Circadian Disruption in Civilian Airline Pilots

Sophie Xin Yang; Siyu Cheng; Yuanfeng Sun; Xiangdong Tang; Zhijiao Huang

INTRODUCTION: Most airline pilots reported having suffered from sleep disorders and fatigue due to circadian disruption, a potential risk to flight safety. This study attempted to uncover the actual scenario of circadian disruption and working load status among airline pilots.

METHODS: In study 1, 21 pilots were invited to participate in a 14-d sleep monitoring and a dual 2-back test to monitor their sleep patterns and cognitive function level. To provide an in-depth view, data from scheduled flights, including 567 airline pilots, was analyzed in Study 2. The present study used cluster analysis to reflect the distribution of the flight scheduling characteristics, including working time and actual working hours. A simulation model was then developed to predict the pilots' 1-mo sleep-wake pattern.

RESULTS: The results indicated that sleep problems were prevalent in this population, especially the night before an earlier morning shift. Regarding the cognitive test, they scored the lowest on earlier morning shifts compared with daytime and evening shifts. It was found that over 70% of the flight schedules can lead to circadian disruption, and 47.44% of the pilots worked under high-load status.

DISCUSSION: Airline pilots inevitably work irregular hours and the current policies for coping with circadian disruption seem inefficient. This study thus calls for urgency in improving scheduling and fatigue management systems from the circadian rhythm perspective.

KEYWORDS: aviation, N-back, sleep disorder, fatigue, shift.

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Circadian disruption caused by irregular working schedules is prevalent in airline pilots. A national civil aviation industry reported that between 2010 and 2019, 4010 incidents (defined as dangerous actions and phenomena that threaten flight safety during flight operations but do not result in an actual accident) occurred, and the number showed an upward trend.[22] Over 70% of civil and military aviation accidents are caused by human factors related to pilots' decision-making and operation failures,[40] which could be closely related to airline pilots' cognitive function level. According to the airline companies' reports, accidents always started when pilots misreported critical information when repeating the control tower's instructions. Working memory, the system involved in the temporary storage and manipulation of information,[2] plays a key role in completing cognitive activities, including repeating information. Therefore, it is necessary to pay attention to pilots' working memory. A recent study of 95 airline pilots conducted by a research team from the United States reported that subjects who experienced higher self-reported fatigue and poor cognitive performance all had previous flights encroaching on a biological night, suggesting that circadian disruption was likely the leading cause of physical and mental fatigue.[1] In agreement with these findings, another study investigating 90 commercial airline pilots highlighted the impact of flights covering the whole domicile night on pilots' fatigue status.[31] The International Civil Aviation Organization (ICAO) reported that passengers worldwide exceeded 2.3 billion in 2021.[42] Aircraft have become the most prevalent transportation for long-distance travel and the annual cost of flight accidents is worth $1.6–4.6 billion.[4] Therefore, airline pilots' mental and physical well-being is vital to flight safety.

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Circadian disruption refers to the misalignment of circadian rhythm due to external factors such as shift work or jet lag.[36] When the internal body clock is incompatible with the external environment, abnormal periodic fluctuations in various indicators will occur.[27] In practice, the definition of circadian disruption is mainly focused on the scenarios that potentially cause circadian disruption instead of the phenomenon itself, thus the quantitative measurements of circadian disruption still need to be clarified.[36] A study on shift work schedule and biorhythm suggested that regular working time is between 09:00–17:00, whereas working between 21:00–05:00 can lead to an out-of-sync 12-h light-dark cycle.[39] The severity of circadian disruption could be classified by working time in short-haul flight.

The direct health consequence of circadian disruption is sleep disorder-related symptoms, such as sleep loss,[34] which considerably impacts the human body's metabolism and steady-state regulation process.[28] Individuals with long-term sleep disorders are prone to emotional, cognitive, and physiological pathologies. Cardiovascular and cerebrovascular diseases,[41] tumors,[3] mental health problems,[37] and neurological diseases[16] are associated with sleep disorder related symptoms. Shift work has been officially classified as 'probably carcinogenic [Group 2A]' by the World Health Organization (WHO).[11]

In addition, previous research has provided substantial evidence indicating that cognitive function impairment is a consequence of circadian disruption. An experimental study reported that as subjects stayed awake longer, their brain information processing became slower, thus resulting in a decline in cognitive function.[6] Research simulating the state of sleep loss of pilots under heavy-loaded working schedules revealed that sleep-deprived Air Force pilots in the United States had significantly lower scores on cognitive tests such as multitasking, alertness, and working memory.[19] Additional research has confirmed that the cognitive flexibility of junior pilots decreases with increasing waking time, which affects optimal decision-making.[25]

Current literature generally suggests that cognitive impairment occurs in individuals after short-term sleep deprivation. Chronic cognitive function impairments may develop if the circadian rhythm is disrupted for a prolonged period. For instance, shift workers exhibited significantly poorer cognitive performance than the average population, and the cognitive impairment associated with shift work was equivalent to 4.3 yr of age-related cognitive decline.[21]

The effects of cognitive impairment on airline pilots caused by long-term circadian disruption can be significant.[22,40] Flight operation includes a series of complex human-computer interaction interfaces which place high requirements on pilots' cognitive function and physiological well-being. However, long-term irregular sleep-wake cycles may cause an ongoing state of fatigue in this population, affecting the efficiency of flight operation and thus increasing the number of incidents.

As airline pilots consistently work under the effects of circadian disruption, current fatigue management policies require working hours to be strictly controlled within a limited range, such as flight time and flight duty period. Based on the official guidelines in China, one-day flight hours are defined as when the aircraft starts to move under its power in preparation for takeoff and stops moving at the end of the flight.[7] The flight duty period for 1 d is from the report time to the end of the last flight mission, including the preparation time before takeoff and uninterrupted time when multiple flight missions are connected. If the pilot has a suitable place to rest during the duty period, this period is considered the pilot's rest time.[7] Nevertheless, the definition of working hours (flight duty period) overlooks several practical issues that may occur during a day's duty.

Firstly, according to the statement of the scheduling manager of an airline company in China, when the scheduled segment between two flights on the same day is longer than 3 h, the pilots will be sent to the hotels nearby during the segment, and this period is accounted as rest time. The rest time length depends on the scheduled segment length and driving time from hotel to airport. The new report time is "60 minutes plus the driving time" before the next flight. However, pilots may be unable to rest adequately and feel they are still on duty. If the flight is delayed for a long time due to factors such as weather and military, the pilots will also face a similar situation. Moreover, when the pilot's duty hours may exceed the required maximum hours in a single day under unexpected conditions, they have to take another break to accumulate sufficient rest hours to qualify for executing subsequent flight operations. The break described above is accidental, and the length needs to be considered for the individual duty time and flight schedule. Accordingly, these 'rest times' mentioned above may not guarantee a good quality of rest but constitute a reason for delaying duty completion. Therefore, the present study defined the pilot's actual working hours for 1 d as the time between reporting for the first flight task and the end of the last flight, including the rest time between the flight segments on the same day of duty.

Developing scientific guidelines for fatigue management is necessary to benefit flight safety and airline pilots' health. The present study mainly discusses Chinese regulation and investigated the real-world scenario of circadian disruption and airline pilots' actual working hours in China because the subjects and data were obtained from a Chinese company.

Study 1 investigated the changes in pilots' sleep patterns under chronic circadian disruption in a small range, including sleep time, wake time, and sleep disorders-related symptoms. Meanwhile, the cognitive function of pilots before performing flight tasks at different times was tested to verify the effect of extreme working schedules.

To highlight the severity of the chronic circadian disruption, Study 2 described the overall situation of 567 airline pilots' working schedules in 2019. The pilots were divided into three groups according to their working time and hours. Finally, a simulation model was developed to predict pilots' circadian disruption in each group.

STUDY 1

The objectives of Study 1 were to: 1) understand airline pilots' 14-d sleep-wake cycle and sleep quality; and 2) investigate the impact of different scheduling on airline pilots' cognitive performance.

Methods

Subjects. Civilian airline pilots were contacted by related departments from an airline company. After receiving an explanation regarding the purpose of the study, 24 pilots expressed interest in participating.

The subjects were eligible for the study if the following criteria were satisfied:

1. Pilots could attend to their schedules without absence during the study period of sleep monitoring and cognitive function.
2. No severe respiratory disease, including asthma, chronic obstructive pulmonary disease, severe obstructive sleep apnea-hypopnea syndrome, or severe liver and kidney disease.

The sample included 21 male subjects: 9 captains (M age = 42.78, SD = 7.66) and 12 copilots (M age = 28.33, SD = 4.44). The average length of working experience was 10 yr (SD = 8.01). Of the subjects, 14 were married, and none had a particular medical history. All subjects performed short-haul domestic flights.

Before the quantitative study, researchers conducted a semistructured interview with the subjects and the airline company staff to explain the purpose of this study and understand the pilots' actual working conditions in depth. The discussion provided helpful information for the researchers to design the project.

Materials. Sleep quality was monitored by Huawei Watch (GT 2 Pro ECG; Huawei Technologies, Shenzhen, Guangdong, China) and sleep diary. The wearable device monitored sleep patterns based on cardiopulmonary coupling.[20] A sleep diary for 14 d was developed from the Pittsburgh and consensus sleep diaries.[5,23]

The N-back test targets subjects' working memory, the temporary storing of external information.[2] The study adopted the dual 2-back classical paradigm, widely used to assess working memory.[17] Participants needed to decide whether the current stimuli matched the stimuli presented two trials earlier. There were two stimuli in this study taken from Brain Workshop.[14] One was the position of the squares which appeared and the other was the number heard. The two stimuli needed to be remembered at the same time. The subjects were asked to complete the 1-min test with 30 sets of stimuli before their report. The accuracy score was defined as {1 − [(number of errors + number of omissions) ÷ total possible correct]} × 100.[29] A higher accuracy indicated better cognitive function.[29]

Procedure. All procedures performed in studies involving human subjects were approved by the ethical standards of the Ethics Committee on Biomedical Research of West China Hospital of Sichuan University with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards (2022, No.1529). The researchers informed all subjects of the entire study content, and they signed an informed consent form before the study.

Subjects were first required to participate in a 14-d sleep monitoring study. They were instructed to use a Huawei Watch (GT 2 Pro ECG) and complete the sleep diary for 14 consecutive days. In order to guarantee the 14-d sleep data was consecutive, if the subjects forgot to wear the device on a certain day during this period, the counting for monitoring days would start again. Sleep diaries were asked to be completed within an hour of waking up. The analysis was based on the monitoring data and the sleep diary was used to check for device malfunctions. When a significant discrepancy was observed between the self-reported diary and monitoring data, the administrators contacted the pilots to confirm the accuracy of the monitoring data.

Subjects need to complete a dual 2-back task three times via a mobile application developed by the research team, based on Brain Workshop.[14] The study was arranged with different flight schedules, including earlier morning, day, and evening flights. The selected flight needed to be the first flight mission of the day. According to the suggestion put forth by the scheduling manager of the airline company, earlier morning flights take off between 06:30–08:00, and the report time is approximately 05:00–06:30. The evening flights take off between 21:30–23:00. The landing time is between 23:30–01:30. Therefore, the daytime flight schedule between 09:00 and 17:00 was used as the baseline for comparison with the earlier morning flight schedule (06:30–08:00) and evening flight schedule (21:30–23:00).

Statistical analysis. Repeated measures analysis of variance (ANOVA) is typically used to compare the same subject's and variable's numerical differences under different conditions.[33] Repeated measures ANOVA was performed using SPSS 25.0 to analyze the sleep monitoring data and N-back scores and to identify the differences in airline pilots' sleep quality and cognitive function over different work schedules.

The researchers were able to access the data from the subjects' Huawei Health App through authorized systems. The two variables selected for assessing the pilots' sleep quality were sleep latency and duration, and they were recorded every day. A sleep latency of less than 30 min was rated acceptable,[26] and a sleep lasting for 7–9 h was rated good sleep quality.[13] In the pilot semistructured interview, the subjects generally complained that insufficient sleep duration was the main problem; therefore, the present study calculated the number of days when sleep duration was ≤7 h. The condition was rated relatively severe if a specific sleep-related problem occurred three times per week.[35]

Results

The results of repeated measures ANOVA are shown in **Table I**. We first evaluated whether the variance between the

Table I. Repeated-Measures ANOVA.

	STATISTICAL RESULT				
				SIG. (ADJUSTED)	
VARIABLES	TYPE III SS	*F*	SIG. (SPHERICITY ASSUMED)	GREENHOUSE-GEISSER	HUYNH-FELDT
Sleep latency	13,511.524	34.593	0.000	0.000	0.000
Sleep duration	193,463.841	30.296	0.000	0.000	0.000
Dual 2-back score	5645.365	27.211	0.000	0.000	0.000

observed values at each time point satisfied spherical symmetry. The results of Mauchly's test of sphericity were w = 0.447 ($P < 0.05$) for sleep latency; w = 0.524 ($P < 0.05$) for sleep duration. Therefore, the adjusted *P*-values for sleep latency and duration should be used with Greenhouse-Geisser and Huynh-Feldt corrections. The sleep latency and duration differences among the three work schedules were statistically significant (Greenhouse-Geisser $P = 0.000$, Huynh-Feldt $P = 0.000$; Greenhouse-Geisser $P = 0.000$, Huynh-Feldt $P = 0.000$).[32] However, no significant difference was observed in sleep latency before daytime and evening flights. The average sleep latency before the earlier morning, daytime, and evening flights was 56.810 min (SD = 27.595), 23.619 min (SD = 12.500), and 28.429 min (SD = 13.739), respectively. The average sleep duration before the earlier morning, daytime, and evening flights was 314.429 min (SD = 77.317), 404.952 min (SD = 55.061), and 447.286 min (SD = 55.812), respectively. Sleep quality was inferior before an earlier morning flight. There was little difference between the daytime and evening flights.

For cognitive function, Mauchly's test of sphericity results were w = 0.976 and Sig = 0.792. Repeated measures analysis of variance was used (sphericity assumed $P = 0.000$). The dual 2-back test scores were significantly different in these three groups. The average score before the earlier morning, daytime, and evening flights was 50.524 (SD = 20.738), 73.524 (SD = 24.425), and 59.476 (SD = 24.266), respectively. The N-back score was meager before the morning flight, followed by the evening flight. The highest score was observed for the daytime flight.

As presented in **Fig. 1**, none of the 21 pilots could maintain a regular sleep-wake time for 7 consecutive days. The average difference in the earliest and latest sleep time was 6.66 h and the average difference in wake time was 7.63 h.

All subjects exhibited different sleep problems. Of the pilots, 76.2% could not fall asleep within 30 min three times or more per week, and one pilot reported an average of 88.29 min to fall asleep over 14 d. In total, 15 subjects were consistently not getting enough sleep (≤7 h, ≥3 times per week). Two reported substandard sleep hours on 13 out of 14 d (see **Table II**).

Discussion

Our findings suggested that among airline pilots, cognitive function declined significantly due to working schedules associated with circadian disruption. Circadian disruption may be inevitable for airline pilots, as the flight tasks can be arranged from early morning to later at night, with a high possibility of flight delays. Further, 14-d sleep monitoring data indicated that the internal causes of circadian disruption during nonworking days were likely due to sleep problems triggered by irregular sleep-wake time. This suggests that the effects of circadian disruption manifest under extreme flight schedules and during regular shift times. As the biological clock in pilots is frequently perturbed, establishing a normal sleep-wake cycle is difficult. In turn, chronic cognitive impairment is likely to occur.

STUDY 2

The objectives of Study 2 were to 1) uncover the pattern of airline pilots' circadian disruption through their working schedules; and 2) analyze airline pilots' working load status.

Methods

Subjects. The data sample was from a civilian airline company comprising 567 male pilots. The average age of these pilots was 37.6, ranging from 24–62 yr of age. Selected were 66,027 data items on short-haul domestic flight scheduling in 2019,

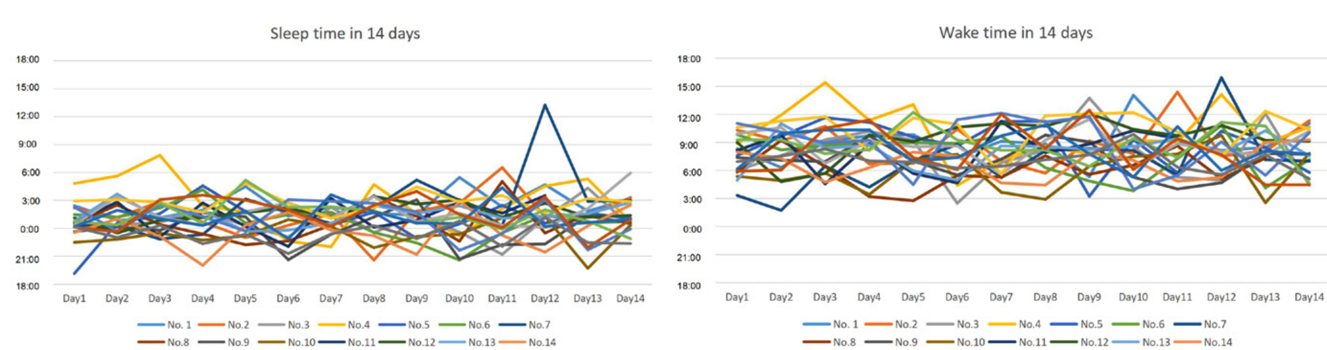

Fig. 1. Sleep time and wake schedule. Each colored line represents 14-d sleep time or wake time for one subject.

Table II. Sleep Latency and Sleep Duration for 14 Days.

NUMBER	SLEEP QUALITY			
	SLEEP LATENCY (MIN; AVERAGE ± SD)	NUMBER OF DAYS (SLEEP LATENCY ≥ 30 MIN)	SLEEP DURATION (MIN; AVERAGE ± SD)	NUMBER OF DAYS (SLEEP DURATION ≤ 420 MIN)
1	53.71 ± 39.91	**9**	383.43 ± 89.68	**9**
2	42.00 ± 33.43	**7**	443.86 ± 82.48	5
3	52.79 ± 39.34	**10**	433.50 ± 150.18	5
4	50.36 ± 34.86	**9**	441.79 ± 150.44	**7**
5	88.29 ± 54.33	**13**	472.36 ± 159.68	**6**
6	31.86 ± 49.08	4	419.29 ± 89.80	**7**
7	6.21 ± 3.36	0	269.07 ± 100.31	**13**
8	27.50 ± 8.49	**8**	322.93 ± 76.30	**13**
9	49.79 ± 34.34	**10**	433.21 ± 64.12	**6**
10	28.36 ± 12.73	**8**	393.21 ± 83.83	**9**
11	49.79 ± 34.34	**10**	413.07 ± 58.92	**7**
12	52.50 ± 35.10	**9**	465.93 ± 82.67	2
13	33.79 ± 19.30	**7**	395.57 ± 78.86	**9**
14	23.29 ± 11.91	5	419.43 ± 121.24	**8**
15	40.00 ± 26.36	**8**	408.79 ± 121.88	**8**
16	28.79 ± 18.05	4	455.64 ± 87.48	5
17	31.21 ± 18.35	**6**	473.43 ± 105.47	5
18	31.07 ± 21.13	**6**	440.21 ± 88.69	**6**
19	29.50 ± 13.03	**7**	430.07 ± 97.42	**7**
20	37.50 ± 23.60	**7**	386.64 ± 139.92	**9**
21	19.86 ± 11.32	2	465.86 ± 79.63	4

Difficulty falling asleep or sleeping for a short time over 6 d or more in 2 wk indicated that the symptoms related to sleep disorder were severe.[35] The number is bold when the number of days were equal or greater than 6. SD = standard deviation.

reflecting the airline company's routine operation, which COVID-19 did not influence.

Procedure. All procedures performed in studies involving human subjects were approved by the ethical standards of the Ethics Committee on Biomedical Research of West China Hospital of Sichuan University with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards (2022, No.1529). The airline company provided the data from scheduled flights and did not include the pilots' private information. The research team signed an agreement of confidentiality and the data were only used for the present study.

Firstly, to investigate the sleeping patterns of each pilot, this study aimed to cluster a large sample of pilots into different categories based on their scheduling. We extracted each pilot's flight schedule to calculate the proportion of irregular working time and annual working hours. We then conducted a cluster analysis to divide the pilots into groups based on their actual working hours per year and the proportion of irregular working time. A subject was then randomly selected from each group based on the prior cluster analysis, and the simulation models of the selected subjects' sleep-wake cycles over 31/32 d were developed using the individuals' actual flight schedules.

Materials. This study identified three categories based on the pilots' flight time for cluster analysis[39]: 1) regular working time: the take-off and landing times of the flight were between 09:00–17:00; 2) very irregular working time: the flight occurred between 21:00 and 05:00; and 3) less irregular working time: the other periods of flight operations. The simulation model of each cluster group defined regular sleep time as between 22:00 and 06:00,[24] according to the suggestion of the Sleep Medical Center of West China Hospital. If the circadian rhythm was disturbed due to a flight arrangement, the model tried to ensure the pilots' sufficient sleep duration. Random situations were considered. According to the pilots' statements in the semi-structured interview, the local airport the airline company often used was not far from the urban areas and 30 min was enough for them to go back home from the airport. When pilots are required to live out of town, the airline company will reserve the hotels close to the airport, generally 15–20 min by car. Therefore, we assumed that the pilot would be ready for bed 1 h after completing the night flight mission.

Statistical analysis. SPSSAU was used to conduct a K-means cluster analysis. The basic principle involves clustering with K objects as the center, allocating data objects to the classes represented by the most similar clustering center, followed by iteration until the best clustering result is obtained. A total of 567 airline pilots were divided into three groups.

Results

The planned working hours refer to the pilots' flight duty period arranged by the airline company. In this study, actual working hours included the short break between the flight segments of each duty on the same day (see the introduction for more details). According to the calculation of actual working hours, most pilots had 900–1500 duty hours per year. Under the regulations proposed by the Civil Aviation Administration of China (CAAC), pilots in the present study were planned to work between 700–1200 h.[7] The findings of this study reveal a failure to comply with current regulations.

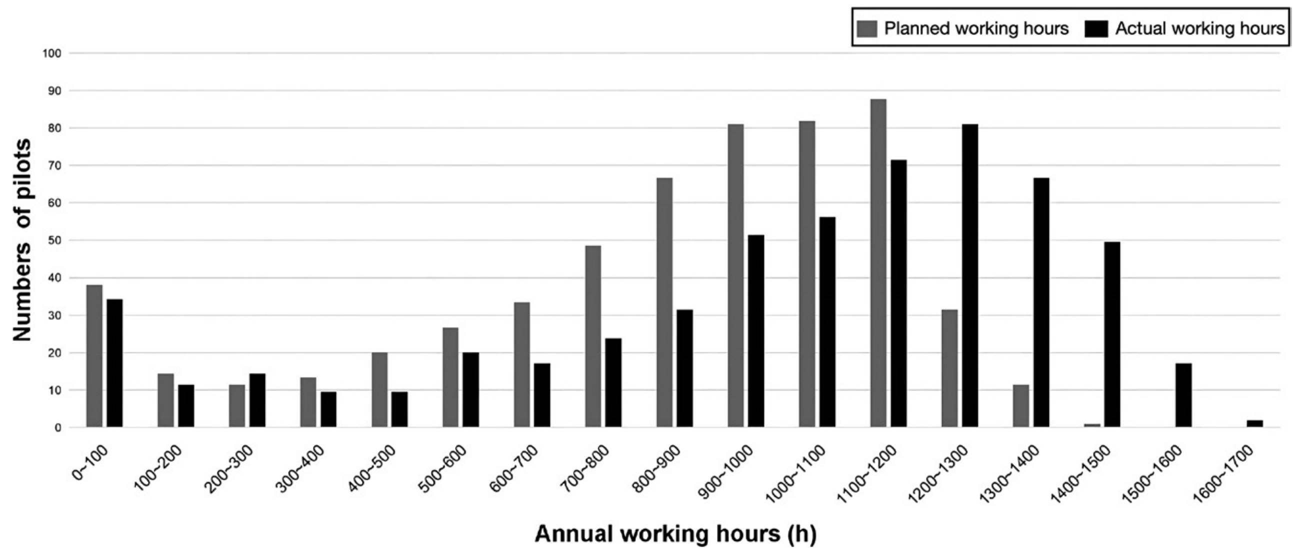

Fig. 2. Distribution of annual working hours in 2019.

In **Fig. 2**, the light and dark gray bars represent the number of pilots within different planned and actual working hour ranges, respectively.

Moreover, the average number of planned daily working hours was 6–8 (78%). However, the present study indicated that 51% of pilots worked an average of 8–10 h daily, and only 35% worked an average of 6–8 h. According to the definition of circadian disruption described in the introduction, very irregular and less irregular working time accounted for 23.4% and 50.34% of flight schedule structure frequency, respectively.

About half of the pilots' daily actual working hours were very long and they experienced severe disruption of circadian rhythm. In other words, pilots' fatigue caused by circadian disruption was not alleviated by reducing working hours in actual working conditions.

The cluster analysis aimed to categorize the airline pilots into different groups according to their features. Cluster 1 accounted for 36.51% and Cluster 3 was 16.05%. Cluster 2 (47.44%) appeared to be the most severe group with circadian disruption, as an average of 79% (SD = 0.04) of flights were arranged at irregular times, and the average actual annual working hours were 1221.45 h (SD = 183.37). The average proportion of irregular working time in cluster 1 was 64% (SD = 0.06), and the average annual working hours were 1074.79 (SD = 263.40). The average annual working hours in cluster 3 are the lowest, 426.11 (SD = 224.11), and the average proportion of irregular working time was 77% (SD = 0.11).

Pilot A, B, and C were randomly selected subjects from each group based on cluster analysis. Pilot A in group 1 worked for 19 d in the month, and day and night were reversed on Day 5. From days 11–14 and 18–24, pilot A maintained a relatively regular sleep-wake schedule and exhibited an irregular state on the other days (**Fig. 3**, A – Group 1).

Group 2 was identified as the group with the most severe circadian disruption tendency. Pilot B's flight schedules varied periodically, and an adjustment was observed almost daily. The earliest and latest time to sleep were 20:00 and 04:00 (Fig. 3, B – Group 2).

Pilot C from group 3 worked for 10 days and the total working hours were relatively short. The Day 8 circadian rhythm was abnormal and there was little change in the sleep phase on most of the other days (Fig. 3, C – Group 3).

Discussion

Our analysis revealed that over 70% of flight schedules were arranged during irregular working times with no fixed shift schedule. Of the pilots, 47.44% had a high workload status, with over 75% irregular flight shifts and 1200 actual working hours annually. The simulation model only demonstrated pilots' sleep-wake time over a month. We hypothesize that the real situation could be even worse than the simulation model, as circadian disruption tends to be accompanied by sleep disorder-related symptoms, such as difficulty falling asleep and waking up frequently at night.

DISCUSSION

The present study verified the severity of circadian disruption in pilots using multiple approaches. The night before an earlier morning shift, sleep-related problems became more serious, leading to cognitive impairment and a decline in working memory. In this regard, long-term disturbance of circadian rhythm does not lead to the adaptation of brain function, such as the development of cognitive self-regulation; instead, it damages normal biorhythms and self-regulation mechanisms.

An empirical study published in *Lancet Health Longevity* indicated that specific biological rhythm changes accompany the aging process, and the deterioration of cognitive function demonstrated a consistent trend with this change.[18] To an extent, flight schedules forcibly disrupt airline pilots' normal biorhythms for a prolonged period, which may accelerate the aging process and cognitive decline. When temporary

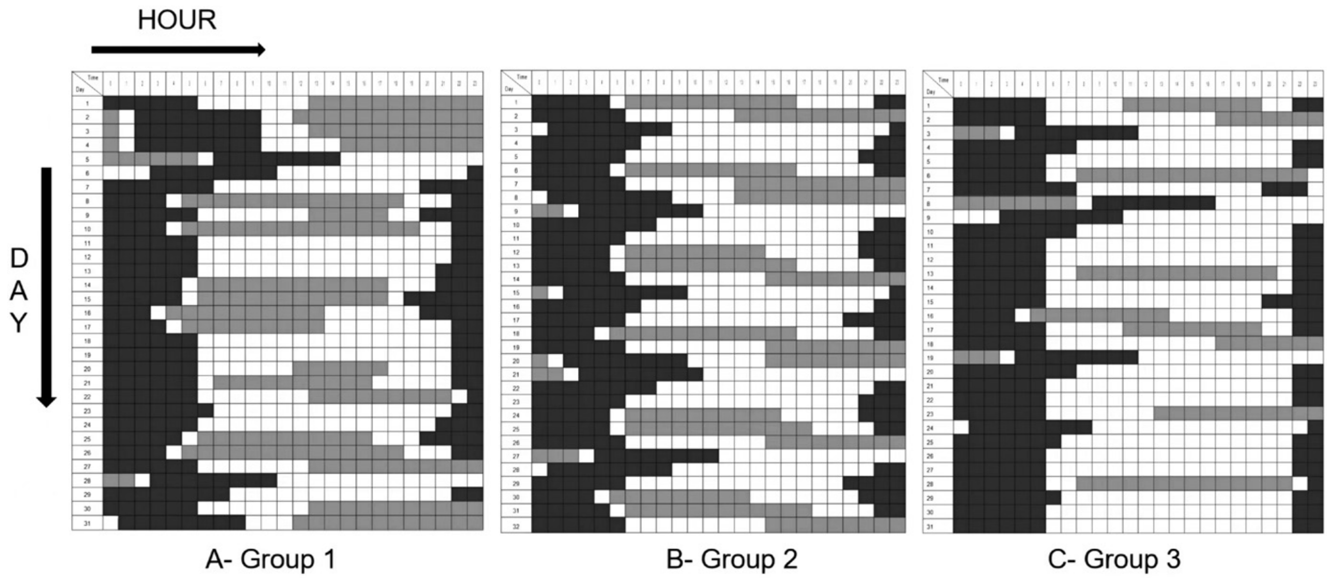

Fig. 3. Sleep-wake time simulation. The three graphs describe the 1-mo simulation schedule of the three representative pilots. The 24 cells in each row represent the 24 h of a day. White, gray, and black cells indicate waking, working, and sleeping times.

cognitive impairment develops into chronic disorders, the effect on pilots' flight operations is significant.[30]

To optimize pilots' work schedules and reduce the impact of circadian disruption, several measures have been specified by the flight management department. After reviewing existing regulations, it was observed that limiting flight duty periods in different schedules constitutes a significant approach to alleviating fatigue. China (Chinese Civil Aviation Regulations 121 Revision 7, CCAR-121-R7)[7] and the United Kingdom (Civilian Aviation Publication-371, CAP-371)[8] have used "report time" and "number of flight segments" as critical criteria in setting the limitation of flight duty period in a day. The European Union (Flight and Duty Time Limitations, FTL)[9] and the United States (Federal Aviation Rule 117, FAR 117)[10] added the "fitness for duty" factor, emphasizing the impact of cross-time zone flights on pilot status. Specifically, international regulations consider factors such as the number of flight segments and time zone differences. There are differences in defining the "report time" according to national regulations. Chinese Civil Aviation Regulations 121 Revision 7,[7] Civilian Aviation Publication 371,[8] Flight and Duty Time Limitations,[9] and Federal Aviation Rule 117[10] have 3, 5, 13, and 10 time periods to classify the report time, respectively.

As demonstrated by the monitoring data and simulation model, these regulations' effectiveness in reducing circadian disruption's impact is insignificant in China. There are two potential reasons underlying this. First, a minor reduction in working hours may not be effective in assisting pilots to adopt a regular sleep-wake cycle. Second, the definition of working hours needs to be verified. In this regard, this study emphasized the difference between planned and actual working hours. In reality, the airline pilots' working load is heavier than expected by the airline company, whereby the fatigue rate was calculated based on policies from the regional aviation administration without considering the actual scenarios in the pilots' daily schedules. It is thus unsurprising that 81% of the pilots said they required more rest time, further supporting the necessity of considering the inefficient break time between flight segments.[38] While we discuss the efficiency of on-duty breaks, many aviation administration regulations worldwide do not encourage this policy to be exercised in practice. For instance, controlled rest (CR), a short, in-seat nap with strict constraints for on-duty pilots, is a policy supported by the International Civil Aviation Organization (ICAO).[15] However, CR can only be adapted to a certain extent and is prohibited for most short-haul flights because the cruise time is insufficient to qualify for CR.[12] In addition, CR is only allowed in some countries and is illegal except for military operations in the United States.

The pilots' flight scheduling is a vital factor causing circadian disruption. Therefore, optimizing the scheduling arrangement is the most effective way to eliminate these effects. Possible strategies for optimization include:

1. To verify the effectiveness of current policies by understanding the pilots' subjective perception. For example, reducing daily work hours is the current strategy to alleviate the flight fatigue caused by circadian disruption. Still, it may lead to more attendance days to meet monthly/annual flight targets, reducing pilots' continuous rest duration. It means there is not enough time to adjust the circadian rhythm to a normal state. Sleep efficiency in rest days may also be affected. Therefore, the effectiveness of such current measures is open to debate.
2. Refine the definition of working hours in China. This study stated the concept of actual working hours, although its implication in practice remains unclear. Nevertheless, it draws attention to the need to further refine the definition of duty (working) hours. The intervals between flight segments

and inefficient rest time should be evaluated comprehensively while new regulations are developed in the future.

3. Improve the existing fatigue risk management system. In addition to evaluating the overall operational fatigue of the airline, the individual pilot's fatigue status also needs to be considered. This study indicated the importance of improving the fatigue risk management system from a circadian disruption perspective. It underscored the need to develop a scientific approach to ensure each pilot is fit for executing the flight task instead of the overall scheduling situation.

Most research on pilots' occupational health has focused on the effectiveness of short-term sleep and cognitive function, but tended to overlook the impact of long-term circadian disruption among this population. To date, no scientific conclusion relating to pilots' circadian rhythm features has been drawn. It is thus difficult to develop an effective medical intervention for this population. Although the scheduling system is improved to a certain degree in the civil aviation industry, it remains challenging to avoid irregular sleep-wake cycles. Therefore, developing a targeted program to train airline pilots to fall asleep quickly and rest efficiently based on understanding circadian disruption mechanisms is necessary.

Our findings are pertinent to airline pilots, as their health condition is critical to their career development. The conclusions of this study reveal the real-life working conditions of airline pilots and highlight the severity of circadian disruption in this population, which was more severe than expected. Our study underscores the need to understand better how the factors impact pilots' circadian rhythm and the urgent need to develop specific management strategies and medical guidelines.

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REFERENCES

1. Arsintescu L, Pradhan S, Chachad RG, Gregory KB, Mulligan JB, Flynn Evans EE. Early starts and late finishes both reduce alertness and performance among short-haul airline pilots. J Sleep Res. 2022; 31(3):e13521.
2. Baddeley A. Working memory and language: an overview. J Commun Disord. 2003; 36(3):189–208.
3. Bhatti P, Cushing-Haugen KL, Wicklund KG, Doherty JA, Rossing MA. Nightshift work and risk of ovarian cancer. Occup Environ Med. 2013; 70(4):231–237.
4. Boyd DD. A review of general aviation safety (1984–2017). Aerosp Med Hum Perform. 2017; 88(7):657–664.
5. Carney CE, Buysse DJ, Ancoli-Israel S, Edinger JD, Krystal AD, et al. The consensus sleep diary: standardizing prospective sleep self-monitoring. Sleep. 2012; 35(2):287–302.
6. Li C, Liu K, Chen T. Effects of acute sleep deprivation on brain cognitive function in young male military volunteer. China Journal of Health Psychology. 2017; 25(2):195–199 [in Chinese].
7. Civil Aviation Administration of China (CAAC). China Civil Aviation Regulations, 121-R7 (CCAR-121-R7), 2021.03. Beijing (China): CAAC; 2021.
8. Civil Aviation Authority (CAA). CAP 371: Avoidance of Fatigue in Air Crews, 2004.01. Crawley, West Sussex (UK): CAA; 2004.
9. European Aviation Safety Agency (EASA). Commission Regulation (EU) No 83/2014. Cologne (Germany): EASA; 2014.
10. Federal Aviation Administration (FAA). Part 117. Flight and duty limitations and rest requirements: flightcrew members. Washington, DC (U.S.): FAA; 2014.
11. Foster RG. Sleep, circadian rhythms and health. Interface Focus. 2020; 10(3):20190098.
12. Hilditch CJ, Arsintescu L, Gregory KB, Flynn-Evans EE. Mitigating fatigue on the flight deck: how is controlled rest used in practice? Chronobiol Int. 2020; 37(9-10):1483–1491.
13. Hirshkowitz M, Whiton K, Albert SM, Alessi C, Bruni O, et al. National Sleep Foundation's sleep time duration recommendations: methodology and results summary. Sleep Health. 2015; 1(1):40–43.
14. Hoskinson P. Brain workshop – a dual n-back game. (n.d.). [Accessed February 19, 2024]. Available from http://brainworkshop.sourceforge.net/.
15. International Civil Aviation Organisation (ICAO). Fatigue management guide for airline operators. Montreal, Canada: International Civil Aviation Organisation; 2015.
16. Jin Y, Hur T, Hong Y. Circadian rhythm disruption and subsequent neurological disorders in night-shift workers. J Lifestyle Med. 2017; 7(2): 45–50.
17. León-Domínguez U, Martín-Rodríguez JF, León-Carrión J. Executive n-back tasks for the neuropsychological assessment of working memory. Behav Brain Res. 2015; 292:167–173.
18. Li P, Gao L, Gaba A, Yu L, Cui L, et al. Circadian disturbances in Alzheimer's disease progression: a prospective observational cohort study of community-based older adults. Lancet Healthy Longev. 2020; 1(3):e96–e105.
19. Lopez N, Previc FH, Fischer J, Heitz RP, Engle RW. Effects of sleep deprivation on cognitive performance by United States Air Force pilots. J Appl Res Mem Cogn. 2012; 1(1):27–33.
20. Lu M, Penzel T, Thomas RJ. Cardiopulmonary coupling. In: Penzel T, Hornero R, eds. Advances in the diagnosis and treatment of sleep apnea: filling the gap between physicians and engineers. Cham (Switzerland): Springer; 2022:185–204.
21. Marquié JC, Tucker P, Folkard S, Gentil C, Ansiau D. Chronic effects of shift work on cognition: findings from the VISAT longitudinal study. Occup Environ Med. 2015; 72(4):258–264.
22. Mi Z, Zhu Y, Luo Y, Li Z, Si Q. A study on the influencing factors of civil aviation accident symptoms based on the fishbone diagram analysis. Scientific and Technological Innovation. 2021; 2021(3):161–162 [in Chinese].
23. Monk TH, Reynolds III CF, Kupfer DJ, Buysse DJ, Coble PA, et al. The Pittsburgh sleep diary. J Sleep Res. 1994; 3(2):111–120.
24. Moosavi-Movahedi AA, Moosavi-Movahedi F, Yousefi R. Good sleep as an important pillar for a healthy life. In: Moosavi-Movahedi AA, ed. Rationality and Scientific Lifestyle for Health; Cham (Switzerland): Springer; 2021:167–195.
25. O'Hagan AD, Issartel J, McGinley E, Warrington G. A pilot study exploring the effects of sleep deprivation on analogue measures of pilot competencies. Aerosp Med Hum Perform. 2018; 89(7):609–615.
26. Ohayon M, Wickwire EM, Hirshkowitz M, Albert SM, Avidan A, et al. National Sleep Foundation's sleep quality recommendations: first report. Sleep Health. 2017; 3(1):6–19.
27. Reid KJ, Zee PC. Circadian rhythm disorders. Semin Neurol. 2009; 29(4):393–405.
28. Roenneberg T, Foster RG, Klerman EB. The circadian system, sleep, and the health/disease balance: a conceptual review. J Sleep Res. 2022; 31(4): e13621.

29. Rostami M, Razeghi M, Daneshmandi H, Hassanzadeh J, Choobineh A. Cognitive and skill performance of individuals at sitting versus standing workstations: a quasi-experimental study. Int J Occup Saf Ergon. 2022; 28(1):544–554.
30. Rouch I, Wild P, Ansiau D, Marquié J. Shiftwork experience, age and cognitive performance. Ergonomics. 2005; 48(10):1282–1293.
31. Sallinen M, Sihvola M, Puttonen S, Ketola K, Tuori A, et al. Sleep, alertness and alertness management among commercial airline pilots on short-haul and long-haul flights. Accid Anal Prev. 2017; 98:320–329.
32. Shin JH. Application of repeated-measures analysis of variance and hierarchical linear model in nursing research. Nurs Res. 2009; 58(3):211–217.
33. Singh V, Rana RK, Singhal R. Analysis of repeated measurement data in the clinical trials. J Ayurveda Integr Med. 2013; 4(2):77–81.
34. Sletten TL, Cappuccio FP, Davidson AJ, Van Cauter E, Rajaratnam SM, Scheer FA. Health consequences of circadian disruption. Sleep. 2020; 43(1):zsz194.
35. Smyth CA. Evaluating sleep quality in older adults: the Pittsburgh Sleep Quality Index can be used to detect sleep disturbances or deficits. Am J Nurs. 2008; 108(5):42–50.
36. Vetter C. Circadian disruption: what do we actually mean? Eur J Neurosci. 2020; 51(1):531–550.
37. Walker WH, Walton JC, DeVries AC, Nelson RJ. Circadian rhythm disruption and mental health. Transl Psychiatry. 2020; 10(1):28.
38. Wang Y. Mental health status of pilots in an airline company. Psychologies Magazine. 2019; 14(17):47 [in Chinese].
39. Wang Z. Chronobiology. Beijing (China): People's Medical Publishing House; 2008:202–203 [in Chinese].
40. Wiegmann DA, Shappell SA. A human error analysis of commercial aviation accidents using the human factors analysis and classification system (HFACS). Washington, DC (U.S.): Federal Aviation Administration, Department of Transportation; 2001.
41. Zhang L, Sabeh MK, Jain MK. Circadian rhythm and cardiovascular disorders. ChronoPhysiology and Therapy; 2014; 4:27–40.
42. International Civil Aviation Organisation (ICAO). The world of air transport in 2021. [Accessed 21 May 2024]. Available from https://www.icao.int/sustainability/WorldofAirTransport/Pages/the-world-of-air-transport-in-2021.aspx.