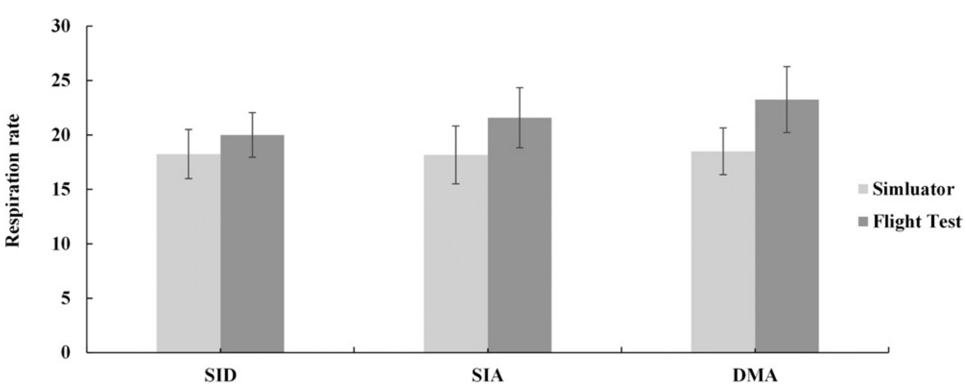


**Fig. 4.** The results of respiration rate for the three flight scenarios, which were standard instrument departure (SID), standard instrument approach (SIA), and direct mode approach (DMA), in the flight simulator and in-flight test. The error bars stand for the standard deviation of respiration rate of the subjects either in the simulator or in-flight test.

environment and task duration;[1] for instance, although HR values can change within seconds, reliable measurements are obtained for periods with a minimum length of 30 s and a maximum of 5 min. For shorter or longer periods, sensitivity decreases.[5] Thus, the best strategy is to combine the results of the NASA-TLX scales and HR-D together in a flight simulator to predict workload experienced during a flight test, particularly when encountering abnormal situations.

Future work should be carried out in three aspects. Firstly, although we implemented certain intervals between the two flights, whether it was enough and the order effect of the sequencing of scenarios on the measures collected require more consideration. Also, since this study was conducted during a compliance demonstration test of a novel type of aircraft, for the sake of safety, we only selected three takeoff and landing flight tasks for the flight test. Subsequently, abnormal flight conditions are going to be introduced. For instance, one engine failure, crosswind handling qualities, etc. Last, but not least, the inconsistency of the implementation of eye movement and respiration rate requires further study, including practical lighting conditions within tasks requiring relatively high workload.

## ACKNOWLEDGMENTS

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