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*Article*

# Multi-Dimensional Ergonomic Evaluation Method for Cockpit Light Environment

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**Featured Application: This paper established a set of ergonomic evaluation methods for aircraft cockpit light environment based on indexes of physiological workload, mental workload, work performance and physiological work performance. According to the experiments data of aircraft cockpit light environment ergonomic evaluation, it can be concluded that, under the light environment of 1500 lx illumination and 5000K color temperature, the ergonomics evaluation of the aircraft cockpit was the best. Additionally, the ergonomics of the aircraft cabin light environment with appropriate load is conducive to the improvement of performance, while the inappropriate light environment will, to some extent, affect people's thinking and performance.**

**Abstract:** To instruct interior lighting design of aviation cockpit and ensure the work efficiency and comfort of pilots, and reduce safety accidents caused by light environment and visual fatigue during flight, it is important to establish a multi-dimensional ergonomic evaluation mechanism of cockpit light environment. In this paper, by improving Jdms' mental load theory, we establish a thorough experimental scheme based on physiological workload, mental workload, work performance and physiological work performance to evaluate the cockpit ergonomic under different light environment multi-dimensionally. Firstly, 12 evaluation indexes including job accuracy, job speed, blinking, heart rate variability, average fixation time, saccadic speed, mental demand, physical demand, operational performance, time demand, degree of confusion and degree of effort are obtained through the experiment, and then the weight of each evaluation index is calculated by entropy method to construct the ergonomic evaluation model. The evaluation results of physiological workload, mental load, work performance and physiological work performance were combined to obtain the final ergonomic evaluation results. According to our experimental results, it was found that light environment for pilot to get the highest ergonomic efficiency is 1500 lx light illumination and 5000K color temperature. The results provide a reference for the ergonomic experiment of aircraft cockpit and the design of aviation cockpit lighting system.

**Keywords:** ergonomics; cockpit; light environment; workload; work performance

## 1. Introduction

Vision is the most important information source for pilots which directly influences the safety of pilot. The visual efficiency of pilots depends on the cockpit light environment, and the change of light environment will have a significant impact on people's subjective feelings, visual physiology and other aspects [1]. According to the NASA flight accident report, 21% flight accidents were caused by the excessively dark lighting environment of the aircraft cockpit [2]. Moreover, the visual fatigue caused by the unreasonable set light environment can increase the error rate of the pilot's interpretation, decision-making and operation under the fatigue state, resulting in flight accidents. In the study on light environment and ergonomics, Armin Mostafavi et al. revealed that inappropriate light environment, to some extent, can affect the brain activity of people, which will further affect the memory and thinking efficiency of people [3]. Therefore, the study of man-machine ergonomics evaluation method is of great significance on guiding the design of aviation cockpit lighting system, improving flight comfort and reducing flight accidents.

Early studies on the light environment of aircraft cockpit mainly focused on the impact of light environment on pilots' visual operation performance without considering human feelings. With the development and progress of man-machine efficiency theory, modern man-machine ergonomics evaluation usually adopts load evaluation model which can guarantee human experience better [4,5]. In the field of load evaluation, Harriott et al. evaluated the workload of man-machine collaboration teams [6] to evaluate the effectiveness of man-machine collaboration teams in 2013. In 2018, Feng Chuanyan et al. proposed a situational awareness cognitive prediction model based on the multi-resource load theory to quantify attention resource allocation [7], however it did not involve the quantitative representation between workload and attention resource allocation. In 2019, Jenhung Wanga et al. proposed a method based on the combination of psychological test and Rasch model to evaluate pilots' ability on coping with spatial disorientation caused by mechanical design with psychological workload [8], so as to find the aviation cockpit design with the lowest workload and optimal ergonomics. In 2019, Manttari et al. studied the relationship between activity level and workload [9], and gave a quantitative evaluation of the effect of human activity based on workload. In 2021, Haraldsson et al. tested the human workload through questionnaires [10], which are used for evaluating and improving the influence of working environment on ergonomics of human-computer interaction. In 2022, Mohammadian's team studied the cognitive needs and mental load of mining control room operators [11]. By reducing the cognitive needs and mental load, the effectiveness of human-computer interaction can be improved.

Among existed Load evaluation systems, the NASA-TLX (National Aeronautics and Space Administration-Task Load) multi-dimensional index subjective evaluation method invented by NASA Index is the most famous scale method [12]. During the study on the workload of the control room team of nuclear power factory in 2021, the multi-dimensional characteristics of NASA-TLX scale in complex cognitive work reported by Braarud's team [13] can effectively evaluate the cognitive workload, situational perception and performance of operators. In 2022, Jame Chenarboo et al. used the NASA-TLX scale to evaluate the physical and psychological workload of automotive industry employees on machining and casting process [14], and offered suggestions on how to improve the work efficiency by reducing the physical and psychological workload of workers.

Although high-load working environment is usually accompanied by low-performance work quality, in the high-pressure industries with low-load working, such as aviation, it is hard to achieve relatively high performance [15]. Since load and performance are not strictly negative correlated, and light environments with different illuminance and color temperature significantly affects visual cognition of human [16], it is difficult to objectively and accurately evaluate the ergonomics of different light environments from the perspective of load or performance. Therefore, ergonomic evaluation under different light environments should take the relationship between load and performance into consideration.

Aiming at evaluating the ergonomic of aircraft cabin in different light environments comprehensively, in this paper through improving D.W.Jdms' psychological workload theory, a multi-dimensional evaluation model including performance evaluation and load evaluation system was constructed, which can be used for evaluating the ergonomic of aircraft cabin lighting system under different light environments. Our model offers guidance on aviation cockpit lighting system design, leading to the improvement of flight comfort and the safety of pilots.

## 2. Ergonomics Evaluation Theory Research

To evaluate the ergonomic experiment scheme under different light environment with multi-dimensional factors, it is necessary to combine performance evaluation and load evaluation. Generally, performance evaluation can be systematically divided into two parts: work performance and physiological performance. Work performance, as an intuitive result, directly reflects the participants'working effectiveness in the ergonomics experiment, while physiological performance objectively reflects the physiological indicators of the participants. Among the two performances, work performance is also an important part of load assessment.

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D.W.Jdms' mental load theory reveals that: workload are consisted by input load, effort level and work performance, and the three parts are functionally interrelated. As shown in Figure 1, input load, as an established factor, does not participate in the evaluation, while work performance and effort are objects need to be evaluated during the load research process.

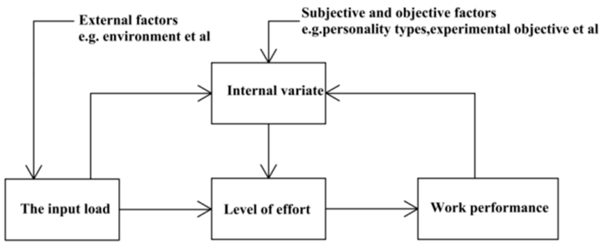


**Figure 1.** D.W.Jdms load model.

It can be seen that, the load evaluation model is not completely composed to the performance evaluation model, and there is some overlap between the two evaluation methods. A load evaluation model consisting of physiological load, psychological load and work performance can be established in accordance with D.W.Jdms' psychological workload theory. The performance evaluation model is composed of work performance and physiological performance. Combining the load evaluation model and performance evaluation model, an ergonomic evaluation method based on physiological workload, mental workload, work performance and physiological work performance can be obtained.

Based on the four quantitative indicators, the ergonomic model can be established, as shown in Figure 2.

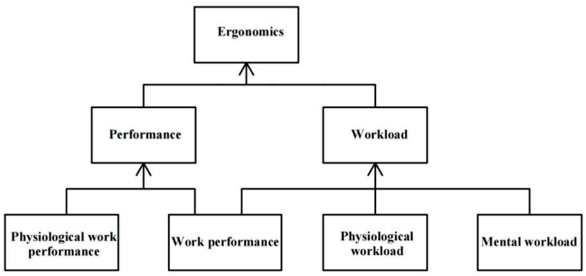


**Figure 2.** Total power model.

Work Performance (WP) is a quantitative score of human-computer interaction performance. It evaluates the task completion objectively, and reflects drivers speed (working speed, S) and accuracy (accuracy rate, AR) of task completion under light environment with different illumination and color temperature. The two most commonly used evaluation methods in the work performance evaluation system are single task evaluation method and double task load evaluation method. Single task assessment can directly reflect the level of load through the single task test performance indicators. Though testing is convenient and fast, its sensitivity is low due to single task working style; The dual-task load assessment method concludes an additional side task to make the test result more objective. Side-task occupies the residual capacity of the main task to increase the sensitivity of load detection. However, existence of side tasks can interfere to the main task, the double task load evaluation method is not often used in the evaluation of high-risk and high-load environments such as driving and flying. Therefore, to obtain the required accuracy and speed of the operation, in our work, we chose more convenient and efficient single task evaluation method.

Physiological Workload (PW) is an important part of modern load evaluation system. This index represents the physiological stress conditions of humans during human-computer interaction under different light environments. A comfortable light environment is of great significance for maintaining

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attention and increasing alertness [17]. The higher the load, the heavier the task will be, and it is more easily for people to get tired; the lower the load, the easier the task will be. Blink (B) is the most suitable physiological parameter to reflect the visual load. In order not to miss valuable information during the working process, people will unconsciously inhibit blinking. When the visual load increases, the blink inhibition phenomenon will become more obvious, and the blink rate will correspondingly decrease. However, excessive load will lead to a rapid increase of the blink rate after eye fatigue, which is contrary to the phenomenon of blink inhibition with higher load. Therefore, only use the blinking could not assess the physiological load accurately, and heart-rate related parameters should be introduced to expand the evaluation dimension to improve the accuracy of physiological load. Heart Rate Variability (HRV) is a highly sensitive parameter and plays a significant role in the evaluation of physiological and psychological load [18,19]. Therefore, to obtain effective physiological workload quantification indexes under different light environments, B and HRV should be combined.

Physiological Work Performance (PP) refers to the quantitative evaluation of human physiological parameters during human-computer interaction under different light environments. Different illuminance and color temperature lighting environments will affect human physiological parameters [20]. However, as a physiological parameter, during the test process, PP cannot give positive and negative feedback as quickly as work performance, so it cannot participate in load evaluation. In ergonomic evaluation of light environment, physiological performance is generally evaluated by visual utilization efficiency. The average Fixation Time (FT) and Saccadic Speed (SS) can directly reflect the difficulty of eyes to obtain information, that is, visual utilization efficiency. Shorter fixation time means shorter time and higher efficiency for eyes' information reading. Similarly, faster saccade duration indicates faster and higher efficiency for eyes' information collection within the visual search range. Therefore, combining the average fixation time with saccadic saccades can obtain quantifiable physiological work performance indicators.

Mental Workload (MW), as another part of the modern load evaluation system, represents the pressure on the psychological performance of the human side in the process of human-computer interaction under different light environments. Illumination and color temperature are the two most important parameters in the light environment, which significantly affect the subjective cognition of pilots. Therefore, the evaluation of mental load under different light environments is an indispensable part of ergonomic evaluation system. Psychological load evaluation system usually adopts subjective evaluation, because subjective evaluation has high correlation, simple calculation and convenient implementation [21]. NASA-TLX scale is the most commonly used subjective evaluation method. Through subjectively evaluate Mental needs (M), Physical needs (Ph), operational Performance (Pf), time needs (T), degree of confusion (F) and Effort (E)the required quantitative psychological load data for evaluation were further obtained. However, the traditional NASA-TLX scale method scores the six sub-scales from 0 to 100 respectively, whose workload and data variability is large and the whole process is time-consuming [22]. In order to avoid the above problems, the simplified NASA-TLX scale is used to replace the traditional NASA-TLX scale for subjective assessment of psychological load, as shown in Figure 3.

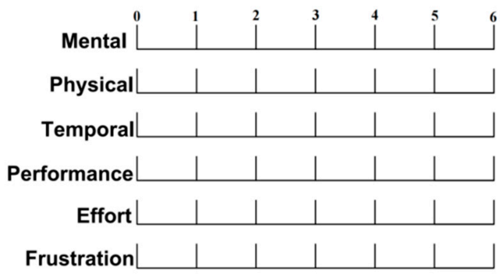


**Figure 3.** Simplified NASA-TLX.

Compared with the original NASA-TLX scale, the simplified NASA-TLX scale simplifies the original 0 to 100 scoring system to a 0 to 6 six-point scale system. The simplification reduces the time required for testing and improves the evaluation efficiency without affecting the effectiveness of mission load assessment [23].

### 3. Establishment of Ergonomic Mathematical Model

In order to establish a set of multi-dimensional ergonomic mathematical model, several indicators under the ergonomic evaluation model are analyzed. Among the four indicators, the value of positive indicator performance is positive correlated with the ergonomic evaluation, the mental workload is negative correlated with the ergonomic evaluation. In addition, the weight of the other two indicators in the final composition of the efficiency score needs to be calculated solely. Therefore, it is necessary to normalize and weighting the data to reduce the error and influence of parameters between each other [24]. In this paper, the weight of each index is obtained by entropy method after normalization, and an effective ergonomic mathematical model is finally established.

Assuming that there are a illumination environments to be evaluated, b color temperature environments to be evaluated, and t evaluation indicators that need to be tested in each light environment, a×b×t data can be measured in total, and a×b×t data can be formed into b a×t order original data matrix Xj, where:

$$X_j = \begin{bmatrix} x_{1j1} & \cdots & x_{1jt} \\ \vdots & \ddots & \vdots \\ x_{aj1} & \cdots & xajt \end{bmatrix}, (1 \le j \le b)' \tag{1}$$

Where xijk is the evaluation value when the color temperature environment is j (0≤j≤b) and the illumination environment is i (0≤i≤a) under the evaluation index k (0≤k≤t). In order to evaluate the obtained data easily, it is necessary to normalize xijk and convert all the obtained data into a positive evaluation index:

$$\begin{cases} x'_{\mathrm{ijk}} = \dfrac{x_{\max} - x_{ijk}}{x_{\max} - x_{\min}}, (1 \le k \le t), x_{ijk} \text{ weree positive dimensions} \\ x'_{\mathrm{ijk}} = \dfrac{x_{ijk} - x_{\min}}{x_{\max} - x_{\min}}, (1 \le k \le t), x_{ijk} \text{ were negative dimensions} \end{cases}, \tag{2}$$

Through the matrix, we can get the result of the proportion of each index in each scheme Pijk:

$$Pijk = \frac{x'_{ijk}}{\sum_{j=1}^{t} x'_{ijk}}, \tag{3}$$

Then, the index entropy ejk can be obtained by Pijk:

$$ejk = -\frac{1}{\ln(m)} \sum_{i=1}^{m} P_{ijk} \ln(P_{ijk}), \tag{4}$$

Further obtain the weight results of each index wjk:

$$w_{ijk} = \frac{1 - e_{jk}}{\sum_{k=1}^{t} (1 - e_{jk})}, \tag{5}$$

Therefore, each parameter measured under the four indicators (work performance, psychological workload, physiological work performance and mental workload) was substitute into equation (5) to obtain the weight w of the indicator, and the evaluation result is calculated by the obtained weight.

Work performance is calculated by two evaluation indexes, AR and S:

$$WP_j = w_{j1} \times AR_j + w_{j2} \times S_j, (1 \le j \le b), \tag{6}$$

Psychological workload is composed of two evaluation indexes B and HRV:

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$$WP_j = w_{j1} \times AR_j + w_{j2} \times S_j, (1 \le j \le b), \quad (7)$$

Physiological performance was calculated by the FT and SS of two evaluation indexes:

$$PP_j = w_{j1} \times FT_j + w_{j2} \times SS_j, (1 \le j \le b), \quad (8)$$

Mental workload is composed of six evaluation indexes: M, Ph, Pf, TT, FF and E:

$$MW_j = w_{j1} \times M_j + w_{j2} \times Ph_j + w_{j3} \times Pf_j + w_{j4} \times TT_j + w_{j5} \times FF_j + w_{j6} \times E_j (1 \le j \le b), \quad (9)$$

After obtaining the evaluation matrix of work performance, psychological workload, physiological work performance and mental workload, these four indexes are taken as new evaluation indexes. Entropy method (5) was used again to obtain the weight w of each new index required by synthetic Ergonomics (Eg), and then get evaluation results:

$$Eg_j = w_{j1} \times WP_j + w_{j2} \times PL_j + w_{j3} \times PP_j + w_{j4} \times ML_j, (1 \le j \le b), \quad (10)$$

Finally, the evaluation results under the influence of color temperature were synthesized into a×b ergonomic evaluation matrix under the joint influence of illumination and color temperature:

$$Eg = \begin{bmatrix} Eg_1 \\ \vdots \\ Eg_b \end{bmatrix}, \quad (11)$$

Through this model, ergonomics can be quantitatively evaluated and represented in the form of a matrix. The ergonomics in each light environment can be judged quickly, accurately and objectively by the size of the data in the matrix. The larger Eg leads to the better ergonomics in the light environment, which can be used to select light environment with the best ergonomics light environment quickly, guiding the design of aviation cockpit lighting system to improve flight comfort and ensure the safety of pilots.

## 4. Experimental Test Method

The purpose of the experiment is to study the ergonomic relationship between the pilot and the cockpit under the light environment with different illumination and color temperature by recording and analyzing the work performance, physiological load, physiological performance and psychological load under different light environment. There were 16 participants in this experiment (the ratio of male to female was 5:3), all of whom had corrected visual acuity of 1.0 or above and had no obstacle in color recognition. All participants wear Tobbi Glass 2 eye tracker and multimodal acquisition bracelet during the experiment.

**Figure 4.** Eye tracker and physiological recorder.

The optical environment parameters are as follows:

Illuminance: 1 lx, 5 lx, 10 lx, 50 lx, 100 lx, 500 lx, 750 lx, 1000 lx, 1500 lx, 3000 lx, 5000 lx, 7500 lx, 10000 lx, a total of 13 points, covering the range of illumination from morning to night all day.

Color temperature: 2700k, 3000k, 3300k, 3600k, 3900k, 4200k, 4500k, 4800k, 5100k, 5400k, 5700k, 6000k, a total of 12 points, covering the color temperature from early morning to night all day.

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This experiment uses the single task evaluation method, and the main task is to do the add and subtract in 100 under specific light environment within 1 minute. The detailed test methods are as follows:

The experimental participants were asked to wear an eye tracker and a physiological recorder and sit in the cockpit simulators. Their eyes were required to be basically at the same level as the center point of the display screen. After sitting for 5 minutes to adapt to the current light environment in the cockpit, the test was officially started. The participants were asked to do the add and subtract in 100 shown on the screen. Only when the participants give answers can they switch to the next calculation question. Each test lasts 1 minute, and the current light environment parameters, the answering speed and accuracy of this test are recorded. At the same time, the eye tracker and physiological recorder are used to record the average fixation time, saccometer speed, blink times, heart rate variability and other indicators during the test. After five repeated experiments, the psychological load was scored by the simplified NASA-TLX scale, and then the light environment parameters were switched for the next round of tests.

The complete test process is shown in Figure 5.

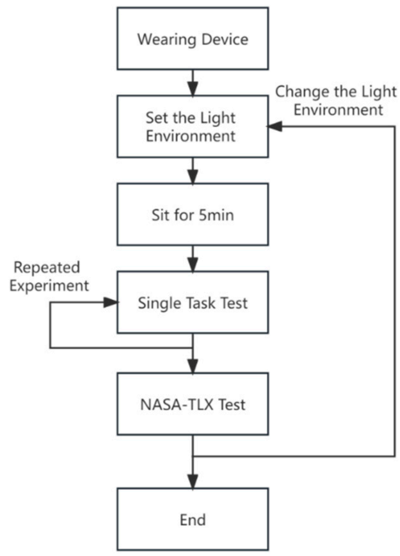


**Figure 5.** Test flow chart.

Based on the experiment, 12 evaluation indexes (AR, S, B, HRV, FT, SS, M, Ph, Pf, TT, FF and E) were measured under 156 light environments with 13 illuminance and 12 color temperatures. A total of 1872 data items of 13×12×12 were substituted into the above mathematical model. Quantified ergonomic evaluation value can be obtained from equation (10) and equation (11), as given in Table 1 and Table 2. If the ergonomic evaluation value is closer to 1, it will obtain higher ergonomic efficiency.

**Table 1.** Ergonomics（2700K~4200K）.

| illumination | color temperature | | | | | |
|---|---|---|---|---|---|---|
| | 2700k | 3000k | 3300k | 3600k | 3900k | 4200k |
| 1lx | 0.041012146 | 0.066132387 | 0.081348051 | 0.137536265 | 0.137415613 | 0.160998043 |
| 5lx | 0.111841538 | 0.138341288 | 0.144727169 | 0.22249636 | 0.254704989 | 0.239306693 |
| 10lx | 0.168538891 | 0.206719879 | 0.264180203 | 0.337311294 | 0.315550971 | 0.297023454 |
| 50lx | 0.186943748 | 0.258677016 | 0.265792175 | 0.383023731 | 0.38597743 | 0.374594775 |
| 100lx | 0.225436858 | 0.276632398 | 0.347545609 | 0.5569128 | 0.515900487 | 0.532471891 |
| 500lx | 0.221180884 | 0.29958932 | 0.333240597 | 0.553273063 | 0.511688366 | 0.590525814 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 750lx | 0.293417554 | 0.356899361 | 0.360324331 | 0.593962238 | 0.596576657 | 0.654362218 |
| 1000lx | 0.359319374 | 0.441753371 | 0.581543953 | 0.70276138 | 0.733426294 | 0.777085796 |
| 1500lx | 0.55016562 | 0.639652318 | 0.769820213 | 0.927924088 | 0.91813712 | 0.948380454 |
| 3000lx | 0.281545996 | 0.318715369 | 0.358825745 | 0.560926615 | 0.605780123 | 0.657087534 |
| 5000lx | 0.193819325 | 0.215645519 | 0.213579031 | 0.311029883 | 0.326981332 | 0.306586753 |
| 7500lx | 0.089337147 | 0.110832923 | 0.118005826 | 0.199652762 | 0.179533192 | 0.198010791 |
| 10000lx | 0.049976105 | 0.064332976 | 0.073162537 | 0.100581831 | 0.121214071 | 0.133690313 |

**Table 2.** Ergonomics（4500K~6000K）.

| illumination | color temperature | | | | | |
|---|---|---|---|---|---|---|
| | 4500k | 4800k | 5100k | 5400k | 5700k | 6000k |
| 1lx | 0.175763422 | 0.242701322 | 0.208478067 | 0.123649263 | 0.076770696 | 0.051018953 |
| 5lx | 0.293762492 | 0.319535437 | 0.321636367 | 0.22256496 | 0.170039926 | 0.117951412 |
| 10lx | 0.325981998 | 0.355785209 | 0.360746919 | 0.282738541 | 0.213705798 | 0.12493132 |
| 50lx | 0.401549524 | 0.409516689 | 0.424006077 | 0.310725711 | 0.221007494 | 0.167408228 |
| 100lx | 0.538093548 | 0.544425142 | 0.52530241 | 0.355967345 | 0.227420766 | 0.167604196 |
| 500lx | 0.608608109 | 0.568344197 | 0.549351154 | 0.37854248 | 0.227903199 | 0.212455437 |
| 750lx | 0.636929785 | 0.642905335 | 0.583459512 | 0.446894565 | 0.265566479 | 0.223811128 |
| 1000lx | 0.784170663 | 0.681022632 | 0.672074064 | 0.50688693 | 0.325631984 | 0.278019701 |
| 1500lx | 0.989581584 | 0.910655388 | 0.779272562 | 0.460501032 | 0.387847709 | 0.343810964 |
| 3000lx | 0.670357882 | 0.618790163 | 0.594117283 | 0.414358065 | 0.29533813 | 0.237152158 |
| 5000lx | 0.337469052 | 0.346041707 | 0.354903144 | 0.29264566 | 0.233585239 | 0.16400574 |
| 7500lx | 0.222167099 | 0.279800452 | 0.271739524 | 0.247790453 | 0.183957343 | 0.146028397 |
| 10000lx | 0.154686782 | 0.193601341 | 0.193167308 | 0.149140118 | 0.108791961 | 0.099258146 |

## 5. Analysis of Experimental Results

After being processed by equation (2), the obtained 1872 data are substituted into equation (3) to obtain 4 13×12 evaluation matrices indicating 156 light environments. At this time, the 4 evaluation matrices of work performance, physiological workload, physiological work performance and mental load are all positive matrices, and the closer the evaluation value is to 1, the better the effect is.

The plane coordinates obtained from the evaluation matrix transformation are shown in Figure 6 to Figure 9.

Figure 6 shows the performance evaluation in the cockpit light environment. When the evaluation value of performance is 1, it means that under the corresponding light environment, the pilot can achieve the highest work efficiency. The performance is greater than 0.8 when the illumination is from 100 lx to 3000 lx and the color temperature is from 3500K to 5000K. The highest work efficiency can be achieved in all light environments. When the illumination is greater than 5000K or less than 100K, the evaluation value of the work performance will decrease significantly. When the evaluation value of the work performance is lower than 0.8, the pilot's work efficiency will decrease, which is not adverse to the safety of flight causing safety accidents. Therefore, when design the aviation cockpit lighting system, in order to ensure the working efficiency of the pilot and reduce the safety accidents caused by the light environment during the flight, the illumination in the aviation cockpit should be kept within the range of high operating performance light environment which is 100 lx to 3000 lx illumination and 3500K to 5000K color temperature.

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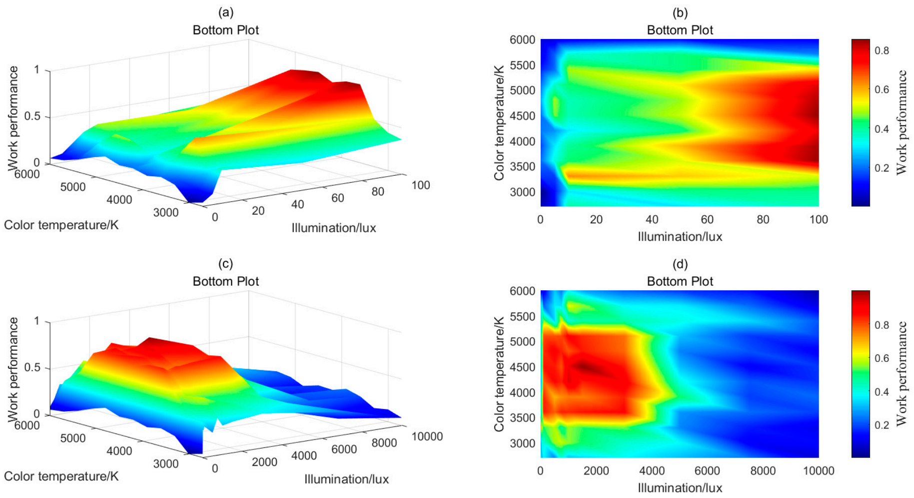


**Figure 6.** **(a)** Work performance evaluation 3d results 0~100lux; **(b)** Work performance evaluation 2d results 0~100lux; **(c)** Work performance evaluation 3d results 0~10000lux; **(d)** Work performance evaluation 2d results 0~10000lux.

As shown in Figure 7, the evaluation result of physiological workload in the aviation cockpit light environment has been positively processed. Higher evaluation value of physiological workload represents lower physiological workload in the light environment and the pilots can be less fatigue. When the evaluation value of physiological workload is 1, under the corresponding light environment, the pilot has the lowest physiological pressure. Compared with the evaluation results of work performance, the evaluation value of physiological workload is greater than 0.8 only when the illumination ranges from 1500 lx to 2000 lx and color temperature is from 3500K to 5000K. When the illumination is larger than 2000K or less than 1500K, the evaluation value of physiological workload decreases significantly, and the increase of physiological workload is more likely to cause eye fatigue of drivers which will influence the flight safety. Compared with Figure 6 and Figure 7, the physiological fatigue of pilots is easier to be influenced by the change of illumination than work efficiency. Therefore, when design aviation cockpit lighting system, in order to ensure the flight comfort of pilots and reduce safety accidents caused by visual fatigue during flight, the illumination in the aircraft cabin should be kept within the low physiological workload light environment whose illumination is in the range of 1500 lx to 2000 lx and color temperature is from 3500K to 5000K.

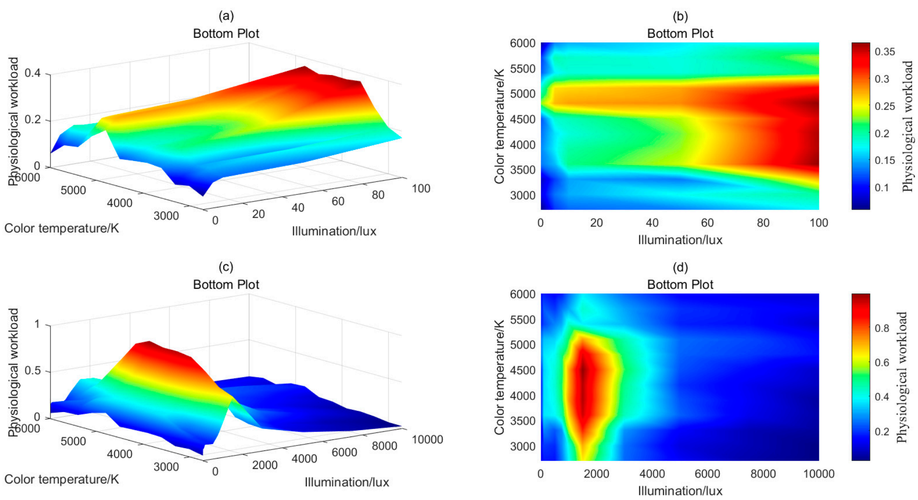

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**Figure 7.** **(a)** Physiological workload evaluation 3d results 0~100lux; **(b)** Physiological workload evaluation 2d results 0~100lux; **(c)** Physiological workload evaluation 3d results 0~10000lux; **(d)** Physiological workload evaluation 2d results 0~10000lux.

As shown in Figure 8, pilots can achieve the highest physiological activity efficiency when the light environment's evaluation value of physiological work performance is 1. The evaluation value of physiological work performance is greater than 0.8 when the illumination ranges from 50 lx to 5000 lx and color temperature ranges from 3500K to 5500K. When the illumination is less than 50 lx or more than 5000 lx, the evaluation value of physiological work performance can still be maintained at about 0.5. We use 156 kinds of light environments to simulated all-weather light environments from morning, noon, dusk to night. It can be seen from Figure 6, 7 and 8 that though different light environments will affect the work efficiency of pilots and cause physiological fatigue of pilots, 156 simulated natural light environments selected in this experiment can be adapted by the human body, and the impact of light environment on physiological work performance is less than its impact on work performance and physiological workload.

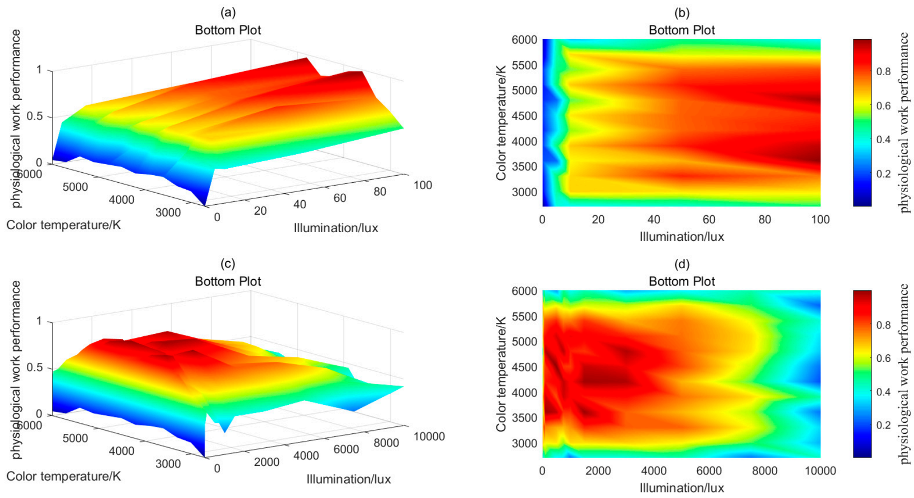


**Figure 8.** **(a)** physiological work performance evaluation 3d results 0~100lux; **(b)** physiological work performance evaluation 2d results 0~100lux; **(c)** physiological work performance evaluation 3d results 0~10000lux; **(d)** physiological work performance evaluation 2d results 0~10000lux.

Figure 9 show the evaluation results of positively processed the mental workload in the cockpit light environment. Higher evaluation value of mental workload means lower mental workload in the light environment, and pilots feel more relax at work. When the evaluation value of mental workload is 1, the psychological pressure of the pilot in the light environment is the lowest. When the color temperature is 5000K, the evaluation result is similar to the evaluation result of physiological work performance. When the illumination ranges from 50 lx to 5000 lx, the evaluation value of mental workload is greater than 0.8. When the color temperature is reduced to 3500K, the results are similar to the evaluation results of physiological workload. The evaluation value of mental workload is greater than 0.8 when the illumination is in the range of 1500 lx to 2000 lx. By combining Figures 6, 7, 8 and 9, it can be concluded that when the color temperature is 5000K, operating performance, physiological workload, physiological work performance and mental workload can achieve the highest evaluation value, which can be valuable reference for light environment design of the aircraft cockpit.

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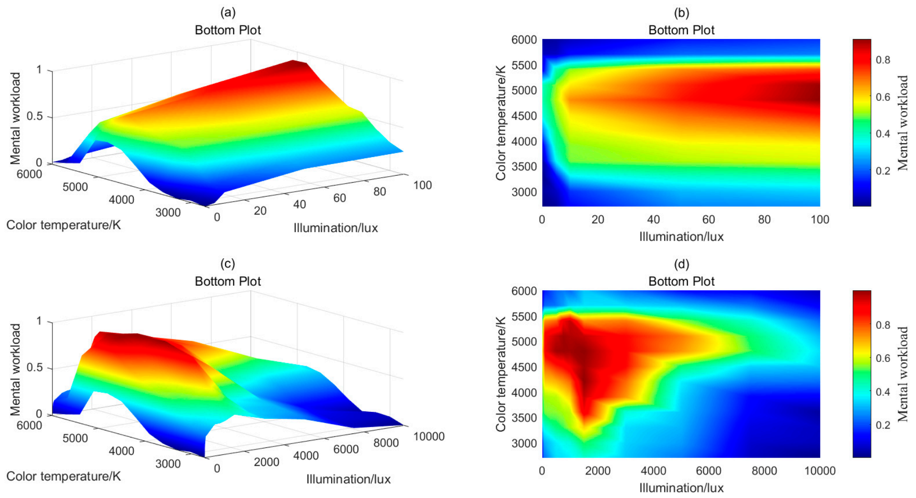


**Figure 9. (a)** Mental workload evaluation 3d results 0~100lux; **(b)** Mental workload evaluation 2d results 0~100lux; **(c)** Mental workload evaluation 3d results 0~10000lux; **(d)** Mental workload evaluation 2d results 0~10000lux.

Based on the above four evaluation results, the final ergonomic evaluation results of the cockpit optical environment obtained from Table 1 and Table 2 is shown in Figure 10. When the ergonomics evaluation value is 1, it means that the light environment can be used as the best light environment for the pilot during the flight. In this light environment, the pilot has the best work efficiency and the lowest load. When the illumination is 1500 lx and the color temperature ranges from 3500K to 5000K, the ergonomics evaluation value is greater than 0.9. When the illumination is larger than 2000 lx or less than 1000 lx, the ergonomic evaluation value decreases significantly, which is not conducive to flight safety.

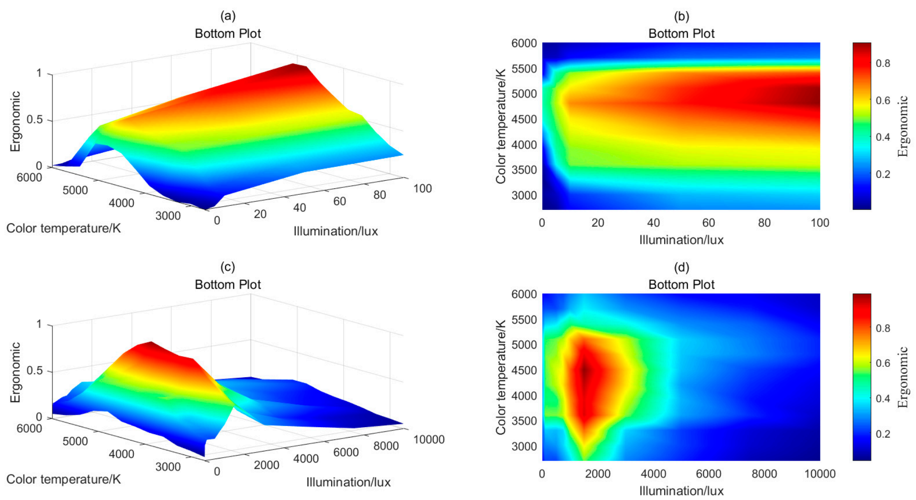


**Figure 10. (a)** Ergonomic evaluation 3d results 0~100lux; **(b)** Ergonomic evaluation 2d results 0~100lux; **(c)** Ergonomic evaluation 3d results 0~10000lux; **(d)** Ergonomic evaluation 2d results 0~10000lux.

By comparing the results of work performance evaluation, physiological workload evaluation and mental workload evaluation, it can be concluded that their exists high performance with high load in the illuminance ranging from 100 lx to 2000 lx and 2000 lx to 3000 lx (Figures 6, 7, 8, 9). This result shows that the workload and work performance are not strictly negative correlated, appropriate workload can promote performance.

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As shown in Figure 6 and Figure 8, the light environment scope corresponding to physiological work performance is greater than that of work performance. The evaluation results obtained by taking the average fixation time and saccade speed as the parameters of physiological performance show that, theoretically, the information reading efficiency in this significant area should be equally high, but the results given by the participants after processing the obtained information are not as ideal as the information reading efficiency. According to the feedback of the participants: they indeed read the correct information during the test but after giving the calculation result, the realized results were wrong. This phenomenon indicates that the inappropriate light environment will affect the participants' brain activities, and then affect their memory and thinking efficiency.

Finally, by combining physiological workload, mental workload, work performance and physiological work performance with the comprehensive evaluation results of ergonomics, it can be concluded that under 1500 lx and 5000K light environment, the ergonomics of aircraft cockpit light environment is the best. In this light environment, the two kinds of performance are the highest, and the two kinds of load are the lowest under each light environment. Consequently, to ensure the working efficiency, guarantee the comfort of pilots and reduce safety accidents caused by light environment and visual fatigue during flight, the light environment in the cockpit should be closer to 1500 lx and 5000K when design the cockpit lighting system.

## 6. Conclusions

Considering the pros and cons of performance evaluation and load evaluation, in this paper, we established a set of ergonomic evaluation methods for aircraft cockpit light environment based on indexes of physiological workload, mental workload, work performance and physiological work performance. According to the experiments data of aircraft cockpit light environment ergonomic evaluation, it can be concluded that, under the light environment of 1500 lx illumination and 5000K color temperature, the ergonomics evaluation of the aircraft cockpit was the best. Additionally, the ergonomics of the aircraft cabin light environment with appropriate load is conducive to the improvement of performance, while the inappropriate light environment will, to some extent, affect people's thinking and performance. The results provide a reference for aircraft cockpit lighting system design.

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**Data Availability Statement:** We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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