Micro-behavior Analysis of Pilots Based on Human-Aircraft-Environment Interaction

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Abstract: Micro-behavior of pilots is one of the most remarkable aspects in flight safety research domain. The study of pilot's micro-behavior and its function are of great significance to enhance active safety warnings of flight and evaluation of flight cadets. Based on the cognitive process of pilots, this paper explores the meanings and contents of previous research on the pilot's micro-behavior. The history and research status of pilot's micro-behavior are briefly introduced from the perspective of their psychology, physiology and physics. The current reviews mainly include the pilot's characteristic, multi-information fusion, integrated cognitive and humanization about controlling environment, etc. The several methods of these studies are discussed, and the mechanisms, experimental contents and applicable conditions of pilot's physiological, psychological and physical characteristics are analyzed. Meanwhile, the advantages and shortcomings of the existing research results are pointed out and analyzed. Combined with flight simulation experiment, the internal mechanism of pilot is explained. Furthermore, with the latest research in the modern flight field, and also from the specialization of application, the diversification of methodologies and the depth of investigation are provided, as well as the development trend of pilot's micro-behavior analysis in the future.

Key words: flight safety; micro-behavior; active safety warning; pilot; flight simulation

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0 Introduction

As air-transport industry develops vigorously, the number of flights has gradually increased. The statistics of Boeing Company's "2016 Statistical Summary of Commercial Jet Airplane Accidents" is shown in Fig.1. Since 1959, with the development and improvement of aircraft autopilot driving and other technologies, the air-transport accident rate has generally declined in the world. The trend has gradually stabilized. However, there are potential defects in the in the autopilot system. For example, although it plays a significant role in eliminating errors and preventing accidents, it causes problems such as a large amount of information processing of pilots. These problems increase the mental workload of the pilot. Aviation accidents continue to occur as the number of flights increases[1].

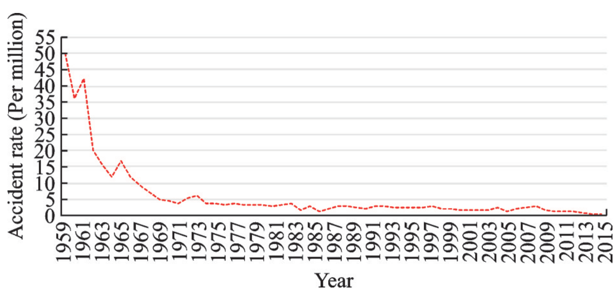

Fig.1 Air-transport accident rate

Air-traffic congestion, pollution, noise and safety problems are coming and becoming increas-

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ingly serious. The center of the development pattern of complex air-traffic system composed of human-aircraft-environment is gradually changing from "aircraft" to "human"[2]. Aiming at building a safe, convenient, green, efficient, comfortable and intelligent air-traffic system, researchers begun to refocus on the importance of pilots in the air-traffic system. Although the pilot is gradually liberated from heavy tasks with the improvement of aircraft automation, the annual accidents caused by human factors account for 70% of the total air-traffic accidents[3-4]. By analyzing the aviation accident statistics of ICAO (International Civil Aviation Organization) and Boeing Company, the proportions of human-aircraft-environment and other factors are displayed in Fig.2. More than half of these factors are caused by the mistakes of the flight crew and the improper operation of the pilots themselves[5-6]. Therefore, it is necessary to study the micro-behavior of pilots, which can ensure that the pilots safely control the aircraft in a limited space. In addition, it also guarantees the rationality of the micro-behavior assessment system for pilots. This paper analyzes and summarizes the micro-behavior of pilots. The model and method involved in the research of pilot's micro-behavior are further elaborated, and the advantages and disadvantages of the existing research are explored. Finally, the future development trend of pilot's micro-behavior research is prospected according to the multi-source dynamic data of the flight simulation experiment.

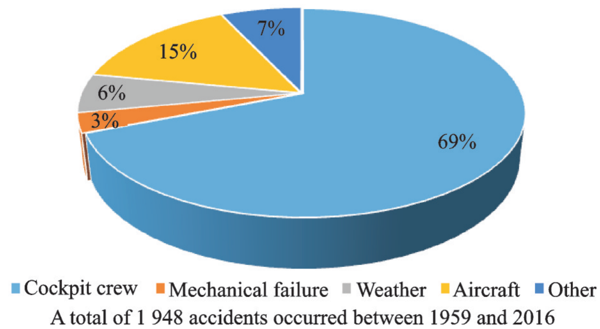


Fig.2 Main reasons statistics of flight accidents in 1959—2016

1 Analysis of Pilots' Micro-behavior

The pilot's micro-behavior refers to the individual characteristics (psychological, physiological and physical, etc.) manifested in the pilot's operation of the aircraft, as well as the overall behavior of the crew and ATC (Air Traffic Control)[7-8]. It runs through the cognitive process of completing tasks in a human-aircraft-environment complex system (Fig.3). In this process, the pilot can obtain information from sensory systems such as eyes and ears. Then, the obtained information is processed by an internal processing system such as brain. Finally, the processed information is output through the limb systems, such as hands and feet. In this paper, the microcosmic characteristics of the pilot are summarized and analyzed from psychology (e.g., the cognitive characteristics of the pilot), physiology (e.g., heart rate, skin electricity, etc.) and physic (e.g., hand and foot manipulation characteristics).

As Fig. 3 illustrates that the pilot's micro-behavior is not only a combination of information perception, working memory, response decision and execution, but also a chain reaction of these processes. Simply put, the pilot perceives multi-sources of information such as human, aircraft, environment and so on through the sensory system, as shown in Fig.3. Under the effect of pilot's attention, the air-

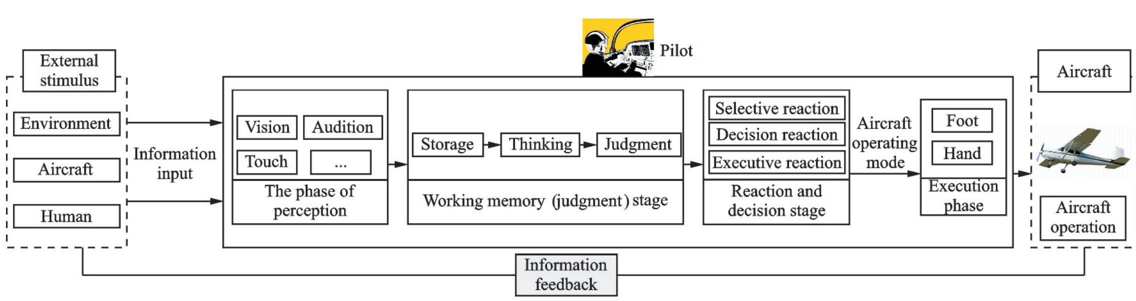


Fig.3 Cognitive process of pilots

craft attitude, ATC communication and flight manual are initially matched in the working memory phase[9-10]. And then the matched information is further processed (control delay). According to flight rules, experience and tasks, the aircraft's altitude, speed and heading are determined. Pilot will make control decisions based on the operating mode of current aircraft to achieve the aircraft acceleration, deceleration, climb, descent and other attitude changes through the hands and feet[11]. After the whole process, the changes in operating parameter of aircraft is fed back to the pilot again under the comprehensive effect of human-aircraft-environment. Furthermore, this feedback has an effect on the next decision and execution of pilot[12].

1.1 Psychological characteristics of pilots

Psychological factor determines behavior, while behavior is the external manifestation of psychological characteristics[13-14]. When psychological characteristics of this special career are in line with the professional demand, pilots will actively adjust their initiative and consciously guide the individual behavior. On one hand, pilots will further stimulate their potential, improve their working ability, and thus greatly increase the safety of flight[15-16]. On the other, if pilot's psychological characteristics are inconsistent with professional demand, then they have a greater psychological burden. However, this large psychological burden can lead to increased error rate for pilot, which is not conducive to safe flight operation. The reasons for the grounding of non-qualified pilots considering flight safety in several countries were analyzed. It is found that the number of pilots grounded for psychological reasons ranked second in all grounding reasons. It can be seen that psychological conditions are important for pilots to fly safely[17-20].

Domestic and foreign scholars have studied the psychological characteristics of pilots from the perspective of occupational suitability. The main research findings are indicated in Table 1.

Scholars at home and abroad have studied the psychological characteristics that pilots should possess by using multiple personality measurement methods and flight selection systems[37-42]. At present, the subjective scale and pilot's traits ubiquitously existed in civil aviation are shown in Table 2.

Table 1 Research on the psychological characteristics of pilots

Researcher	Year	Method	Psychological characteristic element
Xiao[21]	2002	Interview method, Questionnaire	Emotional stability
Morrow et al.[22]	2003	Expert opinion, One-way analysis of variance	Working memory
You et al.[23]	2004	Questionnaire	Mental health level, Work attitude
Wickens[24]	2005	SEEV model	Attention, situational awareness
Johansson[25]	2006	"Multi-indicator" (MI) in the MIMIC model	Attitude, personality trait
Tan et al.[26]	2007	Questionnaire, Significance analysis	Psychological stress
Gruszecki et al.[27]	2008	Heuristic algorithm	Propensity, short-term memory, long-term memory
Wu[28]	2009	Risk management	Congregational psychology
Dai[29]	2010	Questionnaire	Personality traits
Benthem[30]	2011	Simulated flight detection, Multiple regression analysis	Prospective memory
Yan et al.[31]	2012	Questionnaire	Mental health status
Causse et al.[32]	2013	Aviation safety neuro-engineering method	Emotional and mental stress
Jia[33]	2014	Pearson correlation analysis, Variance homogeneity test	Alertness
Schlimm[34]	2015	UPRT(Upset prevention and recovery training)psychological model	Situational awareness
Ji et al.[35]	2016	Literature analysis, Questionnaires and Expert interviews	Attitude, prospective memory
Tavcar et al.[36]	2017	Hybrid multi-agent strategy discovering algorithm (HMASDA),	Well-being, emotional response
⋮	⋮	⋮	⋮

Table 2 Subjective scale of psychological characteristics

Method	Measuring element
Five personality scales (NEO-PI-R)	Openness, conscientiousness, extraversion, agreeableness, neuroticism
16 personality factor questionnaire (16PF)	Music group, intelligence, stability, reluctance, excitement, perseverance, courage, sensitivity, suspicion, fantasy, secularity, anxiety, experimentation, independence, self-discipline, tension
Myers-Briggs Type Indicator (MBTI)	Extraversion-introversion, feeling-intuition, thinking-emotion, judgment-understanding
Eysenck Personality Questionnaire (EPQ)	Internal and external (E), neurotic (N), psychotic
Uchida-Kraekpelin Text	Startup, variability, excitability
⋮	⋮

Although the listed pilot's psychological characteristics are limited, there are some differences in the study time. The psychological characteristics vary with multi-source dynamic data of human-aircraft-environment. In general, it is consistent that some psychological characteristics (e.g., emotions, situational awareness, memory, attitude, etc.) are the key factors affecting pilot behavior. This also shows that stability of psychological characteristics directly affects flight safety.

1.2 Physiological characteristics of pilots

"Physiology" refers to the function of a living organism, that is, the various phenomena of life manifested by the whole organism and its parts[43-44]. As a special profession, pilots are faced with complex and strict information processing[45]. The pilot's physiological characteristics are constantly changing and exhibit individual differences under the interaction of multi-source information such as human-aircraft-environment[46]. In other words, the pilot may have different physiological characteristics in the same flight mission. Changes in physiological characteristics directly affect the pilot's handling of the aircraft, thereby further affecting flight safety. At present, the physiological characteristics of the pilot are mainly analyzed with the focus on the brain load, driving fatigue and visual attention, as illustrated in Table 3.

To reduce the intrusive research on pilots and ensure natural piloting, most scholars use high-level flight simulators to conduct experiments and acquire data. "High-level flight simulator" is a D-class flight simulator. It is the highest level flight simulation training equipment specified by the International Civil Aviation Organization. It can replace real aircraft. A few researchers have combined the real aircraft with the simulation experiment to obtain the data[63-64]. Currently, the measuring equipment commonly used in the study of the physiological characteristics is arranged, as described in Table 4.

There are certain differences in the study of pilot's physiological characteristics, either from the longitudinal continuity of time or from the horizontal contrast in various fields. As an implicit variable in the pilot's decision-making process, physiological characteristics become an important factor affecting flight safety as same as psychological characteristics[65]. The stability of these characteristics is related to decision-making process and the accuracy of the behavior. Therefore, physiological characteristics of the pilot are not only important indicators for pilot selection, but also are important factors affecting flight safety.

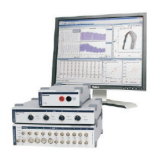
1.3 Physical characteristics of pilots

In the complex system of human-aircraft-environment, the ultimate goal of receiving or processing information is to output the result information through an effector (e.g., hands, feet, etc.)[66]. The output information is expressed as the physical

Table 3 Physiological characteristics of pilots

Researcher	Year	Method	Psychological characteristic element
Bonner et al.[47]	2002	Physiological test, Experimental comparison	Heart rate
Knecht et al.[48]	2003	Regression analysis, SPSS	Visual characteristics
Chernyshov[49]	2004	Use of mathematical expectations based on conditions of input and output variables	Features of eye movements
Dussault et al.[50]	2005	Flight sequence simulation experiment	Electroencephalo-graph (EEG), electro-cardiograp (ECG)
Dahlstrom et al.[51]	2006	Get data from simulation experiments and compare	Heart rate
Shappell et al.[52]	2007	Human factor analysis and classification system	Visual characteristics
Li[53]	2008	NASA-TLX scale	EEG, heart rate, ECG, body temperature, pulse, blood pressure
Damveld[54]	2009	Delft and McRuer method	Neuromuscular system
Simone[55]	2010	Dynamic Modeling Performance and Reliability Analysis of Draper Labs(PARADyM)	Visual and anticourt characteristics
Kenneth[56]	2011	Haptic-Multimodal Flight Control System	Pilot's touch
Gao et al.[57]	2012	Least square method	Vestibular system, neuromuscular system
Li et al.[58]	2013	Simulated flight experiment, Significant analysis	Heart rate variability
Zhang et al.[59]	2014	Single-axis mission, three-axis mission and quadruple mission simulation flight, multivariate analysis of variance, regression analysis	Heart rate
Zhang[60]	2015	Fitts law	Visual characteristics
Mario[61]	2016	Monte Carlo simulation, RegRLS algorithm	Visual and force feedback
Jaquess et al.[62]	2017	One-way analysis of variance	EEG, ECG
⋮	⋮	⋮	⋮

Table 4 Partial physiological measuring equipment and functions

Name	Function	Pattern
Power lab multi-channel physiological recorder	Real-time monitoring and recording of standard lead ECG	
BIOPACMP multi-channel physiological recorder	ECG, EEG, electromyography (EMG), electrooculogram (EOG), gastrointestinal myoelectric activity, blood pressure, dP/dt, PH, body temperature, muscle tone, etc.	
Bio-Harness portabl physiological signal measurement System	ECG, RR interval, heart rate, respiratory wave, respiratory rate, body temperature, body posture, maximum and minimum three-way acceleration, etc.	
Tobii eye view monitoring system	Binocular tracking, binocular acquisition	
Eego mylab full mobile EEG recording analyzer	Analysis of EEG/ERP/MEG, etc.	
⋮	⋮	⋮

action of controlling aircraft's operation (i. e., the pilot's limb movement characteristics). There are few researches on physical characteristics of pilots at home and abroad. This paper mainly reviews the research on the manual behavior of pilots. Among them, the representative is the study by the team of Professor Fu Shan, Shanghai Jiao Tong University. Aiming at the problem of flight safety, they utilized visual monitoring techniques to study the operating gestures of pilots in commercial aircraft cockpits. The main research process and methods are shown in Fig.4[67].

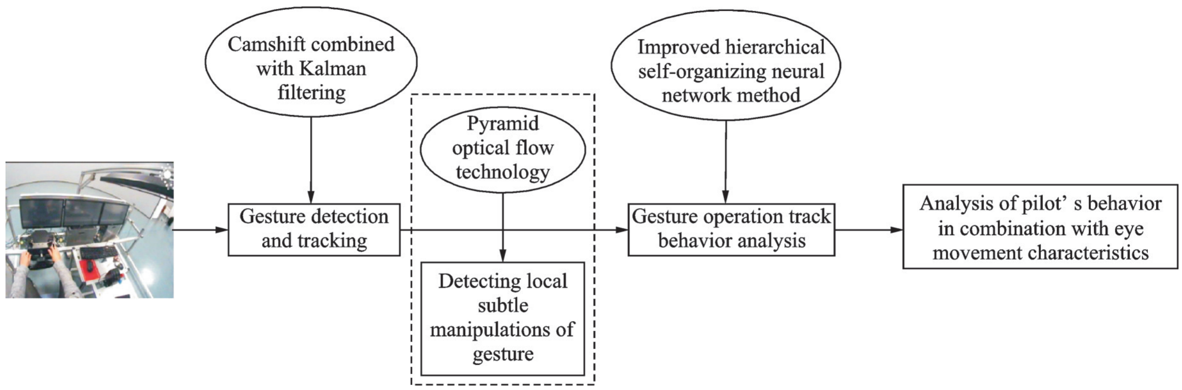


Fig.4 Research on pilot manual behavior

The pilot's physical characteristics are modeled and simulated through subjective evaluation and objective measurement. Afterwards, the actual and synchronous reproduction of pilot's micro-behavior is further realized. The physical characteristics are direct inputs to changes in aircraft status and direct factors affecting flight.

2 Discussion and Analysis

2. 1 Discussion on pilot's micro-behavior

There also exist shortcomings in the study of pilot micro-behavior. Some scholars focused on the "aircraft" (aircraft cockpit design, aircraft control panel improvement, etc.) when discussing the issue of human-aircraft interaction. They regarded the pilot as a single element in the process of human-aircraft interaction, and did not consider the complexity of the pilot. Another scholars analyzed the individual characteristics of the pilot from the perspective of memory, attention, manual mode, and driving fatigue. Others analyzed the generation and loss of situational awareness of pilots in special situations, such as dangers based on cognitive psychology. All these studies lack a multivariate continuity analysis based on time series and investigation in a three-dimensional space combined with time and space.

Based on the summarization and analysis of domestic and foreign research on pilot's micro-behavior, the following conclusions are drawn:

(1) The traditional research on micro-behavior of pilots mainly adopts subjective evaluation. It is a static human-aircraft effectiveness evaluation system with disadvantages of being not synchronous and error interference. And then, it cannot accurately describe and evaluate the detail process of the pilot's aircraft control. Moreover, this kind of evaluation system is generally analyzed and evaluated from certain nodes, and lacks comprehensive consideration of pilot's behavior during the research process. This problem is extremely important for both active safety warning and black box analysis.

(2) The study of pilot's micro-behavior is various and there are great differences between methods. The pilot's micro-behavior is a part of the research on human factors in flight. The reliability analysis method of pilots related to human-aircraft effectiveness can be used to explore it partly.

(3) The ultimate behavioral decision of pilots is the result of interactions such as emotions, cognition, and consciousness. Exploring the coupling mechanism of pilot's microscopic characteristics is the key to perfecting the core algorithm of active

safety early warning system. Hence, studying the internal micro-mechanisms of the pilot can promote the aircraft autopilot. Moreover, it is also helpful to the development of humanized and intelligent aircraft.

(4) The pilot's micro-behavior involves a wide range of aspects, mostly intrinsic mechanistic research. Due to the complexity of the aircraft operating environment and the time-varying interaction between the pilot and the external information, the frequency of changes in pilot's micro-behaviors is higher. In addition, the sources of information that characterize the pilot's micro-behavior are diverse, and the methods of collecting and processing this information are also different. It is because that there is a huge space for the study of pilot's micro-behavior.

This paper starts with the existing research problems and takes the pilot's micro-behavior as the object. On the basis of revealing the interaction mechanism between various information and pilots, the internal mechanism of pilot's operation of aircraft in time-varying environment is discussed. Then, it further draws on the theory and method of artificial psychology and emotional calculation, and uses dynamic data of human-machine-environmental to accurately and quickly identify the pilot's micro-behavior from multiple perspectives.

2.2 Analysis of pilot's micro-behavior

This paper draws on previous relevant research experience[68-69]. Taking the pilot's airfield traffic pattern as an example, on the basis of the combination of the subjective evaluation and the objective measurement, the high-simulation flight platform is adopted to build a virtual environment. The sample size of the experiment was 100 male flying cadets who had obtained the Private Pilot License, Commercial Pilot License and Instrument Rating License. Their age ranged from 25 to 30 with the mean value of 27. Their flight hours were between 250 and 300 h with the average of 275 h. The experiment was mainly conducted in a high-level simulator. The experimental equipment especially included dynamic acquisition system for comprehensive human-aircraft-environment information (including Mangold-10 multi-channel physiological instrument, Tobii S600 high-precision eye tracker Polar watch, BIOHARNESS portable physiological measuring instrument, high-definition camera and so on), high-level simulation platform, NASA-TLX scale, etc. The 100 flying cadets were selected in the experiment, numbered from 1 to 100. And then their age and flight hours were recorded. Experiments were designed to obtain data on the physiological, psychological, physical and other external factors of each flying cadets. The 3D virtual flight scene of simulator provides the pilot with realistic visual, auditory and tactile feelings. The flight scene is an airfield traffic pattern, including acceleration, deceleration, climb, descent, change of heading, etc. The path of flight is indicated, as well as the contents to determine the physiological, psychological, physical and other factors of flying cadets. The experimental process is shown in Fig.5. All subjects signed informed consent before the experiment. The agreement of the experiment complies with the Declaration of Helsinki. Among them, the questionnaire is applied to statically survey pilot's psychological characteristics type. Pilot's psychological

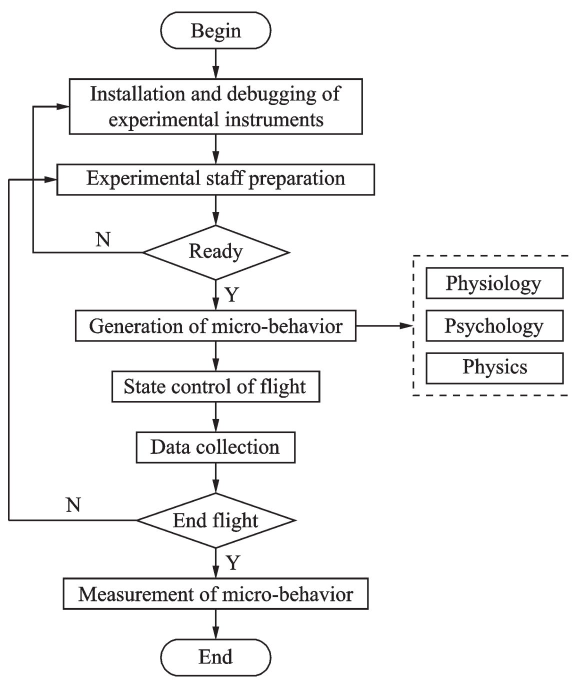


Fig.5 Flight simulation experiment process

characteristic formed in past flight experience is relatively stable. It is always under the control of brain consciousness and exists in implicit form, and is divided into the type of conservative, conventional, and aggressive. The physiological and physical characteristics of pilots are obtained under the premise of natural flight through objective monitoring equipment, such as video surveillance and human-induced wireless sensor.

Only some of the psychological, physiological and physical characteristics of the pilot on the final of airfield traffic pattern are demonstrated here (Fig.6). The main flight process reference[70-71] is indicated by Fig.7.

Fig.6 Partial physiological indicators

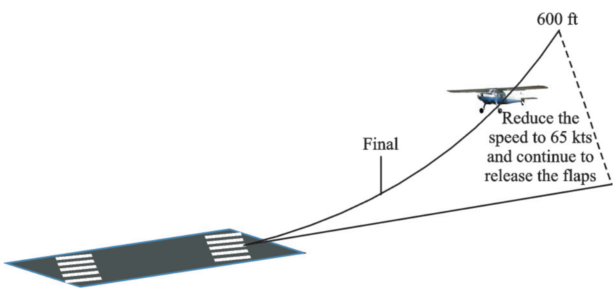


Fig.7 Aircraft descending diagram

By the analysis of the some of pilot's micro-behavior, it is found that different types of pilots exhibit different characteristics in a same task. In addition, a same pilot will have different characteristics in different missions. The pilot's micro-behavior mechanism is shown in Fig.8. The microscopic behavior of pilots is complex and versatile. Therefore, how to study it in the time-varying human-aircraft-environment system and reveal the internal micro mechanism are particularly important for further research on flight safety and so on.

3 Conclusions

The analysis on the micro-behavior of pilots is popular and difficult in human factors of air traffic. Nevertheless, research in this field has achieved certain results in human error analysis, aircraft cockpit design and human-aircraft interaction. This paper reviews the research status quo of pilot's micro-behavior and concludes that these studies have the following features:

The study of pilot's micro-behavior involves traffic engineering, aviation psychology, flight performance engineering, flight principle, mathematical statistics, computer and other disciplines. This research presents a multidisciplinary situation.

The calibration of micro-behavioral parameters is complicated. Because of the differences in the pilot's physical, psychological, and physical characteristics, many conclusions are not universal. Therefore, a large number of experiments need to be repeated to acquire data under different conditions for the calibration of model parameters, such as environment, flight hours, education, and age, etc.

Experimental data in special circumstances are limited. Due to insufficient experimental data in extreme conditions such as engine failure, deviation between simulation and real conditions is common, which makes it difficult to be prevented. In the future, enough attention should be paid to the relevant fields in the special circumstances.

The current research on the micro-behavior mechanism of pilots is rare, and there are many is-

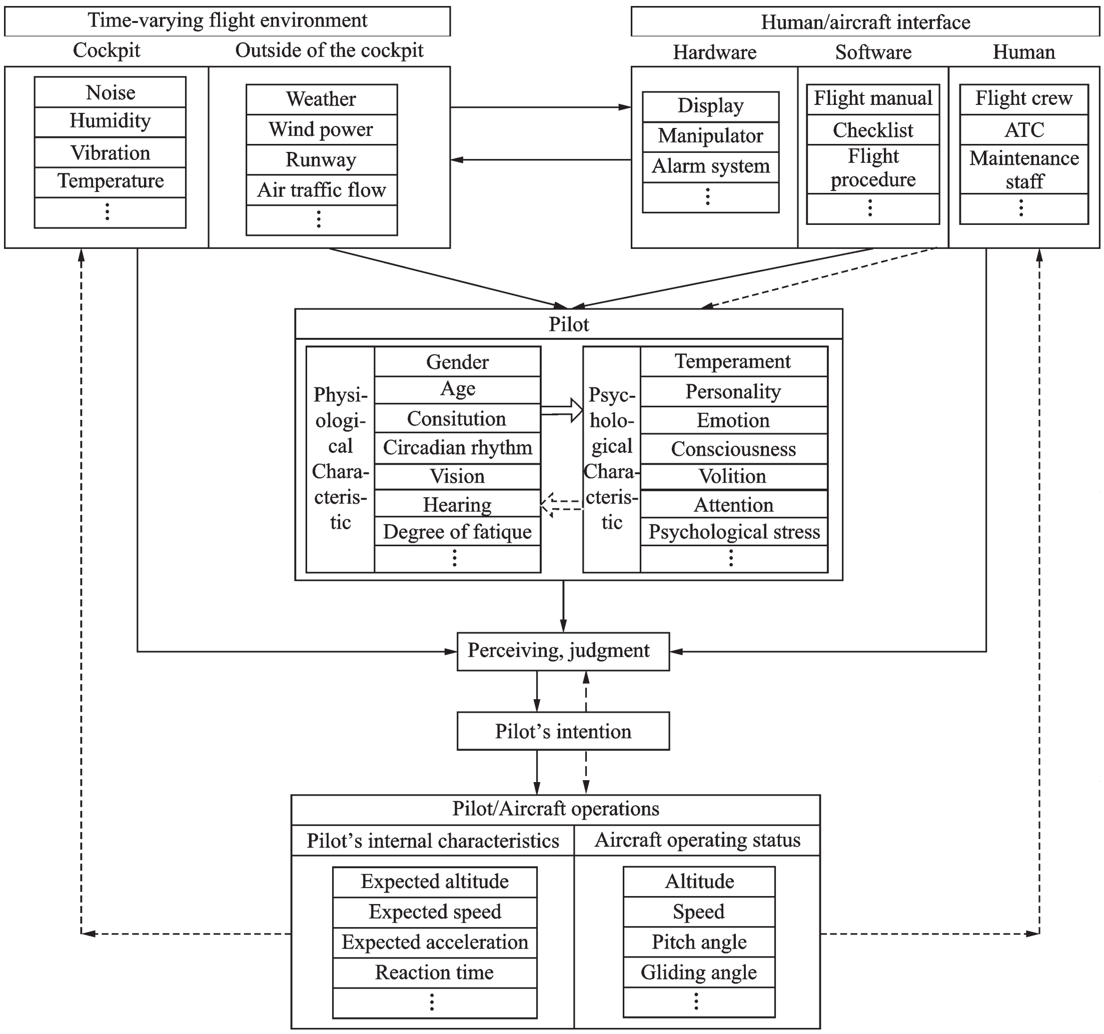


Fig.8 Schematic diagram of pilot's micro-behavior mechanism

sues to be further studied and resolved:

The research should be targeted to a specific application. The pilot's micro-behavior is characterized by diversity, randomness and difficult measuring. It is unrealistic to construct a standard simulation model of pilot's micro-behavior. Contrarily, in a specific flight mission, environment conditions of flight cadets are needed, such as the selection, assessment, etc. It is thus more practical to establish a model of pilot's micro-behavior.

Experimental methodology and data should be multi-sourced. Since the data of pilot's micro-behavior are scarce, some models lack data support and experimental comparison, and the established model cannot be verified and calibrated. Therefore, it is necessary to strengthen the collection of basic data. Moreover, physiological-psychological tests, simulation and real-aircraft experiments should be used reasonably if it is permitted. These experimental measures complement and verify each other. The subjective knowledge and objective laws are comprehensively considered in the process of experimental data acquisition. The multi-sourced dynamic data of human-aircraft-environment are recorded in a more precise and humanized way, thereby providing data support to pilot's micro-behavior.

Research process needs to be staged. Due to the uncertainty and diversity of pilots, the study of micro-behavior is difficult. Therefore, any single level and simple combination of several methods is hard to work. According to various stages of pilot's cognitive process, different methodologies based on the idea of decomposition-coordination and algorithm of multi-level division are adopted. The complex pilot's micro-behavior is thus simplified, and the accuracy of the analysis is improved.

Theoretical model needs to be simplified. Studies on the pilot's micro-behavior should adopt a model with adaptability and strong ability of online modification. It upgrades during the operation process, which is conducive to promote further research in the future.

The analysis of pilot's micro-behavior should be integrated with reality and application value. The pilot is the controller of aircraft and the regulator and decision-maker of air traffic information. How to predictably and dynamically identify the pilot's micro-behavior becomes a core scientific issue in the field of flight safety, pilot's selection and aviation management. Under strict flight rules and regulations, different pilots have different behaviors and habits. Strict and self-disciplined controlling behavior can reduce aircraft energy consumption and improve flight safety. The study of micro-behavior is applied to pilot's assessment for better decision-making and performance in air traffic.

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基于人-机-环境交互的飞行员微观行为研究

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摘要：飞行员微观行为研究是近年来飞行安全领域研究的热点之一。对飞行员微观行为及其功能的研究对于增强飞行者的主动安全预警和对飞行员的评价具有重要意义。本文基于飞行员的认知过程，探讨了飞行员微观行为先前的研究意义和研究内容。从飞行员的心理学，生理学和物理学的角度简要介绍了飞行员的微行为的历史和研究现状。目前关于飞行员微观行为的研究主要包括飞行员的特征，多信息融合，集成认知以及控制环境的人性化。讨论了这些研究的方法，并对飞行员生理，心理和身体特征的机理，实验内容和适用条件进行了分析。同时，回顾并指出了现有研究成果的优缺点。结合飞行模拟实验，阐述了飞行员的内部机理。此外，结合现代飞行领域的最新研究，以及应用领域的专业化，研究手段的多样化和研究水平的深入，给出了飞行员微观行为的未来发展方向。

关键词：飞行安全；微观行为；主动安全预警；飞行员；飞行模拟