Physiological Indices of Pilots' Abilities Under Varying Task Demands

Zhen Wang; Lingxiao Zheng; Yanyu Lu; Shan Fu

INTRODUCTION: This study investigated pilots' ability by examining the effects of flight experience and task demand on physiological reactions, and analyzing the diagnostic meanings underlying correlated parameters.

METHOD: A total of 12 experienced pilots and 12 less experienced pilots performed 4 simulated flight tasks, including normal and emergency situations. Fixation duration (FD), saccade rate (SR), blink rate (BR), heart rate (HR), respiration rate (RR), and respiration amplitude (RA) were measured during the tasks.

RESULTS: More experienced pilots adapted their SR flexibly to changing task demands and had significantly lower SR than less experienced pilots during emergency tasks (29.6 $\pm$ 20.0 vs. 70.1 $\pm$ 67.1 saccades/min). BR, HR, and RR were affected by pilot experience but not by task demand. More experienced pilots had lower BR, HR, and RR than less experienced pilots during both normal tasks (BR: 14.3 $\pm$ 13.0 vs. 32.9 $\pm$ 25.8 blinks/min; HR: 72.7 $\pm$ 7.9 vs. 83.2 $\pm$ 7.2 bpm; RR: 15.4 $\pm$ 2.1 vs. 19.5 $\pm$ 5.2 breaths/min) and emergency tasks (BR: 10.2 $\pm$ 5.0 vs. 32.3 $\pm$ 20.8 blinks/min; HR: 73.3 $\pm$ 7.3 vs. 82.2 $\pm$ 11.6 bpm; RR: 15.6 $\pm$ 1.9 vs. 18.0 $\pm$ 3.2 breaths/min). FD and RA were not sensitive to either flight experience or task demand.

CONCLUSIONS: Physiological reactions have the potential to reflect pilots' ability from different aspects. SR and BR could indicate pilots' differences in information access strategy. HR and RR could reflect a pilot's physical fitness. These findings are useful for understanding a pilot's ability.

KEYWORDS: pilots' ability, flight experience, task demand, physiological reactions, factor analysis.

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Though technology developments have achieved great progress in aircraft reliability, human errors remain the major threat to flight safety (about 70% of aircraft accidents are related to human errors).[22] One of the leading causes of human error is lack of experience.[14,18] It has been found that flight safety is highly correlated with pilot experience.[17] Crash rate decreases as total flight time increases.[18] It is important to find out where the difference in ability between expert and novice pilots is so as to develop training strategy and improve flight safety.

During the flight, aircraft pilots play the role of decision maker. They perceive cues from multiple sources and integrate the useful ones in order to make appropriate assessment of the current situations. Then, actions are selected after evaluating various possible outcomes. Whether pilots can make appropriate and timely decisions determines the safety of the aircraft. A series of studies have been made to investigate the differences of expert and novice pilots during difficult situations. Kasarskis et al.[13] noticed that during visual flight rules flight, expert pilots had significantly shorter dwell times and more total fixations than novice pilots. Expert pilots were also found to have better defined eye-scanning patterns. Schriver et al.[21] found that more expert pilots allocated more attention to problem-relevant cues when malfunctions occurred and made decisions more accurately than less expert pilots. Wiggins et al.[29] found that expert and novice pilots used in-flight cues differently. Yao et al.[31] indicated that more experienced pilots had lower heart rate than less experienced pilots during more demanding flight phases.

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Besides speed, accuracy, attentional strategy, and experienced workload, flexibility to changing task demands has also been considered part of a pilot's ability. Adams et al.[1] have summarized some characteristics of an expert pilot, such as being able to use their knowledge flexibly; being adaptive to the encountered problem and situation, etc. Bellenkes et al.[2] found that expert pilots can modulate their visual strategy more flexibly in response to changing task demands. Yao et al.[31] indicated that less experienced pilots had higher respiration rate during more demanding flight phases than during resting periods. However, for more experienced pilots, task demand did not have a significant effect on respiration rate. Therefore, when investigating a pilot's ability, it is not only essential to consider individual differences between expert and novice during difficult situations, but also a pilot's self-differences among different levels of task demand should be taken into account.

This study primarily focused on the effect of a pilot's ability on physiological reactions. For this purpose, pilots with different levels of experience were recruited and they performed a battery of flight tasks which contained not only normal routine tasks, but also some emergency tasks. On the one hand, we investigated the effects of pilot experience on physiological reactions during normal tasks and emergency tasks, respectively; on the other hand, the effects of task demands on physiological reactions were also investigated among pilots with different experience, respectively.

It is worth noting that physiological reactions are not direct measures of pilots' ability. Researchers have to presume a pilot's possession of a specific ability when investigating differences in physiological reaction. Moreover, different physiological parameters could be sensitive to different stimuli. For example, Veltman et al.[26] found that some physiological parameters such as heart rate and respiration are sensitive to task difficulty, while physiological parameters such as eye blink were not influenced by changing task difficulty and seemed to be effective indicators of visual demands. In order to investigate pilots' ability from different perspectives, multiple physiological parameters were examined in this study. Furthermore, in order to improve diagnosticity, some latent variables were extracted from the physiological dataset via analysis of the commonness and distinction between physiological parameters. Each of the latent variables represented the common characteristics of physiological reactions in a particular aspect and can reveal the nature of a pilot's ability.

METHOD

Subjects

Participating in this research were 24 Chinese male commercial pilots (mean $\pm$ SD age: 38.1 $\pm$ 7.5 yr), including 12 more experienced pilots (mean $\pm$ SD total flight hours: 11,833.3 $\pm$ 3809.9 h) and 12 less experienced pilots (mean $\pm$ SD total flight hours: 1578.8 $\pm$ 1059.8 h). All these pilots passed the airline routine health examination and did not suffer from any illness or take medication. They agreed to wear physiological status monitors during flight tasks and gave written informed consent. The research was approved by the Institutional Review Board of the School of Aeronautics and Astronautics, Shanghai Jiao Tong University (approval number: 2014-019; approval date: December 7, 2014; expiration date: December 6, 2015).

Equipment

The experiment was performed in a 6-degree-of-freedom full flight simulator (CAE Inc.; Saint-Laurent, Quebec, Canada). The arrangement of the cockpit, the system functions, and the aerodynamic model are identical to the Bombardier CRJ-200 model. The simulator complies with the Level C requirement of China Civil Aviation Regulation (CCAR-60) and is certified for the purpose of training commercial air transport pilots.

In order not to affect the pilots' performance, two sets of wearable and nonintrusive physiological status monitors were used in the experiment. The Tobii glasses (Tobii Technology AB, Danderyd, Sweden) is a head-mounted eye tracker. It uses a pair of camera-embedded glasses to capture eye images and front view images with a sample rate of 30 Hz. After image processing, the Tobii Studio software can extract basic information such as pupil size, pupil position, and gaze position (infrared positioning markers and front scene snapshot are required for extracting gaze position). The Bioharness system (Bioharness, Zephyr Technology Corp., Annapolis, MD) was used to detect electrocardiogram (ECG) and respiration. The system consists of a chest strap and an integrated module containing sensors, storage memory, processing circuitry, and power supply. The sample rate of the ECG was 250 Hz and the sample rate for respiration was 18 Hz. The following features were calculated from the raw data for further analysis.

Fixation is the stationary state of the eyes during which gaze is held on a single target of interest. It was derived from gaze data. Changes of gaze position were detected by the Tobii system and used to calculate the angular velocity of the eye movements. When the angular velocity was below the threshold of $30° \cdot s^{-1}$, the activity was classified as fixation.[16] The time from when a fixation was detected to the point when eye speed exceeded $30° \cdot s^{-1}$ was defined as fixation duration.

Saccade is a fast eye movement which enables us to rapidly redirect our line of sight. It was also derived from gaze data. When eye speed was above $30° \cdot s^{-1}$, the eye movement was classified as a saccade.[16] The number of saccades per minute was defined as saccade rate.

Blink was derived from pupil size. When the pupil was occluded by the eyelid, pupil size became zero and a blink was detected. Blink rate was defined as the number of blinks per minute.

Heart rate was derived from the ECG signal. It was calculated by dividing 60,000 by time intervals between successive R-peaks. Respiration was measured by means of detecting the size differential of the thorax with a chest strap. After signal processing in the Bioharness module, respiration rate (breaths/min) and respiration amplitude (voltage on the pressure sensitive resistor) were extracted from the raw data.

Procedure

In the experiment, a series of flight tasks were performed by subjects. The tasks can be classified into two categories: the normal tasks and the emergency tasks. The normal tasks were some routine tasks performed in good weather and airport conditions without any system malfunction, including:

- Standard instrument departure. The task started when the aircraft was parked at the end of the runway and ended when the aircraft reached the cruising altitude of 10,000 ft.
- Standard terminal arrival. The task started when aircraft was at the initial approach fix and ended when the aircraft had stopped on the runway.

In the normal tasks, subjects were asked to followed the standard operational procedure and complete the task safely and smoothly.

The emergency tasks were encounters with serious system failures, including:

- Engine failure. When the subject was performing a standard instrument departure, the left engine suddenly failed after the takeoff decision speed. The participant had to proceed with the takeoff and land at an alternate airport with the other engine.
- Hydraulic systems failure. When the aircraft was cruising at an altitude of 32,000 ft with an airspeed of Mach 0.78, two out of three sets of the hydraulic systems failed. Participant had to use only the left hydraulic system to control the aircraft and land at an alternate airport.

These emergency situations are hazardous to aircraft safety and could lead to fatal accidents. All the system failures were set by the simulator instructor without notifying the subjects in advance. Subjects had to identify the emergencies promptly and perform the proper operation to assure aircraft safety.

During the experiment, the order of the normal tasks and emergency tasks was randomly set by simulator instructor. Between the tasks, there was a half-hour resting period. All the subjects completed the above four flight tasks as pilot flying.

Statistical Analysis

Firstly, the effects of pilot experience on the physiological parameters were analyzed. In order to exclude the influence of task demand, experimental trials were divided into two groups according to task demand (normal tasks and emergency tasks). Then, in each task group, multivariate analysis of variance (MANOVA) was used to compare the multivariate population means between pilots with different levels of experience. It is a good option to use MANOVA when there are more than two dependent variables because it takes into account the intercorrelations of the dependent variables and it is robust to minor violations of the normality assumption.[10] If pilot experience had a significant general effect, then univariate ANOVA was applied to examine the effect of pilot experience on each physiological parameter.

Secondly, the effects of task demand on the physiological parameters were analyzed. In order to exclude the influence of pilot experience, experimental trials were divided into two groups according to pilot experience (more experienced pilots and less experienced pilots). In each pilot group, MANOVA was applied to examine the overall effect of task demand. One-way ANOVA was applied to examine the effect of task demand on each physiological parameter.

Thirdly, exploratory factor analysis was used to identify the interrelationships among the physiological parameters and group those physiological parameters that had a unified trend.[12] This method can help to extract some latent factors to explain the correlated parameters with diagnostic meanings. When applying exploratory factor analysis, principal component analysis was used for factor extraction. The Kaiser rule (only retain the factors with eigenvalues above 1.0) was applied to determine the number of factors and varimax rotation (an orthogonal rotation that maximizes the sum of the variance of the squared loadings) was applied to rotate the factor axes so as to make the factors more understandable.

Data processing and analyses were performed with Matlab R2014b (Mathworks, Inc., Natick, MA) and the statistical software SPSS v19 (SPSS Inc., Chicago, IL). Physiological difference was considered significant when the corresponding P-value was less than 0.05.

RESULTS

Generally, pilot's experience had significant effects on physiological responses during both normal tasks [Wilk's $\lambda = 0.51$, $F(6, 41) = 6.54$, $P < 0.001$, partial $\eta^2 = 0.49$] and emergency tasks [Wilk's $\lambda = 0.52$, $F(6, 41) = 6.35$, $P < 0.001$, partial $\eta^2 = 0.48$]. Specifically, the effect of experience on each physiological parameter was analyzed by univariate ANOVA. Results are presented in **Table I** (during normal tasks) and **Table II** (during emergency tasks), respectively.

During normal tasks, a pilot's experience had significant effects on blink rate [$F(1, 46) = 9.83$, $P < 0.01$], heart rate [$F(1, 46) = 23.25$, $P < 0.001$], and respiration rate [$F(1, 46) = 12.25$, $P < 0.01$]. More experienced pilots showed lower blink rate (14.3 ± 13.0 vs. 32.9 ± 25.8 blinks/min), heart rate (72.7 ± 7.9 vs. 83.2 ± 7.2 bpm), and respiration rate (15.4 ± 2.1 vs. 19.5 ± 5.2 breaths/min) than less experienced pilots, as illustrated in **Fig. 1** (panel B to panel D). Fixation duration [$F(1, 46) = 0.87$, $P = 0.36$], saccade rate [$F(1, 46) = 0.22$, $P = 0.65$], and respiration amplitude [$F(1, 46) = 0.17$, $P = 0.69$] did not show difference between different levels of pilots.

During emergency tasks, a pilot's experience had significant effects on saccade rate [$F(1, 46) = 8.04$, $P < 0.01$], blink rate [$F(1, 46) = 25.57$, $P < 0.001$], heart rate [$F(1, 46) = 9.87$, $P < 0.01$], and respiration rate [$F(1, 46) = 10.22$, $P < 0.01$]. More experienced pilots showed lower saccade rate (29.6 ± 20.0 vs. 70.1 ± 67.1 saccades/min), blink rate (10.2 ± 5.0 vs. 32.3 ± 20.8 blinks/min), heart rate (73.3 ± 7.3 vs. 82.2 ± 11.6 bpm), and respiration rate (15.6 ± 1.9 vs. 18.0 ± 3.2 breaths/min) than less experienced pilots, as illustrated in Fig. 1. Fixation duration [$F(1, 46) = 3.37$, $P = 0.07$] and respiration amplitude

Table I. Difference Between More Experienced Pilots and Less Experienced Pilots During Normal Tasks.

PHYSIOLOGICAL PARAMETER	MORE EXPERIENCED (MEAN ± SD)	LESS EXPERIENCED (MEAN ± SD)	*F* (1, 46)	*P*
FD (ms)	359.5 ± 197.9	307.9 ± 186.0	0.87	0.357
SR (saccades/min)	72.8 ± 66.2	81.8 ± 68.5	0.22	0.645
BR (blinks/min)	14.3 ± 13.0	32.9 ± 25.8	9.83*	0.003
HR (bpm)	72.7 ± 7.9	83.2 ± 7.2	23.25**	0.000
RR (breaths/min)	15.4 ± 2.1	19.5 ± 5.2	12.25*	0.001
RA (volts)	0.020 ± 0.009	0.022 ± 0.014	0.17	0.69

FD = fixation duration; SR = saccade rate; BR = blink rate; HR = heart rate; RR = respiration rate; RA = respiration amplitude.
* $P < 0.01$; ** $P < 0.001$.

[F (1, 46) = 0.98, P = 0.33] did not show significant difference between different levels of pilots.

On the other hand, task demand did not show significant overall effect on the physiological parameters for either less experienced pilots [Wilk's $\lambda = 0.90$, F (6, 41) = 0.76, P = 0.60, partial $\eta^2 = 0.10$] or more experienced pilots [Wilk's $\lambda = 0.80$, F (6, 41) = 1.72, P = 0.14, partial $\eta^2 = 0.20$]. Specifically, the effect of task demand on each physiological parameter was examined by one-way ANOVA. For less experienced pilots, none of the physiological parameters show significant difference between normal tasks and emergency tasks [fixation duration: F (1, 46) = 0.36, P = 0.55; saccade rate: F (1, 46) = 0.35, P = 0.55; blink rate: F (1, 46) = 0.01, P = 0.94; heart rate: F (1, 46) = 0.14, P = 0.71; respiration rate: F (1, 46) = 1.26, P = 0.27; respiration amplitude: F (1, 46) = 0.30, P = 0.59].

For more experienced pilots, saccade rate [F (1, 46) = 9.35, $P < 0.01$] was significantly lower during emergency tasks than during normal tasks (29.6 ± 20.0 vs. 72.8 ± 66.2 saccades/min), as illustrated in Fig. 1 (panel A). Other physiological parameters did not have significant difference between normal tasks and emergency tasks [fixation duration: F (1, 46) = 0.06, P = 0.81; blink rate: F (1, 46) = 2.07, P = 0.16; heart rate: F (1, 46) = 0.08, P = 0.78; respiration rate: F (1, 46) = 0.07, P = 0.80; respiration amplitude: F (1, 46) = 0.03, P = 0.85].

Physiological parameters that showed sensitivity in the above results (i.e., saccade rate, blink rate, heart rate, and respiration rate) were selected for exploratory factor analysis. Principal component analysis was used to extract factors. There were two eigenvalues greater than 1. According to Kaiser's rule, the number of potential factors was 2.

After the varimax rotation, the two factors accounted for 73.02% of the total variance. Specifically, the first factor explained 38.50% of the variance and the second factor explained 34.52% of the variance. In the rotated factor matrix, heart rate and respiration rate loaded strongly on the first potential factor (0.836 and 0.868, respectively). Saccade rate and blink rate had strong loadings on the second potential factor (0.881 and 0.752, respectively).

DISCUSSION

According to the results of exploratory factor analysis, heart rate and respiration rate were correlated and had major contributions to potential factor 1. This factor was thought to represent pilots' physical fitness.

Heart rate and respiration rate did not show sensitivity to different task demand. These results were not in line with some previous studies which indicated that operators had higher heart rates[7,30,31] and higher respiration rates[3,27,28] in more demanding tasks. However, some studies demonstrated that the effects of task demand on physiological responses would be weakened after repeated training.[6,11] The subjects in this study were all certified commercial pilots. They had experienced long-term rigorous training, both physically and technically. The emergency tasks were also the most frequent training items. Therefore, the insignificant difference of heart rate and respiration rate between emergency tasks and normal tasks could be explained as pilots adapting to the stress from the emergency tasks after repeated training.

Meanwhile, it should be noted that, though heart and respiration rates did not show sensitivity to task demands, they were significantly different between pilots with different experience in both emergency tasks and normal tasks. More experienced pilots always had lower heart and respiration rates. This result was not in line with Yao's study,[31] which indicated that there were no significant differences in respiration rates between experienced and less experienced pilots during each phase of

Table II. Difference Between More Experienced Pilots and Less Experienced Pilots During Emergency Tasks.

PHYSIOLOGICAL PARAMETER	MORE EXPERIENCED (MEAN ± SD)	LESS EXPERIENCED (MEAN ± SD)	*F* (1, 46)	*P*
FD (ms)	347.4 ± 153.6	283.2 ± 75.7	3.37	0.073
SR (saccades/min)	29.6 ± 20.0	70.1 ± 67.1	8.04*	0.007
BR (blinks/min)	10.2 ± 5.0	32.3 ± 20.8	25.57**	0.000
HR (bpm)	73.3 ± 7.3	82.2 ± 11.6	9.87*	0.003
RR (breaths/min)	15.6 ± 1.9	18.0 ± 3.2	10.22*	0.003
RA (volts)	0.021 ± 0.009	0.024 ± 0.011	0.98	0.328

FD = fixation duration; SR = saccade rate; BR = blink rate; HR = heart rate; RR = respiration rate; RA = respiration amplitude.
* $P < 0.01$; ** $P < 0.001$.

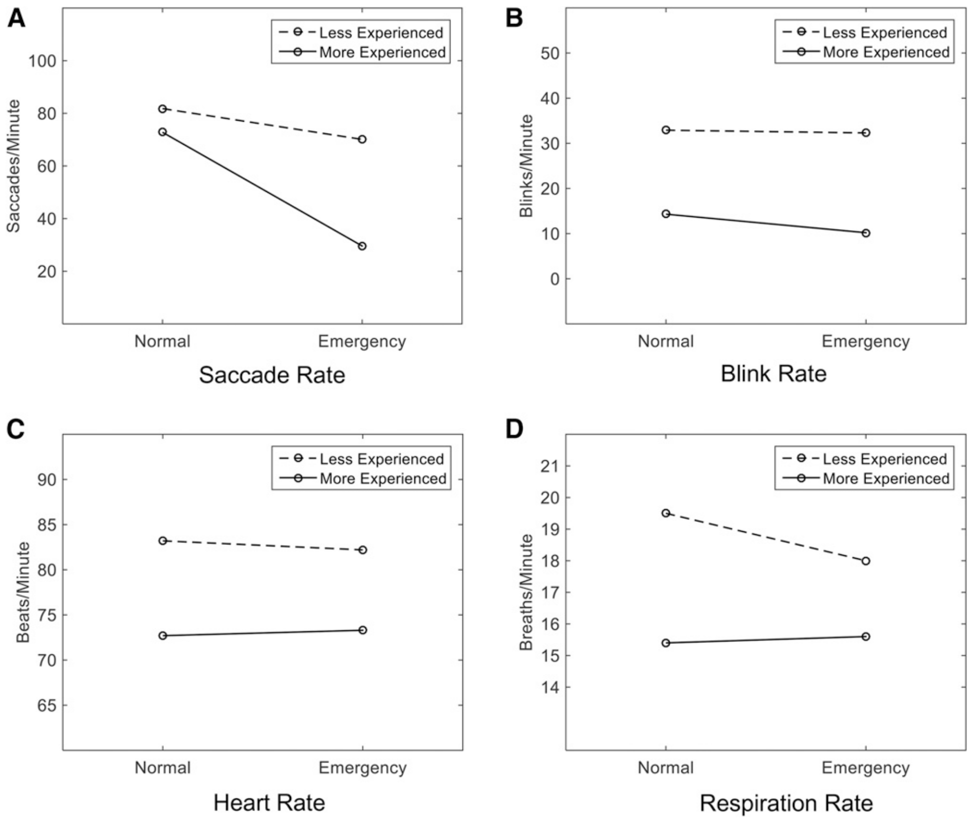

Fig. 1. The estimated marginal means of A) saccade rate, B) blink rate, C) heart rate, and D) respiration rate between different levels of pilots during normal tasks and emergency tasks.

environment during the flight would affect a pilot's motion sensors.[20] Experienced pilots can infer the aircraft attitude more accurately with their vestibular system.[15] This might allow them to allocate more visual attention to the emergency-related cues. Comparatively, pilots with less experience had to trust the displayed information about the aircraft's motion. Therefore, they had to keep to their scanning strategies.

Blink rate was not affected by changing task demand for both levels of pilots. However, blink rate was affected by a pilot's experience. During both normal tasks and emergency tasks, more experienced pilots had lower blink rates than less experienced pilots. It has been found in several previous studies that blink rate declines when there is higher visual demand.[25,26,30] Adams et al.[1] indicated that expert pilots can rapidly perceive large meaningful patterns in a situation which help them match the goals to task demands. Shriver at al.[21] found that more experienced pilots made better decisions in terms of speed and accuracy. This might require expert pilots to acquire and process more visual information per unit time than less experienced pilots do. Therefore, the results in this study were reasonable and blink rate could also be used to indicate a pilot's ability.

Several previous studies have found that more experienced pilots have shorter fixation duration than less experienced pilots.[2,13,21] However, in this study, fixation duration was not affected by either pilot experience or task demand. Fixation duration reflects the time needed for interpreting or relating the component representations on the interface to internalized representations.[8] Notice that in order to reduce a pilot's mental workload and increase flight safety, the major aviation safety agencies around the world require that cockpit information should be easy to access and clearly understandable. Also, during pilot recruitment, airline companies have strict requirements for pilot eyesight. These aspects would enable pilots to acquire cockpit information without difficulty. On the other hand, in order to maintain situation awareness, pilots are required to scan all the information needed instead of concentrating on one gauge. This could also be the cause of the insignificant results of fixation duration.

Respiration amplitude was not sensitive to either pilot experience or task demand. It has been observed in previous studies that respiration amplitude decreased as stress increased, but was also highly dependent on physical activity.[4] Since in this

the whole flight. However, several studies have indicated that long-term physical training could improve physical fitness in terms of shifting cardiorespiratory baselines (e.g., lower heart and respiration rates).[5,23,24] Therefore, the lower heart and respiration rates of more experienced pilots could be due to the steady accumulation of practice.

The factor analysis indicated that saccade rate and blink rate were the major contributing parameters of potential factor 2. It was thought that this factor reflected the pilot's information access strategy. Some studies have indicated that saccade rate is negatively related with task demand.[9,19] From our experimental results, only more experienced pilots had significantly lower saccade rates during more demanding tasks. Less experienced pilots did not show a significant difference between normal tasks and emergency tasks. It is also noteworthy that more experienced pilots had significantly lower saccade rates than less experienced pilots during emergency tasks. This result was in line with the conclusion by Bellenkes et al.,[2] who said "expert pilots adapted their visiting strategy more flexibly in response to changing task demands."

Why can expert pilots change their information access strategy when encountering emergency situations, but pilots with less experience cannot? It is known that perception of position and motion is determined by central nervous system integration of concordant and redundant information from multiple sensory channels (somatosensory, vestibular, and visual). However, the variations of the gravitational-inertial force study all participating pilots were well-trained, the effects of task demand may be weakened. The results of heart and respiration rate also proved this point. On the other hand, because modern cockpits are equipped with advanced automatic systems to assist the flight and it is not necessary for civil aircraft to be extremely maneuverable, civil aircraft pilots do not need to invest a large amount of physical effort. Therefore, it is reasonable that respiration amplitude did not show a significant difference.

In conclusion, this study investigated pilots' ability via examining the effects of experience and task demand on pilots' physiological reactions. By extracting underlying factors from parameters which had a similar trend, some facets of pilots' abilities were revealed. Saccade and blink rates could reflect a pilot's information access strategy. More experienced pilots adapted their saccade rate flexibly according to task demand. They also had lower blink rates than less experienced pilots. Heart and respiration rates are more likely to reflect a pilot's physical fitness. They were not sensitive to task demand, but showed significant differences among pilots with different experience. These results are very useful for understanding a pilot's ability and they suggest that physiological parameters have the potential to reflect a pilot's ability from different aspects. One limitation of this study is the relatively small sample size, which may limit the generalizability of our results. In future research, the findings need to be verified with a larger sample size. Various other physiological parameters should also be examined to investigate their diagnostic meanings. Moreover, expert pilots' information access patterns need to be carefully studied so that applicable methods can be provided to optimize pilot training strategy.

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