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Research article

Study on the development process of apron controller's work fatigue based on heart rate characteristics

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ABSTRACT

In order to study the fatigue development and change pattern of apron controllers in the process of each work, experiments were carried out at Beijing Daxing International Airport, and the physiological data of personnel were collected by smart band senselessly. The incremental relationship between heart rate characteristics and personnel reaction time before and after work was compared and analyzed; the change in duty time, workload and heart rate of controllers were studied quantitatively, and the regulatory role of the body and fatigue changes were analyzed, then the pattern of heart rate changes with fatigue development was found. The results of the study showed that the heart rate characteristics were related to the workload of the controllers, correlated with the change pattern of personnel reaction time characteristics. The p-values are less than 0.05. So the fatigue state of personnel could be objectively characterized by heart rate. The heart rate of apron controllers showed a jittering decreasing trend during 3 h of work, and its distribution showed obvious banded dense areas. The relative heart rate gradually decreases from 0.6 to about 0.2. The 95% confidence intervals for time of the occurrence of minimal values of heart rate during the first 2 h and the last 1 h of work time were statistically estimated as [57.38,81.42] and [143.79,155.45] respectively, and further calculated the corresponding confidence intervals for number of flights, which are the possible fatigue severity intervals. The study can provide valuable references for controller shift management and personnel status monitoring timing during daily work.

1. Introduction

The work of apron controllers mainly revolves around the whole process of aircraft operation within the active area of the airport. Compared with other types of control work, although they do not need to withstand the work pressure of serious accidents such as air conflicts, their work is more complicated and they need to coordinate more matters, and these exhausting tasks more likely lower their alertness due to the distraction of information interchange, which in turn causes aircraft taxiing conflicts and large delays at the airport, and fatigue, as an important part of aviation human factors, is one of the most common factors causing human errors in the work of controllers. Human factors is not a separate part of the production, but has to be integrated into various organization and safety management system actions [1]. Approaches for managing controller fatigue vary, from prescriptive hours-of-work regulations (for example in the UK), to an enterprise bargaining agreement between the service provider and the union (Australia) [2]. Air traffic

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control is a stressful job, and that complaints regarding excess work stress should be taken seriously. A short time of relaxation after ardent stress during work hours is conducive to reduce the stress level and physiological responses. The effect of status the number of aircraft handled and the effect of age on fatigue was significant [3]. A proposal for a hybrid approach between the prescriptive and non-prescriptive systems is presented for the regulation of fatigue [4]. In complex work environments, changes in mental workload plays a critical role in human performance [5]. The profession is cognitively demanding and stressful and, consequently, training difficulty is related to job difficulty [6]. Therefore, to ensure safe and efficient apron operations, the fatigue status needs to be monitored scientifically and reasonably.

Fatigue is mainly divided into mental fatigue and exercise fatigue. For apron controllers, it is mainly the mental fatigue generated by the brain in the generation of control command scheme, followed by the exercise fatigue generated by the operation of radiotelephony communication and ATC automation system. Mental fatigue led attention failure is associated with accidents causing injuries and fatalities [7]. There are many reasons for fatigue, such as work pressure, work load, etc. Work shift is also an important factor in generating fatigue. The typical shift system for controllers, for example, is divided into morning shift (06:00–13:00), day shift (08:00–18:30), evening shift (15:00–23:00) and night shift (19:45–06:00). Working shifts and irregular hours were stated as contributors to sleepiness and fatigue [8]. ATCOs' work period and work shifts have an effect on work fatigue through their workload [9]. While ATCOs reported a shorter sleep duration prior the morning shift compared to the other shifts, they indicated decreased sleep satisfaction and alertness and increased on-job fatigue prior both morning and night shifts compared to evening shifts [10]. So the main problem with day shifts is unbalanced work hours in the morning and afternoon, causing high fatigue with some specific shift types. The problem of night shifts is mainly related to people's circadian body clock, and air traffic controllers' sleeping time and hours are the most important factors that influence their fatigue levels [11]. The rise in fatigue was greater among working night shifts compared to day shifts, which could place them at greater risk for fatigue-related consequences [12].

There are many ways to manage fatigue, such as workload management, work time adjustment, etc. The workload of job stressors had the most effect on turnover tendency [13], Existing strategies to manage human fatigue in transportation are primarily by undertaking prescriptive "hours-of-work" regulations. However, these regulations lack certain flexibility and fail to consider dynamic fatigue-inducing factors in the context. A context-aware machine learning approach is proposed to reduce the risk of human fatigue by providing appropriate work arrangements for a particular group of people at a specific time [14]. Bio-mathematical models of fatigue attempt to predict the effects of different working patterns on subsequent job performance, reflecting scientific data concerning the relationships among work hours, sleep and performance [15]. There are also many ways to relieve fatigue. Emotional stability mobilizes body functions for the successful performance of a particular activity [16]. There was a significant decrease in work stress after being given relaxation therapy [17]. Self efficacy mediated the effect of perceived stress on occupational burnout syndrome [18]. The shift mechanism of control work leads to the contradiction that controllers have to adapt to maintain high alertness at different times or master methods to alleviate fatigue, while human physiology determines that human beings tend to be distracted when they do not have a normal rest and relaxation routine. This contradiction leads to fatigue being inevitable.

Summarizing the existing research results, it is found that the following two problems need further research: First, for the extraction of physiological parameters of controllers, mainly for auxiliary equipment such as oculomotor, EEG. The presence of fatigue can be detected by analysing speech utterances [19], Heart rate variability (HRV) is a physiological marker of interest for detecting driver fatigue that can be measured during real life driving [20]. The HRV spectrum analysis gives a direct relationship between fatigue and the HRV [21]. Although the data obtained from the test are very accurate, these devices will have a certain psychological burden and influence on the controllers' work, so cannot obtain the real working state; secondly, the research on controllers' fatigue state is mostly focused on the fatigue state determination before and after the duty, or the fatigue state trend research of the whole duty cycle, while the research on the fatigue state development characteristics for the single working process is very little.

In this paper, we use smart band to collect controllers' physiological data in response to the above problems. Compared with other devices, the whole data collection process is more senseless, and the quality of the collected data is guaranteed by the device manufacturer and recognized by authoritative testing departments; its advantage is that controllers do not need to have any operation on the device, nor do they need to change any work and life habits. We can not only collect heart rate, sleep and other physiological data of controllers at work and resting time smoothly, but its convenience also allows the experiment to be carried out continuously and monitor personnel status at any time. Moreover, many of the existing methods are not practical in practical testing; We innovated and found the relationship between heart rate and fatigue, working hours and the amount of flights the controller has to handle, so that a simple process can estimate the fatigue status of controllers. Based on this method, in order to provide more scientific support for controller shift resource management and fatigue status monitoring, the paper more microscopically analyzes the fatigue development pattern of apron controllers during the 2–3 h of duty process, highlights the management of this process, and explores the important time periods and flight flow points where fatigue arises.

2. The general properties of apron controllers

Apron control is an important part of air traffic control. Unlike area controllers and approach controllers who are mainly responsible for aircraft air navigation, apron controllers are mainly responsible for directing aircraft driving, taxiing, towing and other activities within the apron area, confirming with the airport tower for release permission or restrictions, and implementing apron aircraft handover; grasping and monitoring the dynamics of aircraft, personnel and vehicles within the apron area. In addition, apron controllers are also responsible for the operation of the airport, timely issuing apron operation instructions to relevant service units, coordinating with ATC units, airlines and field units, and reporting irregularities in apron operation to relevant departments and organizing and directing emergency rescue. Apron control work for about 3 h at a time, usually longer than other controllers. It is therefore easier to observe the development of fatigue.

3. Data sources

Beijing Daxing International Airport opened in 2019, and the airport management organization is independently responsible for apron control work. The apron control module is staffed with a total of 36 personnel, including 30 controllers and 6 back-office duty personnel. The study followed the work of 4 controllers for 1 week, and the following data were collected for the experiment: (1) shift duty, including the duty time and seat division of the controllers on duty; (2) controller's personal heart rate, with the permission of the person concerned, heart rate data were automatically monitored and uploaded to the personal account in real time through the smart band, and the experimenters downloaded it directly on the Internet. The whole process was senseless for the subject controllers; (3) Psychomotor Vigilance Task (PVT) test data before and after work and rest. In many researches, Psychomotor vigilance task testing was used in daytime sleepiness, fatigue analysis [22]. Under the on-site supervision of the experimenters, the controllers were asked to take the test through the computer before and after the work, and the whole process took about 3–5 min, then the data recorded the response time of the controllers at that time, so as to evaluate the fatigue level objectively; (4) the airport approach and departure flight statistics, which were exported through the background of the automation system, according to the seats of the controllers under test corresponding to the volume of flights commanded, so as to evaluate their workload objectively.

A typical controller's heart rate change during work collected by experiment is shown in Fig. 1, and it can be seen that the heart rate range of different controllers varies obviously. Since the heart rate is easily affected by the activity state, the jitter of the center rate during work is larger, but a trend of overall decrease can be found. In order to verify this trend and whether it is related to fatigue and analyze its change pattern, this paper take further analyzes.

4. Experimental procedure

4.1. Relationship between heart rate and PVT

Heart rate is a typical human physiological parameter, and its variation often represents the specific mental state of personnel. In order to analyze the relationship between heart rate and the degree of fatigue of personnel (characterizing the degree of fatigue by PVT values), the experimental data of four controllers before and after each duty during one day of work were counted, as shown in Table 1.

Pearson correlation analysis was performed on the above data respectively, and the values of correlation coefficient R and significance p obtained are shown in Table 2. The p-values are all less than 0.05, indicating that the two sets of data have a strong correlation, then the heart rate can be used to objectively represent the degree of fatigue; the correlation coefficients are all less than -0.8, indicating that the heart rate is inversely proportional to the PVT, i.e., the significance of the PVT is that the longer the reaction time indicates that the personnel are less alert, while the lower the heart rate at work indicates that the personnel are more fatigued and in a worse mental state.

4.2. Analysis of heart rate variation process

4.2.1. Analysis of time and heart rate variation characteristics

We collected all controllers' test data and counted the distribution of controllers' working hours versus absolute heart rate, including the 25% quantile, 75% quantile, mean and median lines, as shown in Fig. 2(a). The vertical axis represented heart rate of controllers and the horizontal axis represented work time, about 180 min once as usual. The median line is less susceptible to extreme

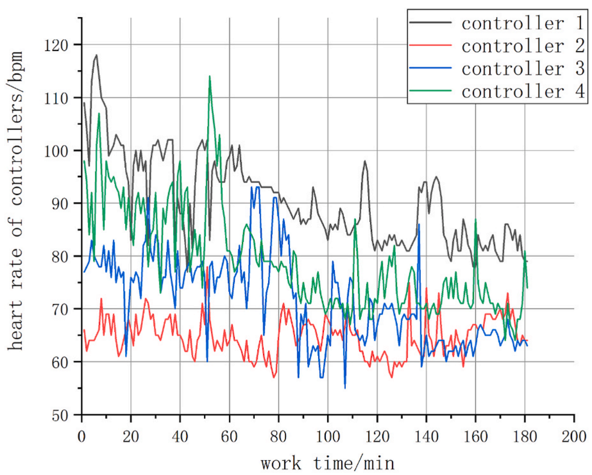


Fig. 1. Heart rate variation during controller work of four different controllers.

Table 1
Heart rate and PVT experimental data.

Time	Controller 1		Controller 2		Controller 3		Controller 4	
	Heart rate(bpm)	PVT	Heart rate(bpm)	PVT	Heart rate(bpm)	PVT	Heart rate(bpm)	PVT
9:30	91	482	98	427	87	339.6	87	426
12:30	91	522	74	552	79	422.5	81	539
15:30	93	436	91	468	85	341.85	77	477
18:30	95	534	82	534	78	480.67	63	545
20:30	92	507	94	501	83	463	65	527
0:00	74	654	78	596	73	645	59	595

Table 2
Correlation analysis between heart rate and PVT.

	Controller 1	Controller 2	Controller 3	Controller 4
R	−0.8483	−0.8857	−0.9165	−0.8182
p	0.0328	0.0188	0.0102	0.0466

numbers and is more practically meaningful, so we use this value as a representative for our analysis. With the increase of working time, the heart rate as a whole shows a jittering downward trend. However, due to the different inherent characteristics of individual physiology, the normal heart rate of a person in a quiet state is distributed between 60 and 100 bpm, which is difficult to determine the severity of fatigue through the absolute value, and it is impossible to compare uniformly. Therefore, in order to minimize the personnel's own differences and discover the distribution pattern of heart rate, we normalized the heart rate data with the following formula:

$$h_i^{'} = \frac{h_i - h_{\min}}{h_{\max} - h_{\min}}$$

Where h_i is the absolute heart rate at time i, $h_{\min}$ and $h_{\max}$ are the minimum and maximum heart rates that occur throughout the work, and $h_i^{'}$ is the calculated relative heart rate.

Then we incorporated the heart rate variation into the specific work process and obtained the heart rate distribution as shown in Fig. 2(b). In contrast to the absolute heart rate variation, the normalized relative heart rate statistics show a more pronounced decreasing trend of heart rate over time. The median line shows a maximum value of 0.629 at min 25 and a minimum value of 0.184 at min 150, which represents a 0.445 decrease in relative heart rate. In the later stages of the work, the upper and lower quartile ranges increase, indicating a greater degree of variability in the data. Controllers at this stage will relieve fatigue and improve their concentration by walking and stretching activities, which in turn leads to a larger range of heart rate distribution.

The above box plot reflects the overall time series of heart rate development changes, but does not reflect the specific those heart rates appearing with higher probability. Therefore, we analyzed the density of the heart rate distribution from the perspective of the data itself, for the unknown distribution of random variables, using the method of kernel density estimation, where the kernel function

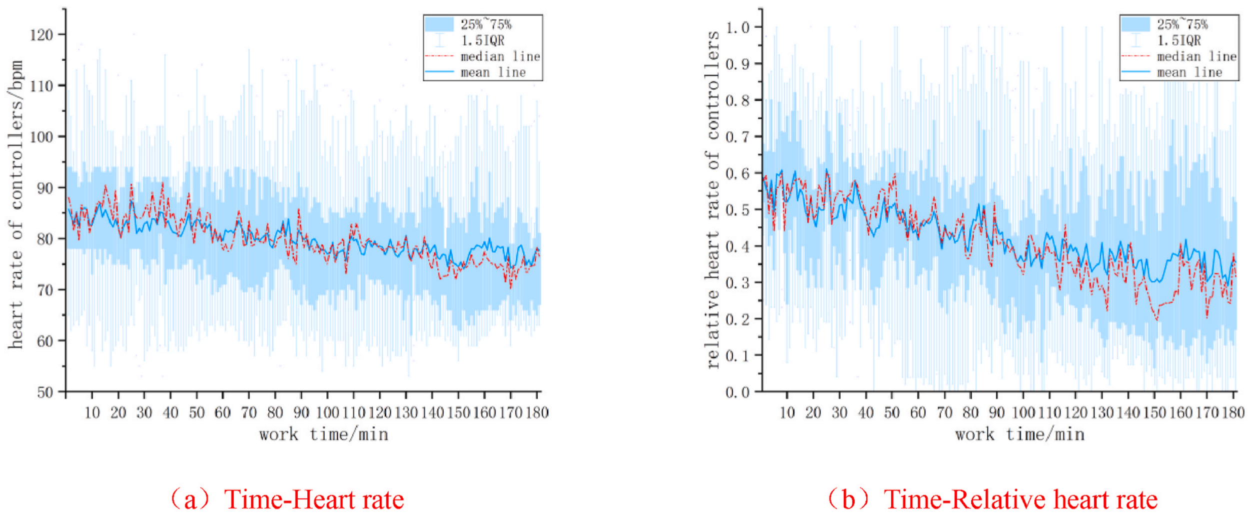


Fig. 2. Variation process of Time-Heart rate and Time-Relative heart rate.

is Gaussian, as shown in Figs. 3 and 4. The left panel shows the scatter plot distribution, and the right panel shows the corresponding contour plot.

The absolute heart rate is mainly concentrated in the interval of 80–90, and the data are more scattered and the trend of change is not obvious due to the difference of human physiological characteristics, as shown in Fig. 3 (a) and (b). In addition, after transforming into relative heart rate, we can see from the scatter plot that the data are more concentrated, as shown in Fig. 4 (a). While from the contour plot, we can find that the heart rate gradually decreases from 0.6 to about 0.2, showing an obvious band-like dense area, as shown in Fig. 4 (b). Therefore, we can assume that this density distribution reveals the development trend of human fatigue. The heart rate under this envelope represents most of the patterns and can provides a reference for applications such as personnel status monitoring.

4.2.2. *Analysis of number of flights and heart rate variation characteristics*

We performed a statistical analysis of the changes in number of flights and heart rate, using the same normalization process, and obtained the heart rate distribution graph shown in Fig. 5. Variation process of Number of flights-Heart rate and Number of flights-Relative heart rate have similar trends, as shown in Fig. 5 (a) and (b). The number of flights means the number of total flights that a controller has to handle. It was obtained by combining control sector with flight plans. With the increase of the number of flights, the heart rate shows a clear decreasing trend. However, in the final stage of the work, the heart rate would suddenly rise back up. After investigation, there are two reasons: one is caused by the physical activity of controllers, because of the large volume of flights, controllers at this time feel tired obviously and need to relieve fatigue by moving their bodies; the second is that such samples are small, usually the number of 3-h flights is less than 110, so it causes a large deviation of data while being influenced by the sample.

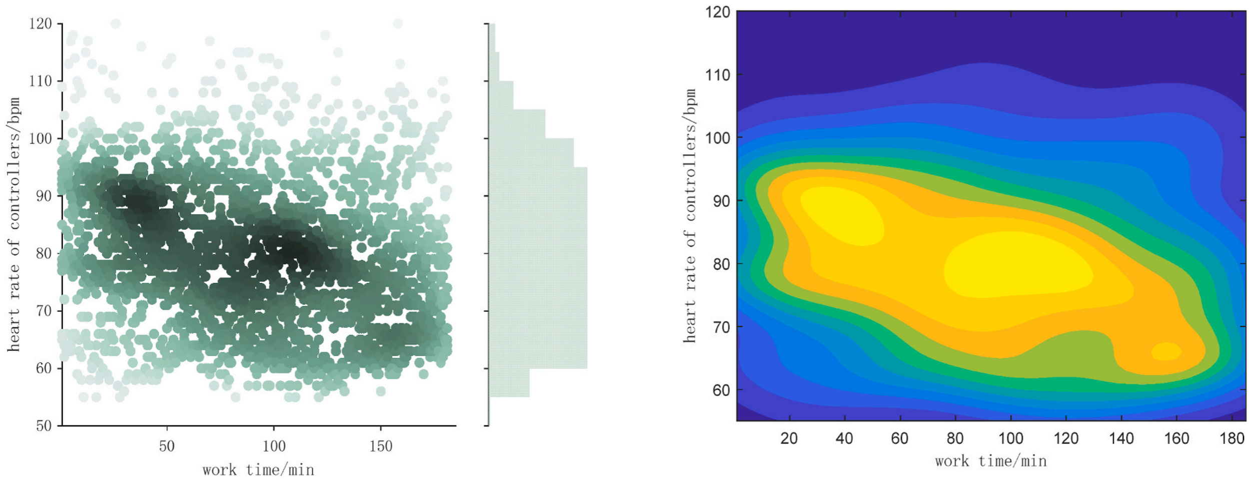
We analyzed the number of flights and heart rate density distribution, and the results are shown in Figs. 6 and 7. In terms of absolute heart rate, it is mainly concentrated in 70–80 bpm, the data distribution was more scattered and formed multiple distribution centers, no obvious pattern was found, as shown in Fig. 6 (a) and (b). From the viewpoint of relative heart rate, the data distribution was obviously more concentrated, only one obvious density center existed in the range of 30–50 flight sorties, and the subsequent formation of an obvious band descending intensive area, as shown in Fig. 7 (a) and (b).

4.2.3. *Characteristics of the minimum heart rate distribution*

In many cases, we were unable to monitor the physiological state of the controllers, including heart rate, in real time, so we tried to use other data for monitoring. The goal is to determine if a controller is fatigued solely by the number of hours worked or the number of flights without monitoring equipment.

Apron controllers generally work for 3 h at a time, while other types of controllers generally work for only 2 h at a time, so we divided the working time into two stages, 0–120 min and 121–180 min, and calculated the distribution intervals for the time and number of flights corresponding to the minimum heart rate, respectively. The aim is to reflect the general status change characteristics of all types of controllers and to reflect the status change characteristics unique to apron controllers. Since the amount of data was relatively small and the standard deviation was unknown, the t-distribution was used for estimation, and the results obtained are shown in Table 3.

We can focus on monitoring the controllers' working status during the two time periods of [57.38,81.42], [143.79,155.45]. During these two working hours, statistics found that the heart rate of the controllers was relatively lowest, i.e. it was the easiest to reach the fatigue state. We can remind the controllers when they are about to enter these two periods, carry out simple physical activities, or have the controllers in the monitoring seat to assist in the command, so that they can get through the fatigue period smoothly.



(a) scatter plot (b) contour plot

Fig. 3. Time and heart rate density distribution by scatter plot and contour plot.

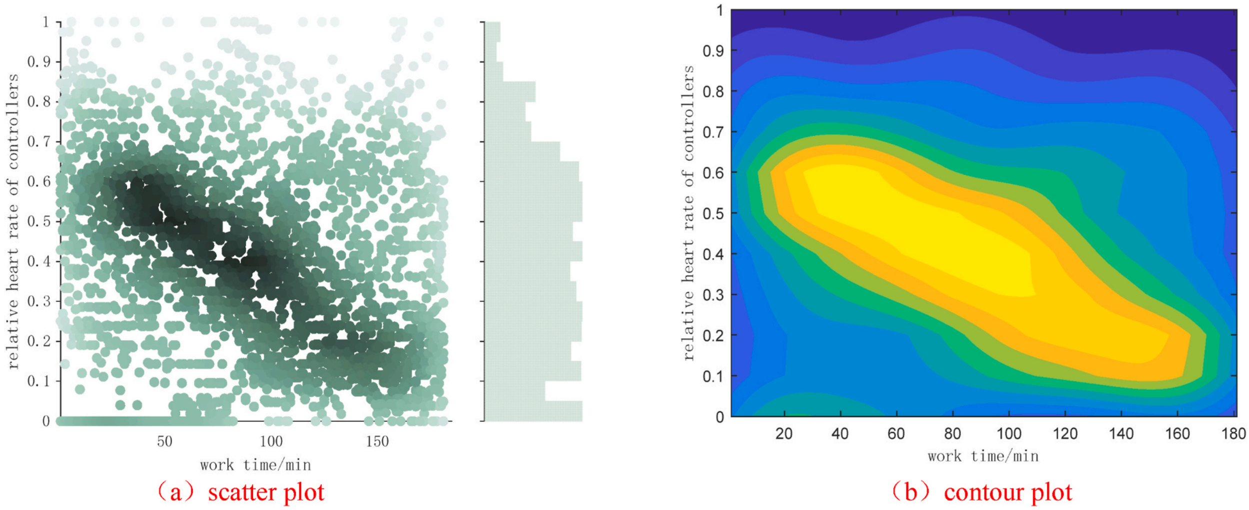


Fig. 4. Time and relative heart rate density distribution by scatter plot and contour plot.

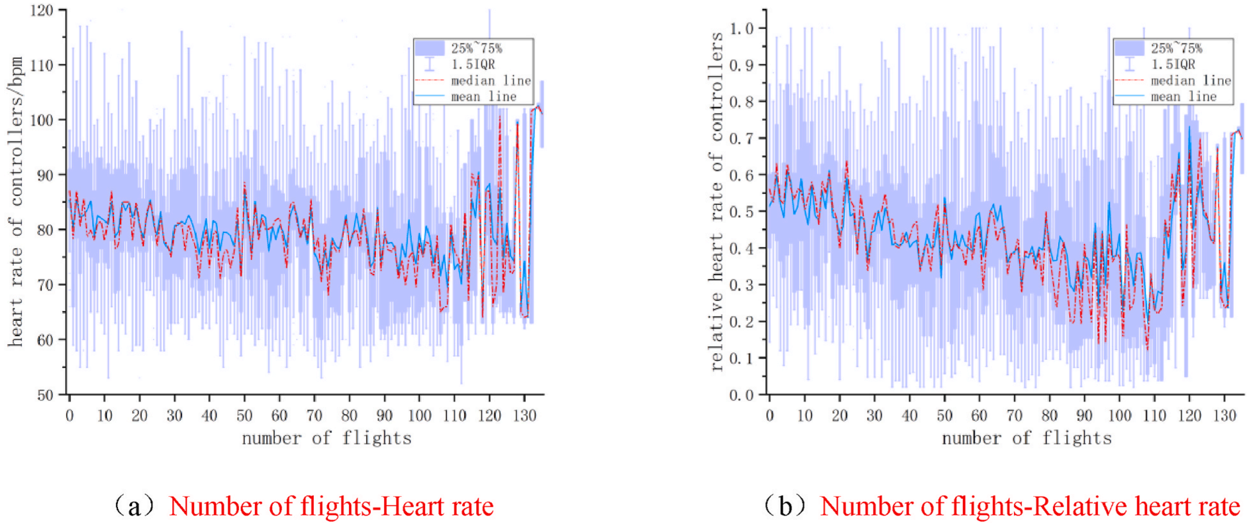


Fig. 5. Variation process of Number of flights-Heart rate and Number of flights-Relative heart rate.

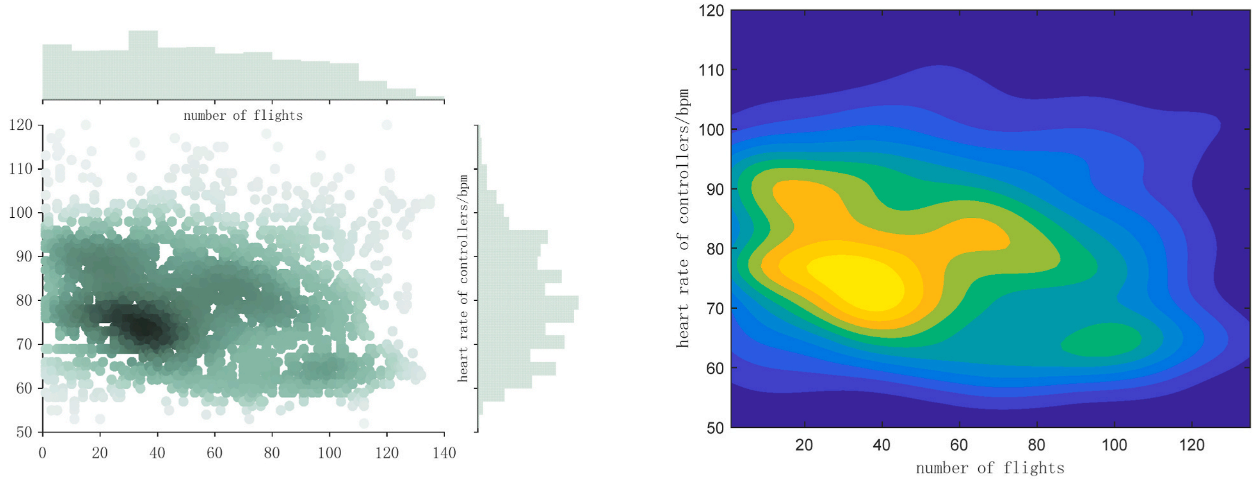
Moreover we also can focus on monitoring the controllers' working status when the total number of flights reaches [35,50], [86,101]. The flight plan information can be used to roughly predict the amount of flights to be commanded during the controller's shift, and then alert the controller accordingly before these two values are reached.

According test in Beijing Daxing International Airport, fatigue management of controllers is more practicable with this methodology.

5. Discussion and conclusions

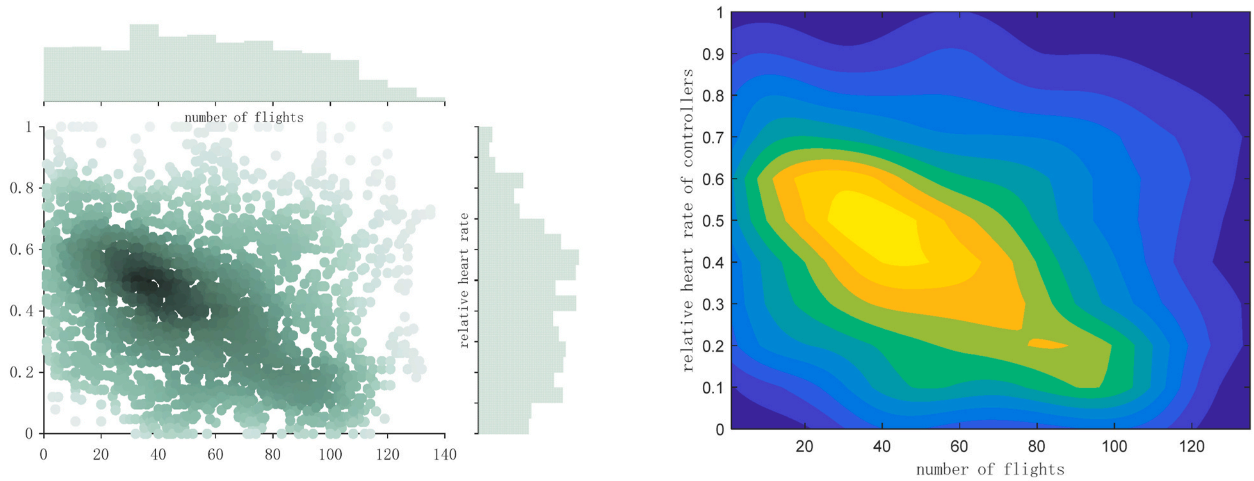
Heart rate can reflect the controller's fatigue state, with a strong correlation, with the increase of work fatigue, the controller's heart rate gradually decreases. By heart rate monitoring and analysis, the fatigue change pattern in the process of control work was found, with the increase of working time and command number of flights, the heart rate showed a jittering decreasing trend, and its density distribution showed an obvious band area. In order to practice, comparing with other types of control work, the apron control was divided into two stages of 0–120 min and 121–180 min, and the 95% confidence interval of the minimum heart rate and the corresponding number of flights were calculated respectively, can be used to detect controller fatigue.

The results of the study are helpful for the team management and personnel status monitoring in the process of control work. Firstly, the team composition can be coordinated to form complementary advantages according to the different physiological functional characteristics of individual controllers. Secondly, the heart rate of controllers can be detected in real time to detect if it is within



（a） scatter plot （b） contour plot

Fig. 6. Number of flights and heart rate density distribution by scatter plot and contour plot.



（a） scatter plot （b） contour plot

Fig. 7. Number of flights and relative heart rate density distribution by scatter plot and contour plot.

Table 3
95% confidence interval for time and accumulated number of flights to minimum heart rate.

	0–120 min	121–180 min	Accumulated number of flights in 0–120 min range	Accumulated number of flights in 121–180 min range
Lower confidence limit	57.38	143.79	35	86
Upper confidence limit	81.42	155.45	50	101

the normal envelope, and for abnormal conditions, immediate judgment should be made and management measures should be taken in time, such as special reminders or assist in commanding by the controller of the monitoring seat.

Furthermore, it is found that heart rate is a weak parameter, and the characteristic changes are obvious under normal continuous work. However, it is easily affected by external influences shortly, such as the physical activities of controllers. Overall, its change pattern can be followed in long time, and the overall development trend is unchanged for a single work process.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

He Sun: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing, Software. **Aiping Jia:** Data curation, Investigation, Project administration, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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