BMC Public Health

RESEARCH

Open Access

Sleep and biorhythm among intercontinental pilots: the effect of exempting flight crews from mandatory layover and flight times during COVID-19

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Abstract

Pilots are crucial to the safety of the airline industry; as a result, their sleep and biorhythm, which are closely related to fatigue, play an important role. During the COVID-19 pandemic, the Civil Aviation Administration of China exempted flight crews from mandatory layovers and imposed limitations on duty period and flight times. Given that the effect of this policy on their sleep and biorhythm is poorly understood, this study explores the key factors affecting the sleep and biorhythm of pilots on intercontinental flights and compares the rest status on and after flying days on exempt and non-exempt flights. Eighty pilots flying from China to five countries wore a body movement recorder, which has been validated for estimating total sleep time, sleep efficiency, and interdaily stability. The results of the K-means clustering analysis showed differences in sleep and biorhythm on flying days between departures during the day and at night, west–east and north–south flights, and exempt and non-exempt flights. ANOVA was performed based on the categorization in which each indicator contributed significantly to the clustering ($p = 0.000$). This study contributes to the literature by validating a new intercontinental flight operation model under the COVID-19 pandemic conditions and proposes critical points for the future management of pilot fatigue on long-haul flights.

Keywords Intercontinental flights, Sleep, Biorhythm, COVID-19, China

Introduction

Flight safety is important for the sustainable development of the civil aviation industry. Pilot fatigue decreases their alertness and cognitive ability, which increases the risk of unsafe events. According to the International Civil Aviation Organization, the main causes of fatigue include short- and long-term loss of sleep, disrupted physiological cycles, and excessive workload [1]. Intercontinental pilots are particularly at risk of fatigue. When compared with short-haul routes, intercontinental flights have long flying times and cross many time zones; moreover, these are often night flights, and the resulting circadian misalignment means intercontinental pilots are more likely to suffer from sleep disorders [2].

Research has shown that sleep deprivation and fatigue in pilots are not only common but pose significant safety risks. For instance, a study by Alzehairi et al. found that sleep disorders are prevalent among commercial airline pilots, with factors such as long-haul flight schedules exacerbating fatigue [3]. Additionally, Sallinen et al. highlighted the challenges pilots face in maintaining alertness, particularly during long-haul flights, where the effects of jet lag and disrupted sleep can impair performance [4].

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The COVID-19 pandemic has led to shifts in aviation operations, including the emergence of ultra-long-haul flights, which are defined as those lasting over 14.5 h and covering distances greater than 12,842 km [5, 6]. Along with these changes, flight crew exemptions from mandatory layovers and flight time limitations have been implemented in many regions, including China, where the Civil Aviation Administration of China introduced the "Measures for Exempting Crew Members from Layover and Flight Time Requirements during COVID-19" (referred to as the exemption policy). This policy has allowed for operational flexibility but also introduced new challenges related to pilot fatigue, as pilots are required to operate without adequate rest during these extended flight hours [7]. Despite the importance of this policy, the impact of such exemptions on pilots' sleep and circadian rhythms remains underexplored. Understanding these effects is crucial for developing effective fatigue management strategies and ensuring flight safety, especially as the pandemic-induced operational changes become the new norm.

This study contributes to the existing literature by examining the sleep and biorhythm patterns of pilots operating under the exemption policy, with a focus on identifying key factors influencing fatigue. Unlike previous research, which often addresses broader operational models, this study specifically investigates how unique pandemic-induced changes—such as ultra-long-haul flights and regulatory exemptions—affect pilots' sleep behavior and biorhythms. By comparing sleep characteristics across different flight routes, departure times, and flight frequencies, the study aims to provide actionable insights for fatigue management. Furthermore, it explores the effects of shift scheduling and quarantine policies on pilots' rest and alertness, offering a scientific basis for optimizing crew scheduling and ensuring adequate rest periods.

The findings of this study have practical implications for the aviation industry, particularly in the context of evolving operational demands. By analyzing real-world data from 80 pilots using Actigraph GT3X + body movement recorders, the research provides a detailed understanding of how sleep and biorhythms are influenced by flight operations under the exemption policy. This knowledge can inform the development of targeted fatigue mitigation strategies, enhance flight safety, and promote the sustainable use of human resources in the aviation sector.

Theoretical background and hypothesis development

Sleep and biorhythm

Sleeping for eight hours daily helps individuals to maintain a good alertness level. If a person is sleep-deprived for a long time, it will raise the drive to sleep and may lead to uncontrollable sleep at work, potentially risking flight safety in the case of pilots [8]. Thus, while a lack of sleep or low sleep quality can exacerbate pilots' fatigue [9], staying in a noisy and dry cockpit for a long time can also adversely impact their rest and mood [10].

Biorhythm, the periodic rhythm of physiological activities, forms the regular cycle established by the functions of humans to adapt to the diurnal changes of the external environment [11]. Night work, shift work, and biorhythm contrary to the circadian rhythm of the region in which individuals are located can indirectly affect their physiological functions and lead to adverse reactions, such as sleepiness and fatigue [12]. Biorhythm theory states that attention is suboptimal at night and in the early morning [13]. Several studies have found that the human body is at the window of circadian low (WOCL) between 3 and 6 a.m. when sleepiness is the most obvious [14, 15]. Thus, for intercontinental pilots, the possibility of errors and accidents is significantly increased at those times; however, because intercontinental flights are long, pilots cannot avoid working during the WOCL. Further, jet lag syndrome caused by rapid travel across time zones can desynchronize the body's internal rhythm, making it difficult to quickly adapt to the time at the destination; this often manifests as insomnia at night and daytime sleepiness [16].

In addition, biorhythm and sleep influence each other. Regular sleep patterns are a prerequisite to maintain good rhythm, which restores work efficiency and alertness by regulating sleep tendencies [17]. Contrastingly, the disruption of biorhythm can cause sleep–wake disorder and prevent pilots from obtaining sufficient rest [9]. Because the sleep–wake cycle is regulated by sleep homeostasis and the biological clock, rhythm disturbances can lead to sleep disorders, such as sleep phase abnormalities, insomnia, and the loss of the sleep–wake cycle. Moreover, sleep disturbance may be experienced simultaneously with sleep deprivation during jet lag [18]. Hence, we posit the following hypotheses:

H1. *Pilots in the critical phases of flights, i.e., takeoff and landing, during the WOCL have worse sleep conditions and a more disrupted biorhythm than crews who depart at other times.*

H2. *East–west flights cause greater rhythm disturbance than north–south flights, with eastward and westward travel leading to more severe jet lag than northward and southward.*

H3. *If biorhythm is disrupted, sleep quality diminishes.*

Exemption and quarantine policies

According to 'Implementation Measures for Exempting Crew Members from Duty Period and Flight Time Restrictions during an Epidemic' [7, 19], long-haul flight crews traditionally must rest for a minimum of 10 consecutive hours at a hotel before completing the return leg of their trip. However, under the exemption policy, some flight crews are exempt from mandatory layover and flight times. For such exempt flights, the expanded crew (at least three sets of flight crew) could complete a direct intercontinental round-trip flight within 2–5 h of arriving at the destination. Further, the exemption policy stipulates that for passenger flights converted to cargo flights, full freighter flights, and passenger flights with independent rest areas, the maximum flight time is 26 h for three sets of flight crew and 30 h for four sets; however, for non-exemption flights with two sets, the maximum flight time is 17 h. The same order of shifts for three sets of round trips is usually scheduled for flight crews: one crew is responsible for takeoff and landing, and the other two crews perform the cruise phase of the flight. For four sets of flight crew, the first takeoff and landing crew is responsible for the take-off and landing period, while the remaining crews are on duty for the cruise flying; for the return trip, the second takeoff and landing crew would be responsible for takeoff and landing [7]. Although the exemption policy enhances operational efficiency, it also increases duty hours and reduces rest opportunities, potentially leading to greater circadian rhythm disruptions among flight crews. Given that exempt flights involve prolonged duty periods, pilots may experience increased sleep deprivation and irregular sleep patterns, which could heighten the risk of fatigue-related impairments. Therefore, we propose the following hypothesis:

> H4. *Sleep disturbances and rhythm disturbances are more pronounced after multiple exempt flights.*

Under COVID-19 quarantine policies, pilots must quarantine for 14 days after a non-exempt inbound trip. Subsequently, they must monitor their health for 7 days, during which they may fly multiple missions. For flight crews on exempt flights, after the first negative nucleic acid test, they are exempt from quarantine and must only undergo health monitoring for 7 days, during which they can fly [7]. Quarantine and isolation measures urgently adopted to control the pandemic might have negative psychological and social effects [20, 21]. Hundreds of flight attendants have been infected with COVID-19 since March 2020, with rates of depression ranging from 14.6% to 48.3% in the general population [22]. The prolonged stress of infection risks and social isolation may contribute to heightened anxiety and disrupted sleep patterns, further compounding fatigue among flight crews. To better align our research hypotheses with the study's findings, we propose the following hypothesis:

> H5. *Quarantine-related stress and isolation contribute to increased sleep disturbances and rhythm disturbances.*

Methods

Instrument, participants, and sample

Classical methods of fatigue measurement include subjective and objective evaluation. Subjective evaluation usually uses a scale for participants to self-assess whether they are fatigued or sleepy, which has a certain degree of subjectivity and uncertainty [23]. Objective evaluation methods reflect the fatigue level indirectly through task performance and biochemical indicators [24]. However, owing to the limited space of the cockpit and relevant regulations, this study required convenient, non-invasive, and easy-to-use instruments.

A total of 80 pilots on intercontinental flights served as the participants in this study. All participants were male, with ages ranging from 28 to 46 years (mean ± standard deviation: 35 ± 5.5 years) and annual flight hours ranging from 140 to 900. The pilots continuously wore Actigraph GT3X recorders on their non-dominant wrists [25], which automatically detected their daily activity and collected sleep-related data (Fig. 1). The participants were required to wear the recorders for 48 h before the first flight on the first four round-trip journeys and for 72 h after the final flight. They could not be removed unless damaged (e.g., when swimming or bathing). The study protocol, including the data collection process and waiver of informed consent, was approved by the ethics review board in accordance with the Declaration of Helsinki, with all participants being fully informed of the procedures.

The sample included exempt and non-exempt flights from China (UTC/GMT +8:00) to Europe (UTC/GMT 0), North America (UTC/GMT −8:00), and Oceania (UTC/GMT +10:00). The routes to North America included China–Canada (YVR[1]/YYZ,[2] non-exempt flights) and China–USA (LAX,[3] exempt flights). The routes to Europe included China–Germany (FRA,[4] exempt and non-exempt flights), China–Netherlands (AMS,[5] exempt and non-exempt flights), and China–UK (STN,[6] exempt flights). For Oceania, we studied one

[1] Vancouver International Airpor.

[2] Toronto Pearson International Airport.

[3] Los Angeles International Airport.

[4] Frankfurt Airport.

[5] Amsterdam Schiphol Airport.

[6] London Stansted Airport.

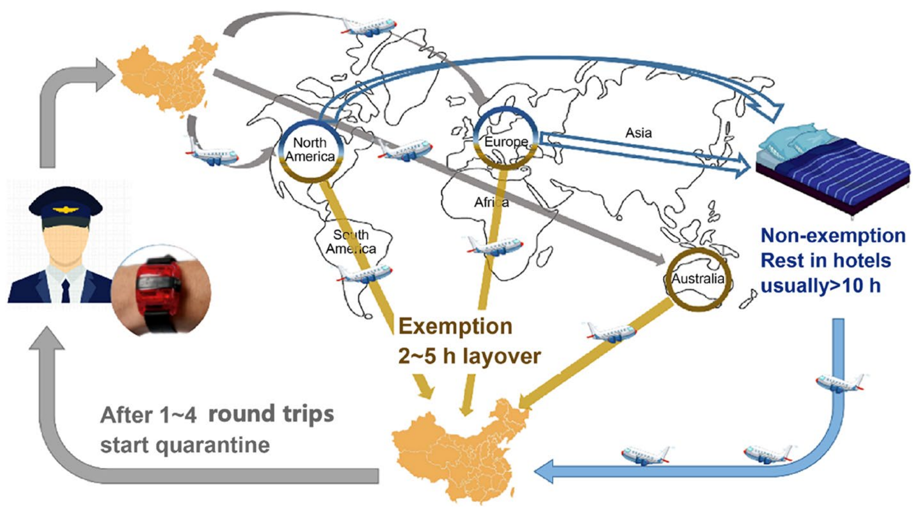

Fig. 1 Exempt and non-exempt intercontinental flights

route, namely, China–Australia (SYD[7]/MEL,[8] exempt flights). A total of 845 days (daily recording time > 22 h) of valid data were collected, with 726 periods of sleep (Table 1).

In Table 1, preflight days are the days before the first flight, inter-flight rest days refer to the interval between the previous mission and next mission when pilots were in China, and postflight days mean the 1 to 3 days after completing the final round trip, often in quarantine or monitoring health.

Measurements

Actigraph GT3X + recorders

For somatic motion recording, we used Actigraph GT3X + recorders (Manufacturing Technology Inc. MTI USA), compact (4.6 cm × 3.3 cm × 1.5 cm) and lightweight (19 g) triaxial acceleration monitors widely used in physical activity and sleep behavior studies [26]. These devices operate at a sampling frequency of 30 Hz, with a high-pass filter at 0.25 Hz and a low-pass filter at 2.5 Hz. They support continuous use for up to 25 days on a full charge and can store up to 180 days of data (4 GB). Data including pilot ID, body position, and recording time were collected and managed using ActiLife 6.13.4 software, which also handled data downloading, analysis, and integration (Fig. 2). Sleep–wake detection was performed using the Cole–Kripke algorithm, a validated method recommended for adult populations. This algorithm has shown high concordance with polysomnography, ensuring accurate sleep–wake identification in our adult pilot sample [27].

[7] Sydney Kingsford Smith International Airport.

[8] Melbourne Airport.

Sleep indices

The followed indices were used to evaluate sleep quality: sleep efficiency (SE), total sleep time (TST), wake after sleep onset (WASO), number of awakenings (NOA), and average awakening length (AAL, Table 2). Sleep Efficiency (SE) is defined as the ratio of total sleep time (TST) to time in bed, expressed as a percentage, indicating how efficiently an individual sleeps. Wake After Sleep Onset (WASO) refers to the total number of minutes spent awake after initially falling asleep, until final awakening, reflecting sleep continuity.

To analyze the sleep characteristics concisely and accurately, the entropy weight method was chosen to assign weights to the indicators and extract the most representative indicators as variables. The specific steps were as follows [28].

Step 1. Construct a judgment matrix X, including n evaluation objects, each with m evaluation indices.

Table 1 Samples and data

		Days	Sleeps
Preflight days		103	94
Flying days	North America (non-exempt flights)	75	61
	North America (exempt flights)	68	56
	Europe (non-exempt flights)	46	38
	Europe (exempt flights)	65	54
	Oceania (exempt flights)	71	52
Inter-flight rest days		240	208
Postflight days		177	163
Total		845	726

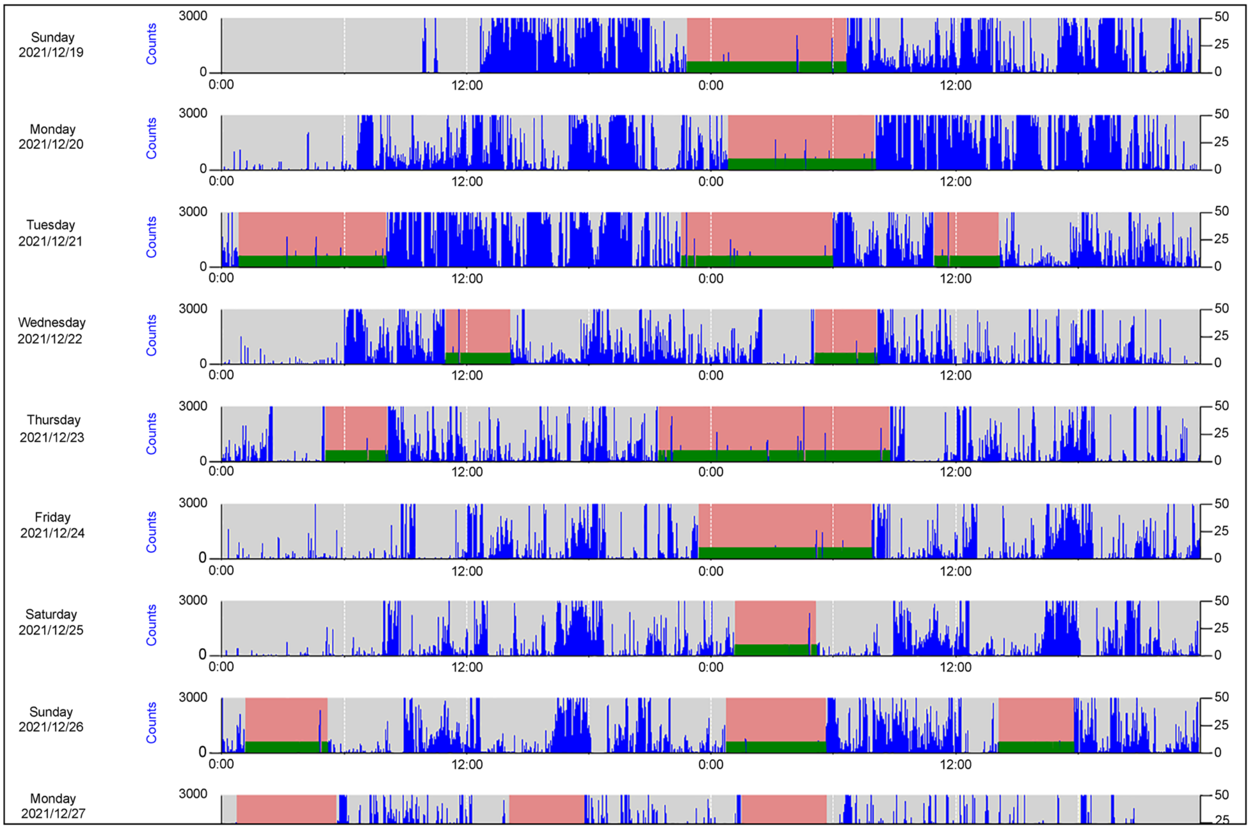

Fig. 2 Sleep analysis diagram based on the ActiLife software

Table 2 Index weight and sleep order

Index	Weight	Sequences
SE	0.259213324	2
TST	0.26251128	1
WASO	0.001623472	6
NOA	0.254629409	3
AAL	0.219183615	4
Movement index	0.001069194	7
Fragmentation index	0.001769704	5

In this case, n is the number of recorded periods of sleep (726) and m is the number of sleep indices (5):

$$X = [x_{ij}]_{mn} \quad (i=1,2...,n; j=1,2,...m;) \tag{1}$$

Step 2. This step normalizes positively the judgment matrix, which transforms X into the "larger-the-better" type.

Positive attributes (SE and TST) are defined using Eq. (2):

$$x'_{ij} = \frac{x_{ij} - \min\{x_{ij}, x_{(i+1)j}..., x_{nj}\}}{\max\{x_{1j}, x_{2j}, ..., x_{nj}\} - \min\{x_{1j}, x_{2j}, ..., x_{nj}\}} \tag{2}$$

Negative attributes (WASO, NOA, AAL, movement index, and fragmentation index) are defined using Eq. (3):

$$x'_{ij} = \frac{\max\{x_{ij}, x_{(i+1)j}..., x_{nj}\} - x_{ij}}{\max\{x_{1j}, x_{2j}, ..., x_{nj}\} - \min\{x_{1j}, x_{2j}, ..., x_{nj}\}} \tag{3}$$

Step 3. Calculate the weight of the ith sleep under each evaluation index:

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} (i = 1, 2..., n; j = 1, 2, ..., m) \tag{4}$$

Step 4. Calculate the entropy for all the criteria using Eq. (5):

$$e_j = -k \sum_{i=1}^{n} p_{ij} In(p_{ij}); k = 1/In(n) > 0; e_{ij} \geq 0 \tag{5}$$

$$d_j = 1 - e_j \tag{6}$$

Step 5. Calculate the entropy weight w_j of the j index:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{7}$$

The entropy weight provides useful information about the evaluation index [28]. Therefore, the three highest weighted indices (SE as a percentage, TST in minutes, and NOA) were used as variables to measure the pilots' sleep characteristics.

Biorhythm indices

As biorhythm indices, interdaily stability (IS) and intradaily variability (IV) were used to assess the stability of the pilots' circadian biorhythm, calculated based on the average vector magnitude of all three axes recorded by the actigraph:

$$IS = \frac{N \sum_{h=1}^{P} (\overline{X_h} - \overline{X})^2}{P \sum_{t=1}^{N} (X_i - \overline{X})^2} \tag{8}$$

$$IV = \frac{N \sum_{h=1}^{N} (X_i - X_{i-1})^2}{(N-1) \sum_{t=1}^{N} (\overline{X} - X_i)^2} \tag{9}$$

where N represents the total amount of data, P is the amount of data per day, $\overline{X}$ is the average of all the data, $\overline{X}_h$ is the average of each hour, X_i is a single data point, and X_{i-1} is the previous data point.

IS measures the individual's 24-h biorhythm, which is the percentage variation in activities in an average 24-h period, with values closer to 1 being more consistent with the 24-h biorhythm pattern. IV assesses the rest/activity rhythm, where a higher value means a greater number of rest/activity transitions and a more fragmented circadian rhythm.

K-means clustering

K-means clustering was selected for its ability to efficiently partition large datasets into distinct, non-overlapping clusters based on similarity measures. This method is particularly suitable for our study as it minimizes the sum of squared errors (SSE) or variance criterion, which is computed as the Euclidean distance between each individual and the cluster centroid to which it has been allocated. The Euclidean distance metric was chosen due to its simplicity and effectiveness in capturing the spatial relationships between data points in a multi-dimensional space. Additionally, K-means clustering is computationally efficient and scales well with large datasets, making it an ideal choice for our analysis [29].

The algorithm process consisted of four steps. First, we grouped the samples into K groups, with K selected individuals as the initial clustering centers. Second, we grouped individuals according to the Euclidean distance from the initial clustering center. Third, we took the mean of the cluster node in each group as the new cluster center and calculated the sum of the squares of the distances $J(c)$ from all the samples to their new center. Finally, we repeated the second and third steps until the clustering center and $J(c)$ did not change to obtain the final clustering center. The calculation process was as follows.

Step 1. To ensure that each index's attribute was paid equal consideration during the K-means clustering, the original dataset was standardized before clustering using Z-scores, where x is the original value of the sleep data, μ is the arithmetic mean of this index, and σ is the standard deviation:

$$z = \frac{x - \mu}{\sigma} \tag{10}$$

Step 2. $X = \{x_1, x_2, ..., x_i, ..., x_n\}$ is a dataset containing n d-dimensional data points, which means $x_i \in R^d$. After normalization, the K-means clustering algorithm was used to partition the data into k clusters $C = \{c_k, i = 1, 2, 3, ..., k\}$. Each cluster represents a group called c_k, and each group has a cluster center named μ_i. The distances from each data point in the group to the cluster center were calculated using Eq. (11):

$$J(c_k) = \sum_{x_i \in c_i} ||x_i - \mu_k||^2 \tag{11}$$

Step 3. The final cluster centers were obtained when the total distance from the individual in the cluster node to the cluster centers $J(c)$ was minimized:

$$J(c) = \sum_{k=1}^{K} J(c_k) = \sum_{k=1}^{K} \sum_{x_i \in c_i} ||x_i - \mu_k||^2 = \sum_{k=1}^{K} \sum_{i=1}^{n} d_{ki} ||x_i - \mu_k||^2 \tag{12}$$

$$d_{ki} = \begin{cases} 1, x_i \in c_i \\ 0, x_i \notin c_i \end{cases} \tag{13}$$

Results

K-means clustering results

Appendix A show the final clustering centers for the sleep and biorhythm indices, respectively. ANOVA was performed based on the categorization in which each indicator contributed significantly to the clustering ($p = 0.000$). The contribution of each sleep index to the clustering was approximated according to the *F*-value, where the sleep indices in order of importance of contribution were NOA > TST > SE (586.4614 > 418.370 > 389.347), while the order of the biorhythm indices was IV > IS (1145.861 > 750.101).

Figure 3 shows the clustering effect. The sleep of intercontinental pilots can be divided into four groups, namely, poor sleep (PS), shorter sleep (SS), longer sleep (LS), and excellent sleep (ES), with means of 163, 271, 144, and 148 occurrences, respectively. Biorhythm comprises regular rhythm (RR) and disturbed rhythm (DR). RR, which accounts for 76% of total biorhythm, conforms to a 24-h rhythm pattern and has a low degree of circadian rhythm fragmentation, while DR does not meet the 24-h circadian rhythm and has frequent transitions between rest and activity.

PS is characterized by the lowest SE (86.6%), a short sleep duration on average (260 min), and more awakenings (16), whereas LS has a longer sleep duration (457 min) but lower SE (88.4%) and the highest NOA (29). SS has the highest SE (94.7%), the lowest NOA (8), and shorter sleep duration (293 min). ES has higher SE (94.5%), a mean sleep duration of 502 min, and a lower NOA on average (14). As shown in Fig. 4, descriptive trends suggest that pilots with RR may be more likely to experience longer sleep durations (ES and LS) compared to those with DR, supporting H3. However, this

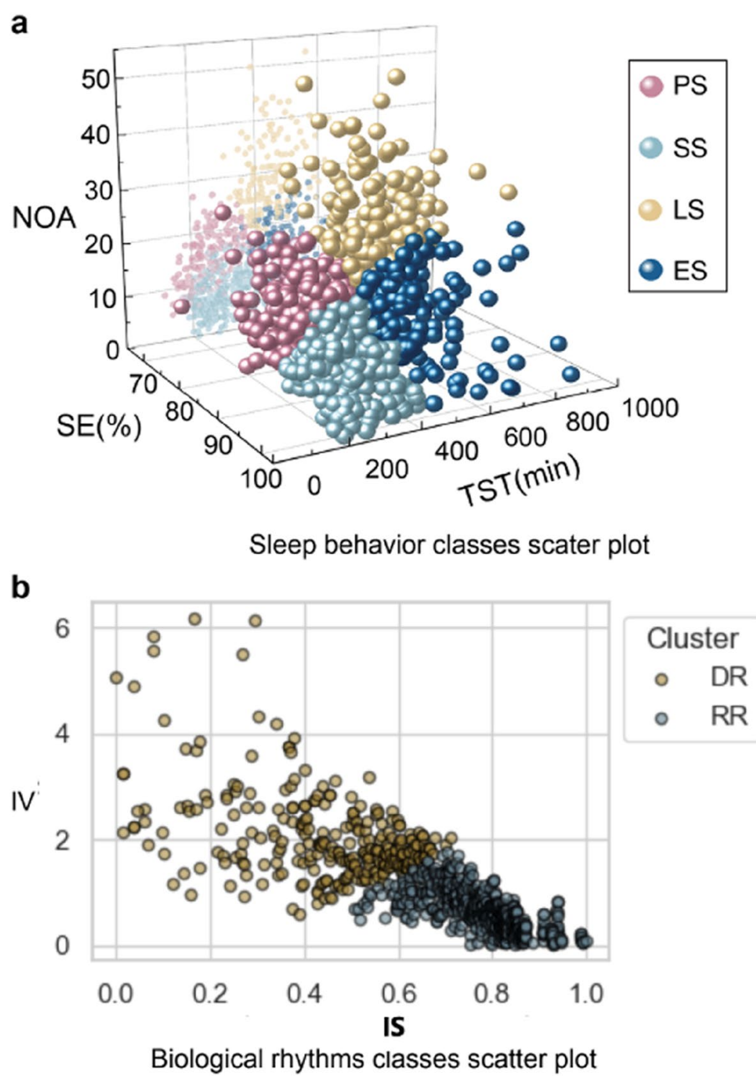

Fig. 3 Sleep and biorhythm classification

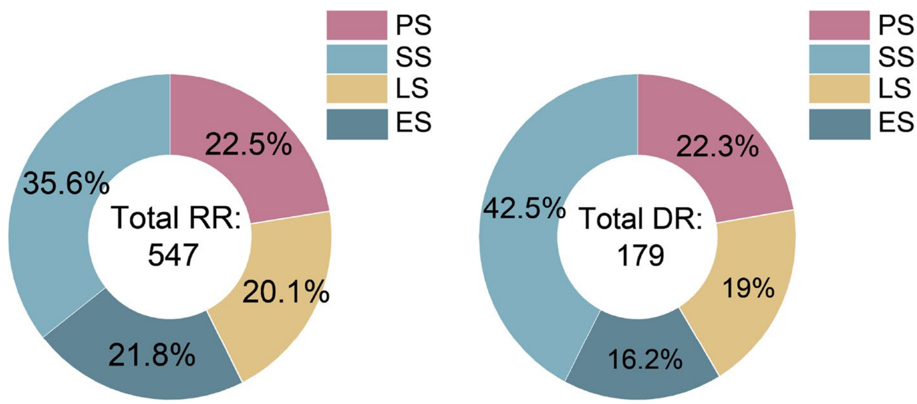

Fig. 4 Percentages of the sleep and biorhythm groups. Note: poor sleep (PS), shorter sleep (SS), longer sleep (LS), and excellent sleep (ES), and regular rhythm (RR) and disturbed rhythm (DR)

observation is based on percentage distributions and has not been confirmed by statistical testing. Additionally, three-quarters (76%) of intercontinental pilots exhibit a physiological rhythm aligned with the 24-h rhythm, with 40% achieving a total sleep time (TST) above 7 h and 57.7% obtaining sleep with high SE (> 90%).

Sleep and biorhythm on different days are illustrated in Appendix B, while inter-flight and postflight rest at various flight frequencies are detailed in Appendix C.

Sleep and biorhythm at different departure times and flight frequencies

Owing to the variations in sample size between the departure periods, the differences in sleep between flights at different departure times were compared by calculating the number of each sleep type in each departure period flight divided by the total number of periods of sleep recorded in that time. As shown in Fig. 5(a), flights departing from 0:00 to 5:59 had higher occurrences of PS and SS, with SS being the most frequent, supporting H1. For flights departing in the daytime (06:00 to 17:59), the incidence of ES and LS increased, while that of PS decreased. Among morning flights, SS was higher, while ES and LS increased distinctly and PS was the lowest for the 12:00 to 17:59 departure flights. There was an increase in the occurrences of PS and LS for departures between 18:00 and 23:59, where LS was not as efficient despite the guaranteed rest hours.

The incidence of each type of sleep at different flight frequencies was calculated by dividing the number of a sleep type on each shift by the total number of periods of sleep recorded on that flight. As shown in Fig. 5(b), during the first flight, 68.8% of the pilots slept efficiently (SS and ES). During the second flight, the probability of PS increased, while SS decreased, and only some of the pilots (12.9%) could guarantee ES. The incidences of ES and PS peaked during the third and fourth flights (19.6% and 23.1%, respectively), contrary to H4.

Figure 5(c) shows the number of sleep types at every departure time for the first to fourth flights. Under the effect of flight frequencies and departure times, ES mainly occurred during daytime departures (6:00 to 17:59) and the highest number of third and fourth flights ($N = 6$) departed in the afternoon. SS had the largest share overall, but this decreased on second flights departing between 18:00 and 23:59, with PS and LS increasing. As shown in Fig. 5(d), the pilots had a higher probability of DR on flights departing from 0:00 to 11:59. The rhythm distribution was similar for all flights departing in the morning, whereas for flights departing in the afternoon, there were fewer occurrences of RR on the first flight. Finally, for both evening and night flights, the occurrence of DR was the highest on second flights, followed by first and then third flights.

Sleep and biorhythm on different routes for exempt and non-exempt flights

East–west vs. North–south routes

In this study, flights to the south (north) were China–Oceania (Oceania–China, about 9 h), flights to the east included China–North America (about 12 h) and Europe–China (about 11 h), and flights to the west included China–Europe (about 12 h) and North America–China (about 15 h). Figure 6(a) shows that DR was more likely on journeys heading east–west than north–south, supporting H2. There were fewer occurrences of SS and more occurrences of PS when flying east, while both LS and ES were lower when flying west. For the north–south route, there was an increase in the number of SS occurrences when flying north. Figure 6(b) compares exempt with non-exempt flights on North American and European routes, showing more occurrences of

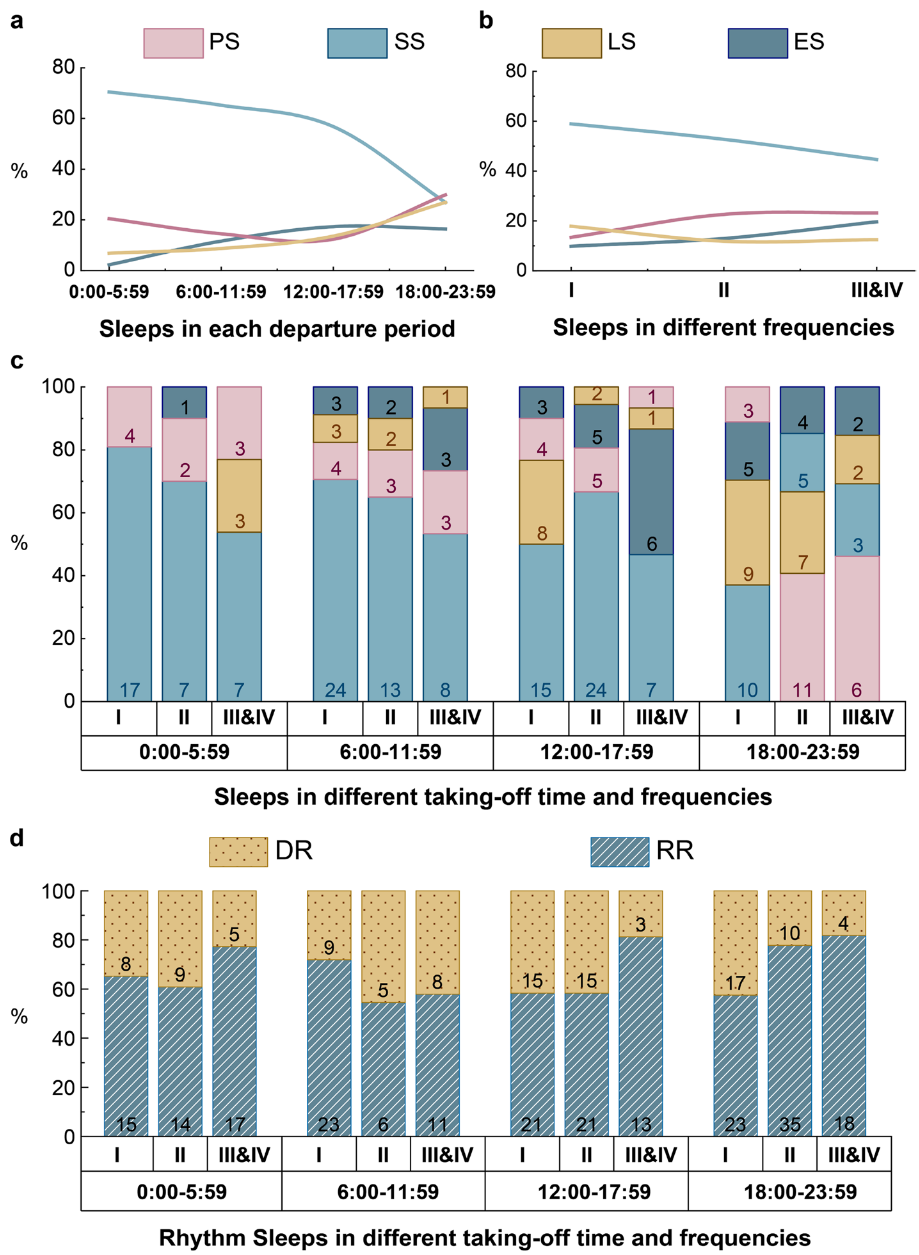

Fig. 5 Sleep and biorhythm on flying days at different flight frequencies and departure times. Note: a) I, II, III, and IV represent the first, second, third, and fourth flights, respectively. b) poor sleep (PS), shorter sleep (SS), longer sleep (LS), and excellent sleep (ES), and regular rhythm (RR) and disturbed rhythm (DR)

LS and ES and a smaller proportion of SS on non-exempt than on exempt flights, and a higher probability of DR.

Inter-flight rest days and postflight days

As shown in Fig. 7, DR was higher at the end of non-exempt flights and more pronounced on the westward route (China–North America), supporting H5. The proportion of SS was lower at the end of exempt flights on both routes and LS was greater than on non-exempt flights. ES was greater after exempt flights in Europe and non-exempt flights in North America, while there were more occurrences of PS after exempt flights in Europe and non-exempt flights in North America.

Discussion

Our results demonstrate that flights from east to west, layovers at destinations with large time zone changes, and departure during the WOCL disrupt pilots' biorhythm.

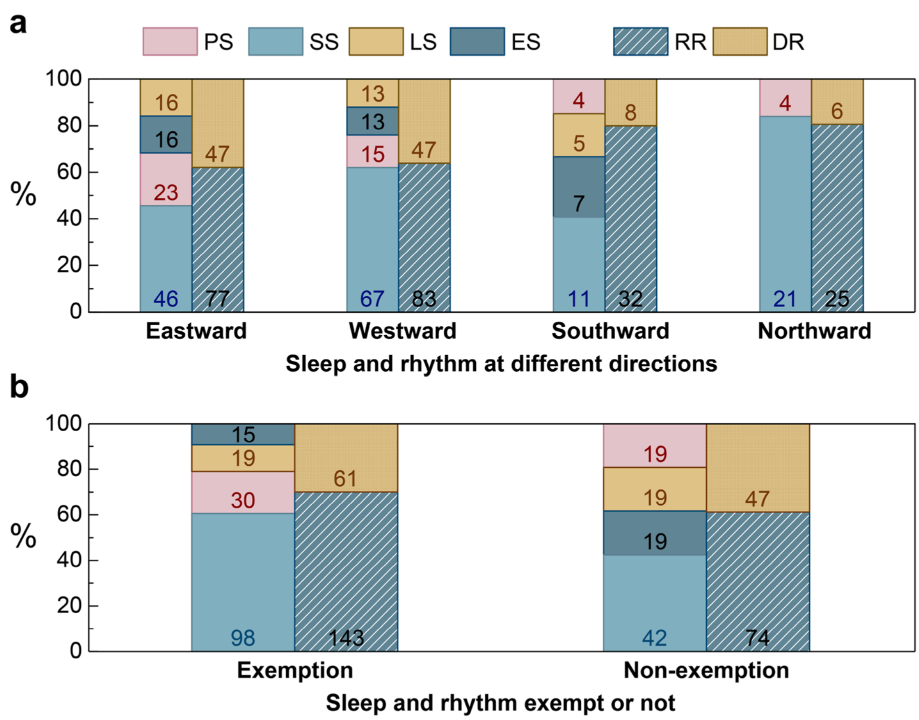

Fig. 6 Sleep and biorhythm on flying days on different routes for exempt and non-exempt flights. Note: poor sleep (PS), shorter sleep (SS), longer sleep (LS), and excellent sleep (ES), and regular rhythm (RR) and disturbed rhythm (DR)

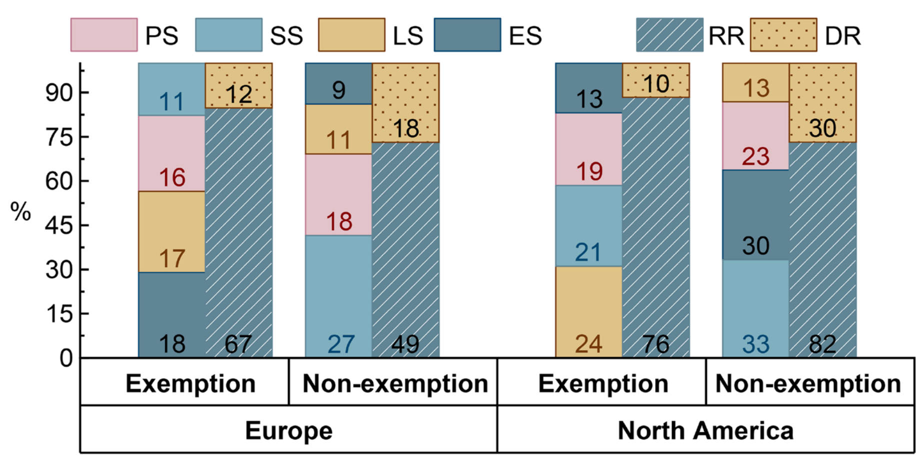

Fig. 7 Sleep and biorhythm after flights to different destinations for exempt and non-exempt flights. Note: poor sleep (PS), shorter sleep (SS), longer sleep (LS), and excellent sleep (ES), and regular rhythm (RR) and disturbed rhythm (DR)

Sleep and biorhythm vary by flight frequency, which is more pronounced on exempt flights than on non-exempt flights. Although most pilots' biorhythm and sleep were in ideal conditions during international flights, excellent sleep and better rhythm tended to occur simultaneously, while the probability of having shorter sleep (PS and SS) was higher on a day when DR occurred, verifying H3. The in-flight biorhythm of pilots is more susceptible to disruption on long shifts. Specifically, pilots are more prone to inefficient sleep on departure days, whereas sleep on return trips tended to be more efficient but shorter. After long-haul and ultra-long-haul flights, pilots' sleep duration returned to preflight levels within 1 to 2 days, which is consistent with the findings of an earlier study [30–32]. However, our findings on sleep quality during rest periods were mixed, with some pilots having high-quality sleep and others exhibiting inefficient sleep.

This mixed finding may be due to individual differences, which could also apply to the current sample of pilots. The 80 male pilots in this study had ages ranging from 28 to 46 years (mean ± standard deviation: 35 ± 5.5 years) and flight experience ranging from 140 to 900 flight hours. Although the pilots were not specifically categorized based on mental toughness or self-perceived exercise exertion, the diversity in flight experience and activity levels could introduce variability in sleep quality and subjective sleep experiences. For example, pilots with greater mental toughness may demonstrate higher sleep efficiency (SE) and better sleep outcomes, such as deeper sleep and fewer awakenings, as suggested in previous studies [33]. Similarly, the level of physical activity or exertion before bedtime might influence sleep patterns, potentially contributing to the variability observed in this sample, though this was not explicitly measured [34]. Further research focusing on these individual factors could clarify their impact on sleep and recovery among pilots.

Key factors affecting sleep and biorhythm on flying days

Preflight status, departure time, and route

Preflight status affects sleep and biorhythm during the journey. We found that better sleep and a more stable rhythm before the flight ensure that pilots are well rested during the flight. We also found a relationship between sleep duration and the start time of work, with pilots who departed during the WOCL and early morning having shorter sleep, in line with the findings of [35]. Moreover, starting work in the evening led to lower SE for pilots on that day. For departures from 0:00 to 5:59, pilots had insufficient TST but satisfactory SE, while flights departing in the evening protected the length of sleep but reduced SE by forcing pilots to catch up on sleep during the day, which is contrary to one's original circadian rhythm. Hence, starting work at unusually early or late times adds to the fatigue experienced by pilots due to lost sleep time, supporting H1 [36, 37]. Daytime departures offer better sleep for pilots, with afternoon departures marginally better than morning departures. Rhythm disorders are more likely to occur on flights departing between 0:00 and 11:59, possibly because the degree of rhythm disruption caused by work and preflight preparation is at odds with the local circadian rhythm. However, Fig. 5d also shows a higher prevalence of DR in flights departing during the daytime (6:00–17:59). This can be attributed to the fact that pilots operating morning flights often need to wake up earlier than usual (e.g., 3:00–4:00) to complete preflight preparations, such as briefings and safety checks, which disrupts their sleep–wake cycle and exacerbates circadian misalignment [38, 39]. Additionally, daytime flights may coincide with the body's natural circadian dip in alertness during the early afternoon, further contributing to rhythm disturbances [40]. These findings highlight that both nighttime and daytime departures can impact pilots' biorhythms, albeit through different mechanisms.

This study also found that east–west flights had a more negative impact on sleep, whereas pilots on north–south routes were generally better rested. Rhythm disturbances were significantly more frequent on east–west flights, supporting H2. Although some differences emerged between eastward and westward travel—such as longer sleep durations after eastward flights compared to westward ones—both directions led to greater circadian disruption than north–south routes. This aligns with previous research indicating that jet lag is primarily influenced by the number of time zones crossed, which is more typical in east–west travel. The severity of jet lag symptoms depends on the route (east or west) and number of time zones crossed [41]. We found that pilots on westward flights slept for shorter periods, consistent with previous studies showing that pilots tend to nap and sleep longer after eastward travel across multiple time zones [42]. However, one study found that for each additional hour of flight time, pilots slept an average of 12.3 min more [43]. This discrepancy may be attributed to variations in crew size under the exemption policy, which affects pilots' work and rest schedules. On the north–south route, TST was shorter when flying north, but the south flights in this study were all departures on the China–Oceania route and were exempt flights (the north flights were all the return trips), which may have been influenced by crews' shift schedules and hampered comparisons of the north–south route.

Flight frequencies under the exemption and quarantine policies

The outcomes of the study did not support H4 on pilots' sleep and biorhythm at different flight frequencies. Sleep and biorhythm on the first flight were poor, probably because of the pilots' daily routine and mood during the quarantine period, which support H5. The first flight post-quarantine was associated with the highest level of rhythm disturbance, likely due to pilots' disrupted biological clocks, reduced social interaction, and the psychological impact of isolation. People in quarantine usually have increased loneliness, a restriction of liberty, and a fear of infection [20], which are associated with an increased risk of mental health issues [21]. As intercontinental pilots experienced multiple quarantines during the COVID-19 pandemic, their mental health could be a concern in the short term. However, as pilots may have regular napping habits to improve alertness and cognitive performance, this may protect them against a depressed mood during the isolation period [41]. Therefore, rhythm may be disturbed on first flights, notably during afternoon departures. On second flights, we found that pilots had lower SE, while on third and fourth flights, pilots whose flights departed at night were more vulnerable to the negative effects of an increased flight frequency. In summary, on multiple round trips, pilots may have higher or lower SE. Therefore, the real-time control of pilot fatigue must inform schedulers to reduce the associated safety risks.

Factors affecting postflight sleep and biorhythm under the exemption policy

We found that the biorhythm of pilots on non-exempt flights with layovers in vastly different time zones was more easily disrupted than those on exempt flights. Individuals' biorhythm and the local time are closely aligned during overnight layovers, with layover sleep being 105 min shorter on average than preflight sleep [32, 44]. In contrast, exempt flights, which operate with expanded crews and reduced layover times, resulted in shorter but more efficient sleep, stabilizing pilots' circadian rhythms. This stabilization not only safeguards pilots' health but also provides a new perspective for managing intercontinental routes post-pandemic and during future public health emergencies.

Furthermore, the degree of rhythm disturbance at the end of non-exempt flights was higher than that for exempt flights, particularly on east–west routes (e.g., China–North America). Crew members often remain aligned with the circadian rhythm of their origin when they first arrive at their destination [45]. For example, pilots on China–North America flights were in the WOCL during Vancouver's daytime hours (11:00–14:00) and London's nighttime hours (22:00–1:00), leading to more severe disruptions. This supports H1 and H2, as rhythm disruption was more pronounced during WOCL operations and on east–west flights compared to other directions.

Pilots tended to rest longer after exempt flights, while sleep efficiency (SE) was suboptimal with longer postflight sleep after North American trips. Long eastward exempt flights may result in sleep deprivation, necessitating extended postflight recovery. After flying east through six or more time zones, the biological clock may adapt by shifting in the opposite direction, slowing adaptation [46]. These findings highlight the compounded effects of quarantine-related stress, isolation, and rapid time zone changes on sleep and rhythm disturbances. This directly supports H5, indicating that isolation and pandemic-related stressors contributed to pilots' disrupted rhythms and reduced sleep quality.

Multiple intercontinental flights also exacerbate the adverse effects on sleep and biorhythm during rest periods and in the postflight period, possibly due to the challenge of adapting to intercontinental flights across many time zones after prolonged periods of isolation (14 days or more). Hence, this results in suboptimal SE between the first and second rest periods. Indeed, we found that SE was distinctly higher for most pilots between the second and third rest periods but lower between the third and fourth rest periods, with some pilots experiencing sleep disturbances, possibly due to the effects of jet lag. These patterns support H4, showing that rhythm and sleep disturbances increased with more frequent exempt flights.

There was also the polarization of SE due to differences in individuals' ability to adjust. Previous research has confirmed that "early bird" travelers are more suited to take westward trips, whereas eastward trips are more suitable for "night-owls" [47]. After two flights, we found that pilots' sleep duration increased; further, after three or four round trips, the proportion of SE rose, which may have been due to the increase in flight frequency exacerbating pilots' fatigue. DR was also more likely to occur after multiple flights and the degree of rhythm disturbance was higher during the breaks between two journeys. Adequate rest after a flight can help pilots' rhythm recovery. These results reinforce H4 and H3, suggesting that the cumulative burden of multiple flights leads to circadian misalignment, which subsequently impairs sleep quality.

Limitations and future research

First, this study did not compare the individual differences of pilots. Although existing studies indicate that gender, age, and position do not have an effect on sleep quality during flights [42], pilots' social relationships and family members' status may have impacted their emotions and motivation [48]. Second, the only flights operating on the north–south route were China–Oceania, which were all exempt flights. Therefore, the results might be less objective for north–south flights. Third, exempt flights may employ six to eight pilots and scheduling and range differences influence the amount of rest time each may receive on board, but these factors were not incorporated into this study. Finally, multi-modal fatigue measurement methods were not used due to the limited space of the cockpit, making it difficult to identify short naps. Future studies could combine pilots' inherent characteristics such as personality and sleep type with their sleep and circadian rhythm during exempt flights to improve the analysis of each influencing factor and provide more accurate data to improve the exemption policy.

Conclusions

The results of this study provide evidence that exempt flights help pilots avoid jet lag to a certain extent. Jet lag and departure time had an impact on the stability of pilots' biorhythm, especially on east–west trips, when stopping at layovers with large time zone differences, and when starting work during the WOCL. Simultaneously, pilots' sleep on exempt flights was more optimal than that on non-exempt flights, which supports the need to manage fatigue on exempt flights. These findings suggest that more attention should be paid to sleep and rest conditions on east–west routes than on north–south routes and that exemption and other route-related policies should be refined to guarantee that pilots have sufficient time to recover. Further, the adverse impact of quarantine on the physical and mental health of pilots warrants urgent attention, especially their adjustment before the first flight and after multiple journeys. Simultaneously, good rest before a flight can better guarantee the sleep and biorhythm of the pilot on board.

Abbreviations

SE	Sleep efficiency
TST	Total sleep time
WASO	Wake after sleep onset
NOA	Number of awakenings
AAL	Average awakening length
IS	Interdaily stability
IV	Intradaily variability
PS	Poor sleep
SS	Shorter sleep
LS	Longer sleep
ES	Excellent sleep
RR	Regular rhythm
DR	Disturbed rhythm

Glossary

Biorhythm	A periodic rhythm of physiological activities that determines the cycle for humans to function.
WOCL	The window of circadian low of the human body between 3 and 6 a.m., when sleepiness is the most obvious.
Exemption	A policy that exempts flight crew from mandatory layover and flight times during the COVID-19.
SE	Sleep Efficiency is overall sleep efficiency; SE below 85% indicates poor sleep quality.
TST	Total sleep time is the cumulative number of minutes of sleep per day.
WASO	Wake after sleep onset is the duration of wakefulness after initially falling asleep.
NOA	Number of awakenings is the number of brief awakenings after sleeping at night.
AAL	Average awakening length is the average length of each awakening after going to sleep.
IS	Interdaily stability is used to measure the stability of activity within a day, based on the mean and overall variability.
IV	Intradaily variability is used to evaluate rhythm fragmentation and based on hourly activity values, measuring differences in diurnal activity.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-23061-z.

Supplementary Material 1.

Acknowledgements
The authors thank all the pilots who participated in data collection.

Authors' contributions
Yanru Zhou participated in experimental design, organizing the experiments, and was a major contributor in writing the manuscript, who also analyzed data. Jingqiang Li conducted overall planning of research, designing the experiment, and modified this paper. Huanxi Zhang participated in experimental design, and revising the English vision of manuscript, and analyzed data. Xining Zhang performed the experiment organization and data analysis. All authors read and approved the final manuscript.

Funding
This study was supported by the National Natural Science Foundation of China (U1933122) and the Civil Aviation Safety Capacity Building Foundation of the Civil Aviation Administration of China (grant number ASSA2023/20).

Data availability
The datasets generated and analyzed during the current study are not publicly available due to the confidentiality principle of private information of participants. However, they are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study protocol was approved by the Ethical Committee of Research Institute of Civil Aviation Safety, Tianjin, China. Given that the present study participants only wore a body movement recorder on the wrist, it does not elicit adverse physiological and psychological reactions from the participants. Informed Consent was waived by an Institutional Review Board of Informed Consent was waived by an Institutional Review Board of the Ethical Committee of Research Institute of Civil Aviation Safety.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 11 January 2024 Accepted: 6 May 2025
Published online: 22 May 2025

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