Changes in Heart Rate Variability during Manual Controlled Rendezvous and Docking with Task Complexity

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Abstract. This research aims to study how HRV parameters change with task complexity during manual controlled Rendezvous and Docking (RVD). One one-factor experiment was conducted. The experiment task was manual controlled Rendezvous and Docking (RVD) operation and the factor was task complexity which was divided into three levels. Eight male volunteers participated in this experiment, which consisted of three trials, and each of which consisted of ten operation units containing three complexity levels. The dependent variables were main performance parameters and HRV parameters. Results showed that operation time and fuel consumption changed significantly with different complexity levels. Besides, there were significant differences on partial HRV parameters. It can be inferred that some HRV parameters are useful for mental workload evaluation. However, the relationship between the insignificant parameters and complexity levels needs to be validated and the way how HRV should be used for mental workload evaluation deserves further study.

Keywords: Heart rate variability, Rendezvous and Docking, Task complexity, Mental workload.

1 Introduction

Manual controlled RVD is a task that is full of continuous operations in a dynamic environment. It requires that the astronauts have excellent operation skills and reaction capacity, make a good distribution of attention capacity, keep the eye-hand coordination and ensure the operations on the six degrees of freedom. Owing to these high demands, astronauts used to bear a heavy mental workload when executing the task [1].

In recent years, some research has shown that heart rate variability (HRV) has a remarkable correlation with mental workload in different fields, such as aviation and

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driving. It is a sample, measurable and real-time index to reflect the activity of sympathetic and parasympathetic nervous system and their coordination [2], and it will decrease with the increase of mental workload[3,4,5]. However, HRV still remains to be controversial when measurement is made on workload of different strength and type [6]. The evaluation of mental workload during manual controlled RVD has been studied in the previous work in our laboratory, and skin temperature was found to be a sensitive index [7]. This research aims to study how HRV parameters change with task complexity during manual controlled Rendezvous and Docking (RVD).

2 Method

2.1 Volunteers

Eight male right-handed volunteers, aged between 21 and 26, were recruited for the experiment. They all have bachelor degree or above, some astronautic knowledge backgrounds and no experience in manual controlled RVD operation. In addition, they had passed the psychological and ability tests in the selection link by using DXC-6 Psychological Assessment Instrument (developed by the Fourth Military Medical University, Xi'an, China). These tests included velocity estimate test, rotation test and both-hand coordination ability test. All the requirements above ensured the similarity of astronauts to some extent. The experiment plan had been reviewed by the ethics committee of Astronaut Center of China. Besides, all the volunteers had signed the informed consent.

2.2 Experiment Task and Variable Design

The experiment task was manual RVD operation in which the operators judged the relative position and attitude of the two spacecraft through the monitoring interfaces and then manipulated the chaser spacecraft using the two controllers. This procedure started from the location where two spacecrafts were apart from each other for 140 meters, and continued until they successfully docked or when time limit expired.

One one-factor experiment was designed in this research. The independent variable was task complexity which depended on the deviation of the relative position, attitude, velocity and angle velocity of two spacecrafts. Three complexity levels named as low, middle and high complexity levels were defined in the study according to the engineering requirements of RVD. The less deviation meant that manual RVD had lower task complexity. The dependent variables were main performance parameters and HRV parameters. The two performance parameters were operation time and fuel consumption. The HRV parameters were standard deviation of the RR intervals between normal beats (SDNN), root mean square of successive differences (RMSSD) as time domain features and very low frequency (VLF), low frequency (LF), high frequency (HF), the ratio of LF to HF (LF/HF), normalized LF (LFNU), and normalized HF (HFNU) components as frequency domain features [8].

2.3 Experiment Equipment

The experiment was implemented in the manual controlled RVD simulator, in which the operating data throughout the whole docking procedure was recorded and stored, including the final performance data. The electrocardiography of the volunteers was recorded by a physiological indices recording detector called KF2, which was worn on the chest by every volunteer.

2.4 Experiment Process

Before the start of the experiment, the volunteers were taught the basic knowledge and scientific disciplines of manual RVD techniques. The experiment consisted of three trials, each of which was composed of ten operation units that were classified into three complexity levels. The average time for one trial was about 2 hours, and the time interval between the two adjacent trials was 2-4 days. In order to avoid memory and learning effects for the same unit, the settings of the same complexity level were different in different trials. The volunteers were told to keep in rest state for at least 3 minutes before the operation in each trial.

2.5 Data Analysis

Both the performance and HRV parameters analyzed were the average values of the three trials. The internal for the processing of HRV basic data was 3 minutes. The difference among three complexity levels was analyzed by using one-way ANOVA, while the difference with one other was analyzed by using paired T test. The data processing software was SPSS 16.0, and the level of significance test was set by $p<0.05$.

3 Result

3.1 The Difference of Main Performance Parameters at Different Complexity Levels

Operation time and fuel consumption were chosen as the main performance parameters, and the result of the analysis are shown in Table 1.

Table 1. The effects of complexity level on the main performance parameters ($\bar{x} \pm s, n = 8$)

performance parameters	complexity level		
	low	middle	high
operation time(s)	491.43±35.14	520.23±43.54	567.14±61.48*#
fuel consumption(Kg)	7.32±1.83	8.74±1.33**	10.51±1.85**#

Note: * p<0.05, ** p<0.01, as compared with the low complexity level by using paired T test; # p<0.05, as compared with the middle complexity level by using paired T test.

The result shows that both operation time and fuel consumption increased significantly with the growth of complexity level. The result of ANOVA for operation time and fuel consumption (*p* values were 0.023 and 0.027 respectively) also showed statistically significant effects of complexity level.

3.2 The Difference of HRV Parameters at Different Complexity Levels

The HRV parameters extracted in the rest state before the operation in each trial were analyzed. It was verified that all HRV parameters had no significant difference between different trials, and it can be inferred that each volunteer's physiological status was stable during the experimental period. The effects of complexity level on HRV parameters during the operation is shown in Table 2.

Table 2. The effects of complexity level on HRV parameters ($\bar{x} \pm s, n = 8$)

HRV parameters	complexity level		
	low	middle	high
SDNN(ms)	41.32±18.45	43.81±20.37	47.42±16.39
RMSSD(ms)	28.40±21.37	30.74±20.57	31.49±22.83
VLF(ms^2)	262.47±110.81	255.71±115.32	271.52±109.71
LF(ms^2)	260.32±224.71	275.52±235.88	292.38±242.26*
HF(ms^2)	172.71±143.37	140.51±133.71*	128.42±124.63*
LF/HF	2.40±1.21	3.48±1.75	4.83±2.07*#
LFNU	63.57±12.52	73.72±13.87*	77.36±11.02*
HFNU	38.74±10.94	29.37±12.77*	26.32±11.73*

Note: * p<0.05, as compared with the low complexity level by using paired T test; # p<0.05, as compared with the middle complexity level by using paired T test.

The result shows that there are statistically significant differences between different complexity levels for the parameters of LF, HF, LF/HF, LFNU and HFNU. LF, LF/HF and LFNU rose significantly (*p* values were 0.029, 0.048 and 0.031 respectively by ANOVA) with the increase of complexity levels. HF and HFNU declined significantly (*p* values were 0.046 and 0.033 respectively by ANOVA) with the increase of complexity levels. While other parameters show no significant difference (*p* values were 0.213, 0.492 and 0.334 for SDNN, RMSSD, and VLF respectively by ANOVA) between different complexity levels.

4 Discussion

This study was designed according to the practice of astronaut training, in which theoretical training was conducted before operation and the operation units were classified into three complexity levels. It is found that the complexity level had significant effects on the HRV parameters. The results of the main performance parameters showed that operation time and fuel consumption rose significantly with the increase of the complexity level. The validity of the complexity level design was further verified according to the research results of Park and our laboratory concerning the measurement of operation complexity [9,10], with the addition of engineering requirements and the facts in astronaut training.

The fact has been proved in many studies that HRV parameters are related to mental workload to a certain extent. In quiet situations, pneumogastric excitability dominates in the autonomic nerve system, and the variation of heart rate is adjusted by the pneumogastric nerve system. While, in the situations of sports, strain and high pressure, sympathetic excitability becomes dominated, and the variation of heart rate is adjusted by the sympathetic nerve system. The activity of sympathetic nerve system can be reflected by the low frequency component (LF, 0.04Hz～0.15Hz) of HRV. Meanwhile, The activity of pneumogastric nerve system can be reflected by the high frequency component (HF, 0.15Hz～0.40Hz) of HRV. When operator's mental workload increases, the value of LF will increase and HF will decrease. Besides, it has a good sensitivity. So, HRV is thought to be a physiological index reflecting mental workload [3,4,5]. In this study, only partial HRV parameters showed a significant difference between different complexity levels. The values of LF, LFNU and LF/HF increased significantly with the increase of the complexity level, while the HF and HFNU decreased. An inference may be made that the increase of the complexity level will make the activity of operator's sympathetic nerve system enhanced, thus making the operator's mental workload increase. Therefore, there is a positive correlation between mental workload and complexity level, which can be represented by partial HRV parameters.

The experiment results showed that the parameters of LF, HF, LF/HF, LFNU and HFNU were sensitive to the complexity level and the others were not. There might be two reasons: First, the other parameters themselves are not sensitive to the complexity level; Second, the differences between the designed complexity levels are not high enough to make these parameters clearly show their sensitivity. The results agree well with what were found in some previous studies, but there are still some controversies. Because HRV is vulnerable to many factors, such as experiment environment, mood and mental state, the characteristics of these parameters still need to be further verified.

Nowadays, mental workload is still hard to be defined concordantly. However, the measurement and application of mental workload have been studied for many years in different fields. Physiological method is a kind of popular and critical approach to measure mental workload arising from the characteristics of objectivity, measurability and instantaneity among other methods. The sensibility of different methods and indexes is correlated to certain tasks and environment to some extent. Therefore, the research concerning the measurement of mental workload is usually set on a certain task and certain environment. The correlation of HRV with mental workload was researched in this study. The results indicated the availability of HRV parameters to measure mental workload during manual controlled RVD. Since the operation performance is the only critical index to evaluate the effect of training now, operators who obtain the same performance results can be scored the same. However, it would not be reasonable enough if they have made different efforts. Therefore, the inclusion of mental workload measured by HRV would be helpful to make a more objective, reasonable and comprehensive evaluation.

5 Conclusion

This study showed that operation complexity had significant effects on partial HRV parameters, and the HRV parameters could be used as effective indexes for mental workload evaluation in manual controlled RVD training. The validity of the operation complexity was further verified, which corresponded to the result of previous study on spaceflight operation complexity in our laboratory [11]. The influencing factors of HRV parameters were diverse, and conclusions of researches concerning the variation of HRV parameters were also not concordant. Therefore, the application and variation trend of HRV parameters in mental workload evaluation should be researched and verified in further studies. This study may also provide scientific basis for the design of astronaut manual controlled RVD training methods, comprehensive evaluation of mental workload and training effect evaluation in future. It could also provide some theoretical guidance for the researches on mental workload in other fields, such as nuclear power plant and driving.

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