Objective and Subjective Workload of Remote and Physical Tower Controllers

Haiming Shen; Zhixuan An; Tingting Lu; Yanqing Wang; Wen-Chin Li

INTRODUCTION: The remote tower system is a new mode of air traffic control operation that solves many prominent problems in civil aviation operations. The most important concern is the safety of the remote tower. Therefore, to effectively evaluate the safety of remote tower system operations, this paper discusses and analyzes the workload of controllers in remote towers from the perspective of human factors.

METHODS: Front-line controllers were selected as subjects to conduct control command under two control modes, traditional physical and remote tower. Heart rate variability and NASA-Task Load Index data were obtained from controllers and analyzed.

RESULTS: The results showed that there were no significant differences in standard deviation of NN intervals (SDNN), root mean square of successive differences (RMSSD) between adjacent NN intervals, percentage of successive RR intervals that differ by more than 50 ms (PNN50) indexes, and NASA-Task Load Index data between the two control modes. The SDNN index had a significant positive correlation with the RMSSD index. There was a significant positive correlation between the SDNN index and the PNN50 index. The RMSSD index was positively correlated with the PNN50 index.

DISCUSSION: Compared with traditional physical tower control, controllers in this study had no extra workload increase when carrying out remote tower control. Based on the analysis of objective heart rate variability indexes and subjective workload estimates of controllers in this study, it can be preliminarily judged that the operational safety of remote towers appears to be comparable to that of traditional physical towers.

KEYWORDS: remote tower, air traffic controller, workload, heart rate variability.

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As an important infrastructure within the scope of the airport, the air traffic control tower provides the center of operations for airport flight activities. Compared with other types of air traffic facilities, the tower is mainly responsible for the take-off and landing of aircraft. Flights directed by air traffic controllers in the tower include commercial flights, general aviation, training flights, and so on. The primary role of air traffic controllers is to ensure the safety, order, and efficiency of air traffic within the airport's airspace; provide instructions to pilots regarding takeoffs, landings, taxiing and other ground movements; monitor aircraft separation; and issue clearances to prevent collisions.

At present, the existing control modes include traditional physical tower control and remote tower control. The traditional physical control tower is usually located at the highest point of an airport, and the design of the tower often includes one or more 360-degree panoramic windows to provide controllers with a broad view of how aircraft are traveling on an airport. The remote tower is a collection of facilities and equipment whose geographical location and height are not limited by the location and configuration of the airport. Controllers working at remote towers examine information obtained remotely and displayed on monitors instead of conducting on-site visual observation. They use this information to perform the same

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airport control services (some airports include approach control services) or apron control services for aircraft.[1,2] The remote tower mainly uses sensors such as cameras and image-processing technology[3] and solves different problems existing in different types of airports, such as the blind field of vision problem existing in the ramp control of some large airports, the poor natural environment of remote regional airports, the difficulty in recruiting and retaining controllers to work in certain locations, and the dispersion of traffic of navigable airports.

The remote tower control mode, which is different from the traditional physical tower control mode, is a new control mode. The main differences between the two common control models can be summarized in the following two points.

1. Workplace: Remote tower controllers work in control centers far from the airport, often facing multiple screens showing live video and data. Traditional physical tower controllers work in the tower building within the airport and have a direct visual view of the airport.
2. Technical aspects: Remote tower control relies on communications, networking, video surveillance, and data integration technologies. Traditional physical tower control, while also using technical equipment, relies more on the visual observation of the controllers.

To sum up, the change of the control mode leads to the change of the working state of the controllers. At present, most studies on workload are about the workload of traditional physical tower controllers and pilots,[4–6] and relatively few studies focus on the workload of remote tower controllers.

Workload includes both the physical workload and the psychological workload of controllers. When either the objective or subjective workload of the controllers is too high or too low, it could lead to the occurrence of unsafe events such as losing contact with a pilot in the air, shortening the air safety interval, or aircraft colliding in the air.[7]

Therefore, in order to ensure that remote tower control meets the high level of expectations of civil aviation authorities, it must maintain a level of safety comparable to that of traditional physical towers. We conducted a study to determine whether a controller controlling traffic from a remote tower was likely to experience higher objective and subjective workload than he/she would when controlling traffic from a physical tower. The authors used two types of workload measurement standards. The first, objective workload, included three physiological heart rate variability (HRV) indexes, and the second, subjective workload, was based on the controllers' subjective ratings of their own workload, as measured by the NASA-TLX (National Aeronautics and Space Administration Task Load Index) scale. These workload measures were used to conduct a preliminary comparative analysis of the workload of controllers under the two different control modes. The results provide information that can be of value in further describing the safety and efficiency of aviation operations.

METHODS

Subjects

Eight controllers from an airport in China participated in this study [mean (M) working years = 3.70, SD = 2.50]. All the subjects had an air traffic control license, had both remote tower and traditional tower qualifications at the same facility, and had normal color vision, or corrected vision, and normal hearing. Before the start of the experiment, all subjects met the requirements of both tower control modes before taking up the post. All subjects participated in this experiment voluntarily and were informed of the specific experimental procedures in advance. Ethics Approval Certificate number is No. CAUC-PSY-2023-008.

Equipment

The Inner Balance device HeartMath-HRV-S5753 and Inner Balance App 3.17.1.1218 (HeartMath, Boulder Creek, CA) were used to collect three HRV data in this experiment, as shown in **Fig. 1**.

The NASA-TLX scale (NASA Ames Research Center, Mountain View, CA) is a multidimensional mental load assessment scale. The scale mainly evaluates subjective workload from six dimensions, namely: mental demand, physical demand, time demand, performance level, effort level, and frustration level.[8]

Procedure

The independent variable in this study is the control mode, namely traditional physical tower and remote tower, as shown in **Fig. 2**. The dependent variables were objective workload, measured by three HRV indexes (SDNN, RMSSD, and PNN50), and subjective workload, measured by the NASA-TLX scale. In addition, we controlled Duty Time by inquiring about schedules and combining the data collection event with the time when the subjects' shift started.

Fig. 1. The Inner Balance device and Inner Balance APP.

Fig. 2. Experimental scene.

The process went as follows:

1. Prepared the experiment and informed the subjects of the purpose of the experiment and the basic use method and precautions of the experimental equipment. Assisted the subjects to wear the Inner Balance device correctly without affecting the working state as much as possible.
2. At the beginning of the data collection for each control mode, subjects carried out normal control and command work and the Inner Balance device automatically recorded ECG data synchronously. After the 40-min control task was complete, recording was stopped.
3. After completing the control task, the subjects were assisted to remove the Inner Balance device. The scoring method of NASA-TLX scale was explained to the subjects, and the subjects were instructed to fill in the scale according to their experience.
4. After completion, the scale was collected and the data collection for this control mode was over.

Statistical Analysis

After the experiment, Kubios HRV Scientific 4.0.1 software (Kubios, Kuopio, Finland) was used to export the experimental HRV data and NASA-TLX scale data were imported into Excel (Microsoft Corporation, Redmond, WA) in order to perform data preprocessing. Then GraphPad Prism 9 (GraphPad Software, San Diego, CA) and IBM SPSS Statistics 27 statistical software (IBM Corporation, Armonk, NY) were used to analyze the experimental data.

RESULTS

Fig. 3 showed the average of various HRV indexes under different control modes. As can be seen from the figure, the mean values of various indexes of controllers in different control modes appear to be somewhat different. The mean value of SDNN in the remote tower control mode appears to be smaller than that in the traditional physical tower control mode, the

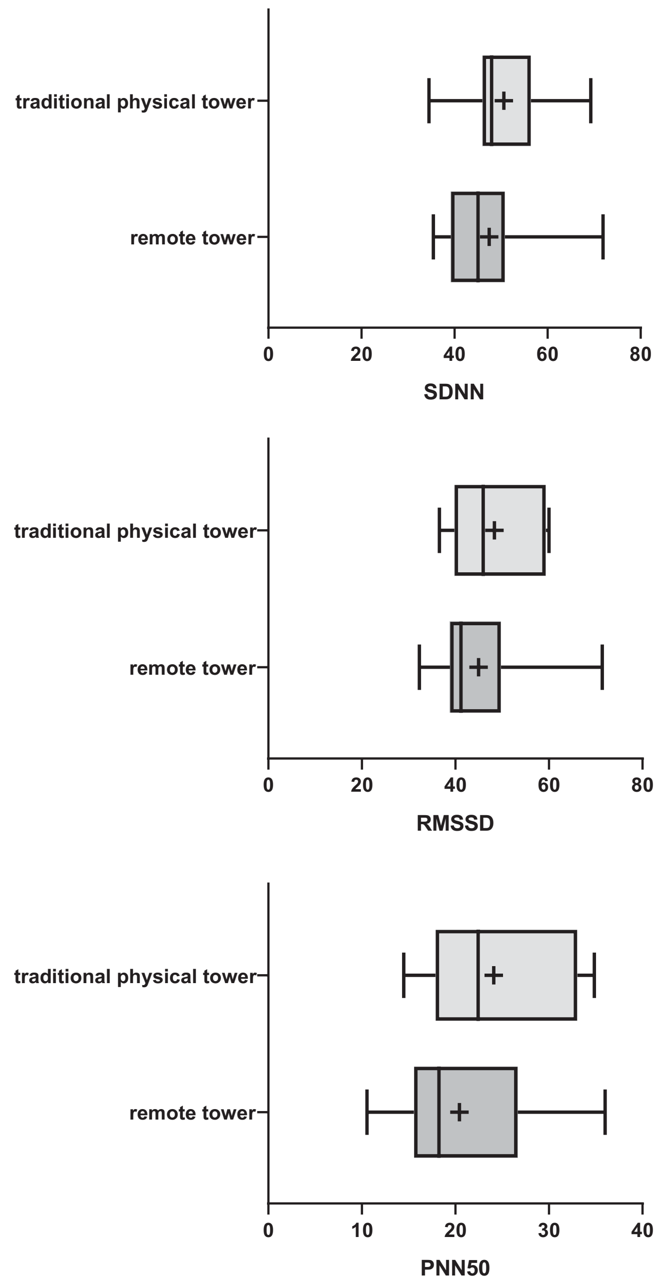

Fig. 3. Comparative analysis of each index under the two control methods.

Table I. Final Results of Paired Sample *t*-Test.

INDEX	*t*	DEGREES OF FREEDOM	*P*
SDNN(R-T)	−0.660	7	0.530
RMSSD(R-T)	−0.699	7	0.507
PNN50(R-T)	−1.167	7	0.281

R stands for remote tower control; T stands for traditional physical tower control.

mean value of RMSSD in the remote tower control mode appears to be smaller than that in the traditional physical tower control mode, and the mean value of PNN50 in the remote tower control mode appears to be smaller than that in the traditional physical tower control mode.

The above chart allows the reader to visually compare the distributions of various HRV indexes under different control modes. However, it is necessary to further determine whether there is a significant difference between the mean value of each index under the two control methods. The paired sample *t*-test was used to analyze the HRV index values under the two control methods. The paired sample *t*-test is a kind of parameter test, which needs to satisfy the premise that the population distribution is normal. In this paper, Shapiro-Wilk test was used to test the normal distribution of the samples. All samples were found to be normally distributed. If the above prerequisite conditions were met, the paired sample *t*-test method could be used for further data analysis. As shown in **Table I**, PSDNN = 0.530, PRMSSD = 0.507, and PPNN50 = 0.281($P > 0.05$), indicating that the probability was very high that there were no significant differences in any of the HRV indexes (SDNN, RMSSD, and PNN50) between remote tower control and traditional tower control.

In addition, we wanted to look at the relationship between the three HRV indexes. To do this, Pearson correlation coefficients were computed. The value of a Pearson correlation coefficient indicates whether there is a linear relationship between two variables. To examine the relationship between the three HRV indexes, three Pearson correlations, one for each of the HRV indexes, were computed. The linear relationship between all three HRV indexes can be seen in **Fig. 4**, which shows plots of the relationships between each pair of the three HRV indexes. All three pairs of indexes appeared to have positive relationships that were highly linear. Analyses were then conducted to determine whether the correlations between each pair of the three indexes were significantly different from 0. As reported in Fig. 4, the correlations were all statistically significant. The SDDN index had a significant positive correlation with the RMSSD index ($r^2 = 0.6478$, $P = 0.0002$). The SDDN index also had a significant positive correlation with the PNN50 index ($r^2 = 0.6689$, $P = 0.0001$). The RMSSD index was also positively and significantly correlated with the PNN50 index ($r^2 = 0.9237$, $P < 0.0001$).

Fig. 5 shows the distribution of the average subjective workload (the arithmetic average of the six individual TLX dimension ratings) under different control modes. As can be seen in Fig. 5, the distributions of average subjective workload appear

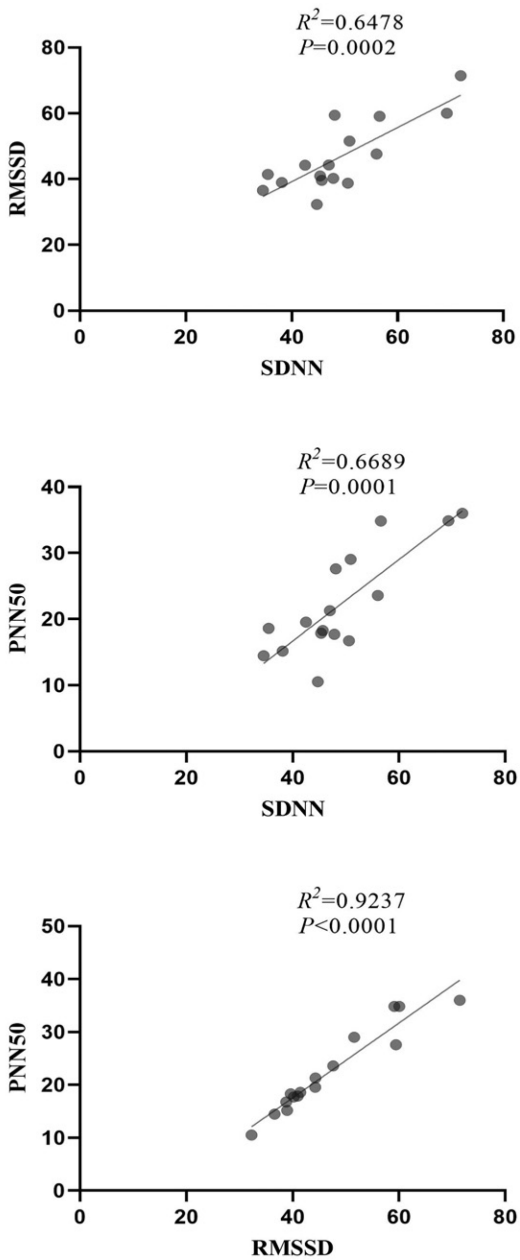

Fig. 4. Correlation analysis between two indexes.

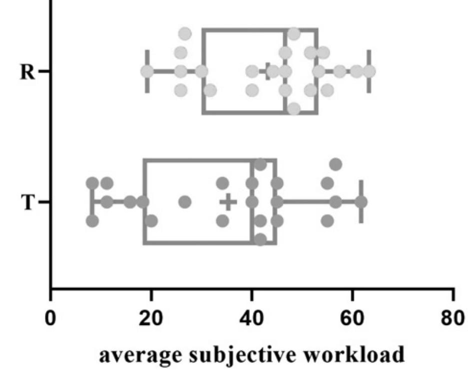

Fig. 5. Distribution of average subjective workload values under two control modes.

Table II. Results of Subjective Workload Analysis Under Two Control Modes.

DIMENSION	x ± s	t	DEGREES OF FREEDOM	P
mental demand(R-T)	−1.154 ± 14.599	−0.285	12	0.781
physical demand(R-T)	−2.308 ± 17.153	−0.485	12	0.636
time demand(R-T)	0.000 ± 16.583	0.000	12	1.000
performance level(R-T)	11.923 ± 37.834	1.136	12	0.278
effort level(R-T)	6.923 ± 17.974	1.389	12	0.190
frustration level(R-T)	9.615 ± 19.839	1.747	12	0.106
average subjective workload(R-T)	4.16846 ± 7.86421	1.911	12	0.080

R stands for remote tower control; T stands for traditional physical tower control.

to be different for the two control modes. The mean value of average total workload in the remote tower mode appears to be greater than in the traditional physical tower mode.

Paired sample *t*-tests were conducted to determine whether the distributions of ratings for all six of the individual NASA-TLX dimensions as well as the average total workload were significantly different for the two control modes. The Shapiro-Wilk normality test was conducted for the six individual NASA-TLX dimension ratings and the average total workload to assess the normality of their distributions. The tests found that the distributions, by mode, of the six NASA-TLX dimension ratings and average total workload were normally distributed and may be used for subsequent analysis. The results of the paired sample *t*-tests for the ratings for the six individual NASA-TLX dimensions and the average subjective workload are shown in **Table II**. As can be seen from Table II, the *P*-values of mental demand, physical demand, time demand, performance level, effort level, frustration level, and average subjective workload were 0.781, 0.636, 1.000, 0.278, 0.190, 0.106, and 0.08, respectively, indicating that the probability was very high that the differences were not statistically significant.

DISCUSSION

This study describes the results of a preliminary experiment. Our initial results suggest that air traffic controllers seem to operate as safely while working in remote towers as they do when working in traditional physical towers. It is true that our study did not identify any important differences in either objective or subjective workload between the two work environments. However, some factors associated with the data collection limited our ability to be confident about that conclusion. For example, not enough controllers were available to participate in the study, which limited our ability to determine whether small differences in reported workload were actually meaningful. That problem could be resolved by conducting a second study of objective and subjective workload in which a larger sample of controllers is able to participate. Another factor that would improve our understanding of how workload affects tower controllers working in different control modes is to collect objective and subjective workload measures under a variety of different conditions which would also require more subjects. These conditions could include time of day, length of shift, different amounts of traffic, different types of flight activities or types of aircraft, different numbers of tower controllers working together (which is often related to amount of traffic), time between first and second data collection, types of activities being performed, etc. Any of those conditions might affect objective or subjective workload experienced by controllers at both types of tower facilities. In addition, as we develop a better understanding of objective and subjective workload measurement in this environment, we can improve the methods used to collect those data. The more we know about factors that affect objective and subjective workload of tower controllers in different types of facilities, the more confident we will be that safety in those environments can be assured.

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