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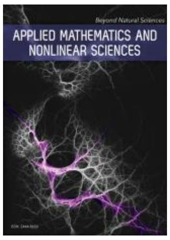

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Influence of Fatigue on Flight Safety: A Structural Equation Modeling Analysis

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Abstract

Currently, pilot fatigue is considered to be a significant factor that affects aviation safety. In order to investigate the impact of fatigue on flight safety, we design a questionnaire to conduct a survey on the pilots of Shandong Airline, process and analyze the data through the SPSSAU data analysis platform, and construct a structural equation between fatigue and pilot unsafe behaviors. The study findings indicate that there is a significant relationship between situational awareness, safety awareness, crew atmosphere, work pressure and pilot fatigue, and the higher the pilot fatigue level, the lower situational awareness and safety awareness, the worse crew atmosphere and the higher work pressure. Compared to physical fatigue, mental fatigue was more vulnerable to the above four factors, and at the same time, it was also more likely to lead to the pilot's unsafe behaviors, thus threatening flight safety. Therefore, in order to guarantee flight safety, airlines and aviation administration should pay more attention to pilot's mental fatigue problems.

Keywords: SEM; pilot fatigue; unsafe behavior; flight safety
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1 Introduction

Fatigue in aviation is a very complex phenomenon with psychosomatic problems, which is an imbalanced state of physiology and psychology caused by the occurrence and development of stress during flight. The International Civil Aviation Organization (ICAO) has defined pilot fatigue in document 9966 as a physiological state of reduced capacity to carry out mental or physical activity due to insufficient sleep, long periods of wakefulness, biological rhythm disorder, or excessive workload (excessive mental and/or physical activities). This state compromises the alertness of crew members and their ability to safely operate the aircraft or perform related duties of security. It is known from the definition of ICAO that insufficient sleep, prolonged arousal, disturbed physiological rhythm, and heavy workload are the main predisposing factors for fatigue [1]. According to different classification methods, pilot fatigue includes many types. Fatigue can be categorized into physical fatigue and mental fatigue based on its effects on the human body [2]. Based on its duration, fatigue can be classified as either acute or chronic. Additionally, fatigue can be categorized based on its severity, with mild, moderate, and severe fatigue being the three possible levels [3]. The classification of physical fatigue and mental fatigue is a widely used method to classify pilots fatigue. Physical fatigue is the fatigue caused by long-time muscle exercise, mainly manifested as limb pain, physical strength decline, dizziness, etc. Mental fatigue is the decline of cognitive ability and motivation caused by monotonous and repetitive work and long-time thinking activities. It is mainly manifested in the decline of cognitive ability, the increase of negligent errors, slow reaction, and difficulty in focusing [4].

In recent years, as China's civil transportation industry has experienced rapid growth, the shortage of civil aviation pilots has become an increasingly severe problem. which causes the increasing pilot workloads, the pilot fatigue problem is also becoming more and more common. In a National Aeronautics and Space Administration (NASA) report, about 21% of flight accidents were directly related to the fatigue of pilot [5]. Meanwhile, the pilot's fatigue problems were more serious due to the increasing number of long flights across time zones and irregular night flights. Fatigue will reduce the pilot's alertness and memory, which has an influence on decision-making and judgment ability, and reduce work efficiency. Severe fatigue conditions will cause more flight incidents and unsafe events, which are important potential risk factors affecting airline safety [6].

As early as the 1980s, NASA had carried out research on issues related to pilot fatigue. The research mainly through simulation analysis, on-site investigation and other methods to study the cause of pilot fatigue, and then carry out relevant teaching, training and policy formulation, with the purpose to find out measures that can effectively improve the attention and working ability in flight missions [7]. Another NASA questionnaire found that 75% of the pilots felt moderate or severe fatigue when performing airline missions, 55% thought fatigue was common when flying, 72% felt that when fatigue occurred during flight, the reaction speed and operation ability of the aircraft during landing would be significantly reduced, and 71% of the pilots said they had experienced napping during flight. Among them, more than 70% of the pilots admitted that they had experienced such sleepiness for many times. The problem of pilot fatigue in airline flight is very common, 60% of the pilots flying long routes will have obvious fatigue symptoms, and about 50% of the pilots flying short routes will show symptoms such as inability to concentrate, reduced attention, and reduced reaction speed when they are tired [8].

The reason for fatigue is one of the key research contents of fatigue in aviation. By analyzing the factors affecting pilot fatigue, Da Van believed that old age, working at night, inability to balance life and work, poor physical condition, too little physical exercise and excessive drinking were important factors leading to fatigue [9]. Kimberly A found that the pilot's operation performance would become worse after taking off and landing for many times through the simulation flight test, so it was suggested that the airline should appropriately reduce the continuous working time when making work arrangements [10]. Through research, Jackson C. A believed that fatigue would reduce memory ability, judgment ability and reaction time. The two main factors that cause pilot fatigue were shift work and sleep loss. Other factors included irregular working and rest time and intercontinental flight [11]. Beth H. M proposed that the important factors causing pilot fatigue during duty were insufficient sleep time and disturbance of circadian rhythm caused by work [12].

The adverse effect of fatigue on flight safety is also an important research content of fatigue in aviation. Through literature research, Salaheddine B found that pilots' thinking ability, judgment, concentration and other problems would be reduced due to fatigue, so fatigue would have a negative influence on flight safety [13]. Wingelaar Jagt Yara Q's research, based on literature review, highlights that fatigue poses a significant safety risk in both civil and military aviation. In addition to decreasing flight performance, chronic fatigue can also have long-term impacts on pilots' health [14].

Due to the threat of fatigue to flight safety, the International Civil Aviation Organization (ICAO) and the Civil Aviation Administration of China (CAAC) have issued relevant documents on pilot fatigue. In 2016, ICAO released the Fatigue Management Practices Supervision Manual (Second Edition), which expanded the content of the first edition in 2012, adding some content related to fatigue management, including information related to fatigue management, scientific principles, normative practices and fatigue risk management systems. One chapter introduces the influencing factors of fatigue, such as sleep quality, circadian rhythm, shift work, jet lag, workload, etc. [1]. In accordance with ICAO regulations, the Civil Aviation Administration of China (CAAC) has issued the Fatigue Management Requirements for CCAR121 Certificate Holders, outlining the necessary measures to manage and mitigate the risk of pilot fatigue, proposed the Fatigue Risk Management System (FRMS), and made detailed provisions on the management requirements for fatigue of transport airline pilots [15].

The issue of pilot fatigue has emerged as a critical factor impacting flight safety [16]. According to the accident-causing theory, flight accidents are caused by the joint action of unsafe human behavior and unsafe state of objects [17]. The operation behavior of pilots is closely related to aviation safety, and the unsafe behavior of pilots may directly lead to aviation accidents. Through the previous literature analysis, we can know that unsafe behaviors of pilots are directly related to pilot fatigue. By building a structural equation between pilot fatigue and unsafe behaviors, and studying the relationship between fatigue and unsafe behaviors, we can reduce flight accidents caused by pilot fatigue, which is of great significance to improve the safety performance of the entire aviation industry.

There are many studies on the causes of pilot fatigue, fatigue hazards and unsafe behaviors of pilots, but these studies either mainly analyze the causes of fatigue or mainly analyze the consequences caused by fatigue. At present, there is no research that combining the factors affecting fatigue, fatigue impact and pilot unsafe behaviors. In the related research of behavioral science, structural equation model is an important tool to establish, estimate and test the causal relationship of multiple variables. The structural equation model can analyze both apparent variables and latent variables that cannot be directly observed, especially the relationship between multiple variables. Sun Ruishan et al. employed a structural equation model to investigate the relationship between five variables, namely sleep, mental health, individual characteristics, crew scheduling, and pilot fatigue. Their analysis revealed a significant positive correlation between pilots' mental health and sleep quality [18]. Elen Paraskevi Paraschi et al. utilized structural equation modeling to examine the relationship between human resource management, work determination, safety, and security risks in commercial aviation. Their findings underscored the critical role of human factors in the field of aviation safety [19].

It can be seen that the usage of structural equations has great advantages in studying the relationship between multiple variables and multiple causes and effects. By building a structural equation between pilot fatigue and unsafe behaviors, and studying the relationship between fatigue and unsafe behaviors, we can reduce flight accidents caused by pilot fatigue, which is of great significance to improve the safety performance of the entire aviation industry.

2 Methods

2.1 Research hypothesis and model construction

The influence of fatigue on pilots is comprehensive. In addition to its negative impact on pilots themselves, it also has an influence on other factors related to flight safety [20], including situational awareness, safety awareness, etc. Situational awareness is a pilot's cognition of himself and the whole flight scene in flight activities, and a prerequisite for safe flight. Narinder Taneja found that the cause of crew fatigue is lack of sleep and disturbance of biological rhythm and thus affect pilots situational awareness through questionnaire research [21]. To ensure flight safety, pilots' safety awareness is indispensable. A questionnaire survey by Weng X Z showed that the overall occupational safety awareness of civil aviation pilots was at a high level, and higher safety awareness was more conducive to ensuring flight safety [22]. A good crew atmosphere is a prerequisite for effective crew cooperation. Beveridge S.D.H used a systematic review methodology to analyze the influence of flight crew cooperation and role assignment on flight safety. The study found that improper crew cooperation can negatively impact the captain's flight performance [23]. Work stress will directly affect the status of pilots. Akantha Gautam discussed the relationship between pilots' attitude towards flight safety, flight experience, perceived stress and flight unsafe events, and believed stress and attitude are closely related to flight performance, which may be one of the important factors leading to flight accidents or incidents [24].

Based on the above analysis, the four important factors that affect aviation safety, including situational awareness, safety awareness, crew atmosphere and work pressure, are included in the construction of the model. In addition, for better research, we divide pilot fatigue into physical fatigue and mental fatigue, then the following hypothesis are obtained.

Hypothesis 1a (H1a). There is a significant negative correlation between situational awareness and physical fatigue.

Hypothesis 1b (H1b). There is a significant negative correlation between situational awareness and mental fatigue.

Hypothesis 1c (H1c). There is a significant negative correlation between safety awareness and physical fatigue.

Hypothesis 1d (H1d). There is a significant negative correlation between safety awareness and mental fatigue.

Hypothesis 1e (H1e). There is a significant negative correlation between crew atmosphere and physical fatigue.

Hypothesis 1f (H1f). There is a significant negative correlation between crew atmosphere and mental fatigue.

Hypothesis 1g (H1g). There is a significant positive correlation between work stress and physical fatigue.

Hypothesis 1h (H1h). There is a significant positive correlation between work stress and mental fatigue.

Hypothesis 2 (H2). There is a significant positive correlation between physical fatigue and mental fatigue.

Hypothesis 3a (H3a). Physical fatigue interacts with situational awareness, safety awareness, crew atmosphere and work pressure. The more serious physical fatigue of pilots, the unsafe behaviors are more likely to occur.

Hypothesis 3b (H3b). Mental fatigue interacts with situational awareness, safety awareness, crew atmosphere and work pressure. The more serious mental fatigue of pilots, the unsafe behaviors are more likely to occur.

The theoretical model of hypothesis is shown in Figure 1.

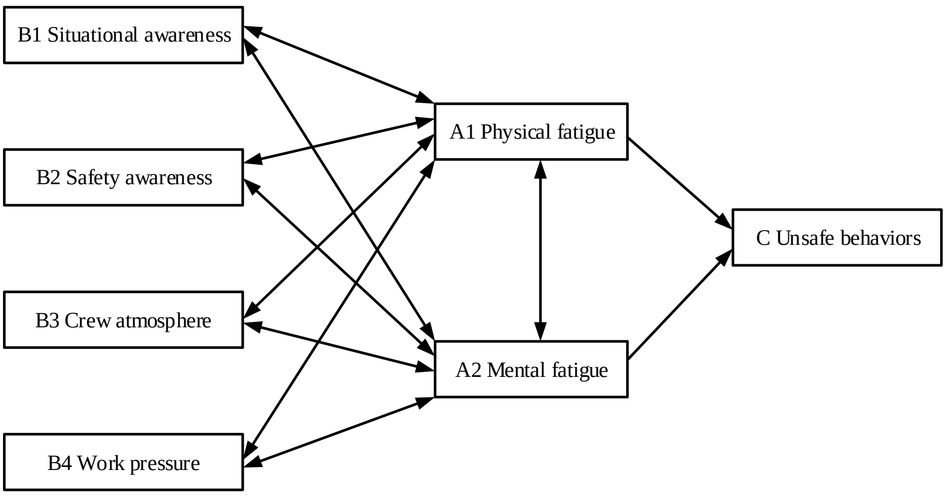

Figure 1. Construction of theoretical model

2.2 Participants

The research method of questionnaire was adopted in this paper. First, 80 small sample pre-test questionnaires were distributed to Shandong Airlines, and 75 were effectively returned. Then, the reliability and validity of the returned small sample pre-test questionnaires were tested, and some unreasonable options were corrected to form a formal questionnaire.

Taking the pilots of Shandong Airlines as research participants, adopting the method of cluster random sampling. 340 respondents were selected from October 2022 to November 2022 to issue questionnaires, and 335 questionnaires were returned, including 333 valid ones, with a response rate of 98.5% and an effective rate of 97.9%. The number of questionnaires met the requirements of data analysis. Inclusion criteria for research participants: All physical examination certificates were within the validity period, with communication ability and no cognitive impairment, and all research participants had informed consent to this study. The participants were all male, of which 81% were captains and 99% were under 50 years old. Because fatigue had no relationship with demographic information of the participants, the basic information of participants was no longer described.

2.3 Questionnaire design

We divided the questionnaire into two sections. The first section focuses on gathering basic information about the pilots, including license type, flight hours, age, gender, etc. The second section is scale. There are 7 variables in total, and 4 items for each variable, the scale design is shown in Table 1. The Likert five level scale is adopted, and 1 to 5 point are used to indicate very non conformance to very conformance. The reverse scoring method is used for 4 questions in the variable of unsafe behavior C. The higher the score, the less unsafe behavior.

Table 1. Scale design

Variable	Items
A1 physical fatigue	A11 I often get sleepy in flight
	A12 I often feel sore during flight
	A13 I often feel dizzy during flight
	A14 I will be in low spirits when flying
A2 mental fatigue	A21 I feel that flying is boring
	A22 I am often absent-minded during flight
	A23 I often feel upset during flight
	A24 I often feel slow in thinking
B1 situational awareness	B11 I have a clear understanding of the current flight status
	B12 I have a clear understanding of the whole flight
	B13 I often communicate with the captain (copilot) about flight
	B14 I know my status very well
B2 safety awareness	B21 I think I can guarantee flight safety
	B22 I do not perform potentially dangerous flight operations
	B23 Before the flight, I will carefully sort out the whole flight process
	B24 I am very alert throughout the flight
B3 crew atmosphere	B31 I would like to fly with the captain (copilot)
	B32 When flying with the captain (copilot), I feel comfortable
	B33 I would like to ask the captain (copilot) for help when encountering problems
	B34 I have a good relationship with the captain (copilot)
B4 work pressure	B41 I feel that the current assessment is more and more strict
	B42 I feel more and more work outside of flight
	B43 I feel that the requirements for flight safety are getting higher and higher
	B44 I feel my body is overdrawn
C unsafe behaviors	C1 I will remind the captain (copilot) of unsafe behaviors
	C2 I can handle various problems in flight
	C3 I can strictly follow the standard operating procedures
	C4 My flight operations are very standard

2.4 Statistical treatment

After the questionnaires were returned, Excel 2013 and SPSSAU data analysis platform was used for data statistical analysis.

2.5 Reliability and validity analysis

The Cronbach's α coefficient was used to evaluate the reliability of each variable, and the results indicated that the internal consistency of the scale was very good, with a coefficient greater than 0.8 for all variables.

To test the validity of each variable, KMO and Bartlett's Test of Sphericity were utilized. The results showed that the scale had good suitability for factor analysis, with a KMO value of 0.977 ($p<0.01$) and a Bartlett's Test of Sphericity approximate chi square value of 7531.643. Each variable had a KMO value of more than 0.7 and a p value of less than 0.01, indicating suitability for factor analysis.

The factor analysis revealed that all factor loads were greater than 0.8 and the average variance extraction value (AVE) of each latent variable was more than 0.5, indicating good convergence of the variables.

The reliability and validity of the questionnaire were examined and the outcomes are demonstrated in Table 2.

Table 2. Reliability and validity analysis

Latent Variable	Items	Factor Load	Cronbach's α	KMO	Composite Reliability	AVE
A1	A11	0.856	0.884	0.839	0.885	0.657
	A12	0.880				
	A13	0.871				
	A14	0.838				
A2	A11	0.842	0.885	0.841	0.886	0.660
	A12	0.863				
	A13	0.866				
	A14	0.879				
B1	B11	0.809	0.838	0.780	0.837	0.564
	B12	0.828				
	B13	0.838				
	B14	0.810				
B2	B21	0.874	0.877	0.833	0.877	0.641
	B22	0.844				
	B23	0.861				
	B24	0.840				
B3	B31	0.847	0.879	0.838	0.879	0.645
	B32	0.853				
	B33	0.867				
	B34	0.859				
B4	B41	0.842	0.866	0.833	0.865	0.615
	B42	0.850				
	B43	0.852				
	B44	0.836				
C	C1	0.851	0.873	0.834	0.872	0.631
	C2	0.852				
	C3	0.850				
	C4	0.850				

3 Results

3.1 Correlation analysis of variables

The Pearson correlation coefficient is a commonly used statistical measure for evaluating the strength and direction of the linear relationship between two variables. If the coefficient value is greater than 0, it indicates positive correlation, on the contrary, if the coefficient value is less than 0, it indicates negative correlation. In this paper, we adopted Pearson correlation coefficient to study the correlation between potential variables. The results are shown in Table 3.

Table 3. Correlation between Variables

Latent Variable	A1	A2	B1	B2	B3	B4	C
A1	1						
A2	0.886	1					
B1	-0.683	-0.697	1				
B2	-0.734	-0.755	0.818	1			
B3	-0.695	-0.723	0.813	0.875	1		
B4	0.828	0.823	-0.660	-0.679	-0.649	1	
C	-0.703	-0.722	0.794	0.871	0.867	-0.637	1

From Table 3, we can see that, A1 and A2 were negatively correlated with B1, B2, B3 and C respectively, and positively correlated with B4. The correlation among variables can basically support the hypothetical relationship between model variables, thus we can do further analysis.

3.2 Model fit test

In this paper, SPSSAU data analysis platform was used to build the structural equation model, and the model fitting results are shown in Table 4. We can see that RMSEA=0.067, which is less than 0.1, CFI, NFI and NNFI are all more than 0.9, GFI=0.897, close to 0.9, so the model has a good fit and is suitable for path analysis.

Table 4. Model fitting results

Index	$\chi 2$/df	GFI	RMSEA	CFI	NFI	NNFI
Judgment criteria	<3	>0.9	<0.10	>0.9	>0.9	>0.9
Value	2.764	0.897	0.067	0.948	0.921	0.941

3.3 Model path analysis

The results of hypothesis verification for the theoretical model are presented in Table 5. It can be observed that all paths in the model show significant correlation or influence, with p values less than 0.01.

Table 5. Results for hypotheses verification

Hypotheses	Path	Std. Estimate	S.E.	C.R.	p	Result
H1a	B1↔A1	-0.427	0.035	-5.516	0.000	supported
H1b	B1↔A2	-0.539	0.032	-6.229	0.000	supported
H1c	B2↔A1	-0.489	0.034	-6.264	0.000	supported
H1d	B2↔A2	-0.603	0.031	-6.864	0.000	supported
H1e	B3↔A1	-0.370	0.032	-5.083	0.000	supported
H1f	B3↔A2	-0.506	0.029	-6.171	0.000	supported
H1g	B4↔A1	0.768	0.041	7.795	0.000	supported
H1h	B4↔A2	0.788	0.036	7.477	0.000	supported
H2	A1↔A2	0.801	0.020	7.247	0.000	supported
H3a	A1→C	-0.370	0.136	-3.746	0.000	supported
H3b	A2→C	-0.387	0.167	-3.942	0.000	supported

The resulting model and path coefficients are shown in Figure 2.

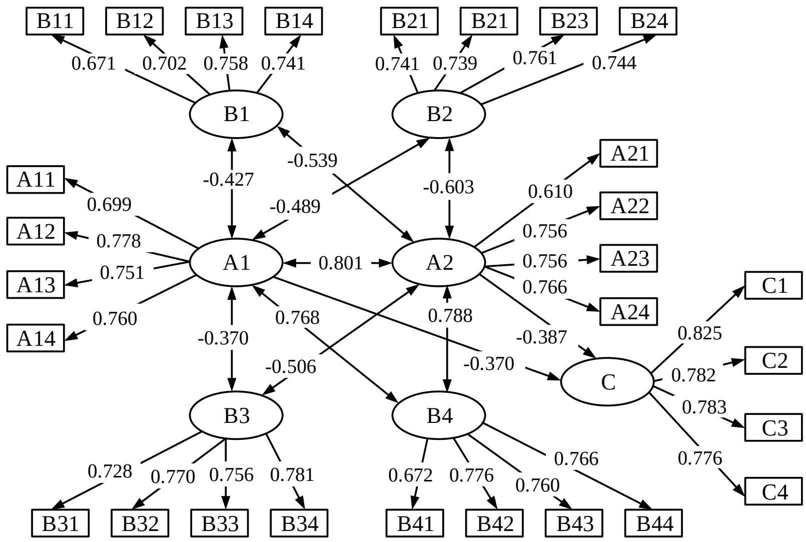

Figure 2. Model and path coefficient

In Figure 2, the correlation coefficients between B1 and A1 and between B1 and A2 are -0.427 and -0.539, respectively, indicating a significant negative correlation between situational awareness and fatigue. This supports H1a and H1b, as more severe fatigue is associated with lower situational awareness. Notably, the correlation coefficient between B1 and A2 is greater than that between B1 and A1, suggesting that mental fatigue has a stronger impact on situational awareness. Similarly, the correlation coefficients between B2 and A1 and between B2 and A2 are -0.489 and -0.603, respectively, indicating a significant negative correlation between safety awareness and fatigue. This supports H1c and H1d, as more severe fatigue is associated with lower safety awareness. Again, the correlation coefficient between B2 and A2 is greater than that between B2 and A1, highlighting the stronger influence of mental fatigue on safety awareness.

Moreover, the correlation coefficients between B3 and A1 and between B3 and A2 are -0.370 and -0.506, respectively, indicating a significant negative correlation between the crew atmosphere and fatigue. This supports H1e and H1f, as more severe fatigue is associated with a worse crew atmosphere. The correlation coefficient between B3 and A2 is also greater than that between B3 and A1, indicating that mental fatigue has a stronger impact on the crew atmosphere. The correlation coefficients between B4 and A1 and between B4 and A2 are 0.768 and 0.788, respectively, indicating a significant positive correlation between work pressure and fatigue. This supports H1g and H1h, as higher work pressure is associated with more severe fatigue. Again, the correlation coefficient between B4 and A2 is greater than that between B4 and A1, highlighting the stronger influence of work stress on mental fatigue.

Furthermore, the correlation coefficient between A1 and A2 is 0.801, suggesting a close relationship between physical and mental fatigue among pilots, and that they can transform into each other. This supports H2. The path coefficient between A1 and C is -0.370, and between A2 and C is -0.387, suggesting that greater physical or mental fatigue is associated with a higher likelihood of unsafe behaviors by pilots, as C uses reverse scoring. This supports H3a and H3b.

4 Discussion

Pilot fatigue has become an important factor that affects aviation safety, but most of the current studies on pilot fatigue are about the causes of fatigue, while the studies about the fatigue influence on the entire aviation system are comparatively limited. Therefore, this paper takes the important factors of aviation safety, such as situational awareness, safety awareness, crew atmosphere and work pressure, as the relevant factors of pilot fatigue. By constructing a structural equation model, this paper analyzes the relationship between pilot fatigue and the four common factors that affect aviation safety, and analyzes how these four factors influence the unsafe behaviors of pilot through flight fatigue.

It can be seen from the results in Table 5 and Figure 2 that among the four factors of situational awareness, safety awareness, crew atmosphere and work pressure, the correlation between work pressure and pilot fatigue is the strongest. This is because with the continuous development of the aviation industry, people have higher and higher requirements for aviation services. At the same time, in recent years, aviation accidents have occurred frequently, and aviation safety pressure is growing. In particular, after the 321 flight accident of China Eastern Airlines, all airlines are conducting safety rectification and learning. Pilots have more and more tasks outside of their flight work, and their safety responsibilities are also growing, which have led to increasing work pressure on pilots and caused more pilot fatigue problems. Meanwhile, these fatigue are mainly psychological fatigue, and they are not easy to attract attention.

Through the research on the correlation between situational awareness, safety awareness, crew atmosphere, work pressure and pilot fatigue, it can be found that the impact of physical fatigue is less than that of mental fatigue, which indicates that the above four factors are more likely to be affected by mental fatigue, or more likely to affect mental fatigue. From the influence of physical fatigue and mental fatigue on pilot unsafe behaviors, the possibility of unsafe behaviors caused by mental fatigue is higher than that caused by physical fatigue. The possible reason is that, with the development of aviation science and technology, aircraft design is becoming more and more advanced and the level of automation of aircraft is getting higher and higher, which significantly reduces the workload of pilots to operate aircraft. However, airlines have higher requirements for aviation safety, and pilots have heavier tasks to monitor and manage flight. Therefore, compared with physical fatigue, pilots are more likely to experience mental fatigue, it is also more susceptible to other factors related to flight.

For the problem of pilot fatigue, many studies have proposed a solution to reduce the workload of pilots, which is also the method adopted by many civil aviation administrations [1-3]. The results of the structural equation analysis indicate a significant positive correlation between physical fatigue and mental fatigue. Although physical fatigue and mental fatigue are used as separate classification methods in this study, it is important to note that fatigue is a comprehensive experience of physical and psychological discomfort. Therefore, whether the pilots have high physical labor intensity or mental stress, the symptoms of physical fatigue and mental fatigue also exist at the same time, and mental fatigue is more easily affected by factors unrelated to work load, such as work pressure and crew atmosphere, thus reducing the workload is not fully effective in reducing pilot fatigue. We can also see that, the influence of fatigue on flight safety is multifaceted. In addition to the obvious problems such as pilot control ability decline, thinking ability decline, inattention, physical discomfort and so on, pilot fatigue also potentially influences other factors related to flight safety, such as situational awareness, safety awareness and crew atmosphere, resulting in reduced situational awareness and safety awareness, poor crew cooperation, and increased work pressure. It will also directly lead to unsafe behaviors of pilot, thereby threatening flight safety.

5 Conclusion

Pilot fatigue is closely related to the characteristics and nature of pilots' work. It is a compound fatigue with physical fatigue and mental fatigue intertwined. The problem of pilot fatigue is also a systematic problem. In addition to the characteristics of flight operation itself, such as long flight, jet lag effect, biological rhythm disturbance, etc., it will also be affected by factors that are not closely related to flight operation itself, such as work pressure, crew atmosphere, etc., which will ultimately lead to unsafe behavior of pilots, thus affecting flight safety. At the same time, fatigue will also have a negative effect on flight psychological quality, such as safety awareness and situational awareness, which is a potential problem, and it will cause more potential threats to flight safety.

In the current aviation operation environment, compared with physical fatigue, mental fatigue is more likely to occur, and is also more vulnerable to other factors. Therefore, mental fatigue brings more potential flight safety hazards. In addition to reducing flight hours and workload of pilots, airlines and aviation management departments should also pay more attention to the mental fatigue of pilots, such as carrying out employee assistance programs, carrying out psychological adjustment of pilots, and relieving the working pressure of pilots, which may play a better role in reducing pilot fatigue and ensuring flight safety.

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