Comparative Study on the Effects of Lighting on Cognitive Ergonomics in Single and Multi-Working Modes

Zhigang Hu*, **Cui Yi, Jing Hao, Xianling Qiao, Xiya Guo**

ABSTRACT

This paper aims to disclose the effects of environmental lighting on cognitive ergonomics in the single working mode of visual display terminals (VDTs) and the multi-working mode involving both the VDTs and hard-copy documents, and identify the optimal lighting parameters for the multi-working mode. To this end, cognitive efficiency experiments were carried out in different lighting conditions and different working modes, taking illuminance and colour temperature as independent variables and reaction time and accuracy as dependent variables. During the research, the subjective questionnaire survey and eye movement indices were treated as corroborating data. The main conclusions are as follows: the multi-working mode is low in speed but high in accuracy, and less likely to cause eye strain; the lighting conditions have no significant effect on VDT cognition efficiency in either working mode; however, the colour temperature of 6,500K and the illuminance of 500lx tend to cause eye fatigue in VDT single working mode; in multi-working mode, the optimal lighting conditions for the best cognitive ergonomics are: high illuminance (700lx) and white light (4000K). The research findings reveal the relationship among lighting conditions, working mode and cognitive efficiency, lay a scientific basis for workplace design.

Key Words: Multi-Working Mode, Cognitive Ergonomics, Lighting Ergonomics, Visual Display Terminal (Vdt), Hard-Copy Documents, Illuminance

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Introduction

With the technology development in such fields as computer, industrial automation and intelligent information, the role of man in the man-machine system has shifted from functional activities of perception and action to cognitive activities like problem-solving and decision-making, leading to substantial changes in man-machine relationship. In view of the changes, scholars have included human cognitive factors, e.g. the environment, into traditional ergonomics, forming a brand-new branch of ergonomics called the cognitive ergonomics. The concept of cognitive ergonomics was proposed by M.E. Sime and M. White in 1971 through the fusion of ergonomics, cognitive psychology and computer science. A typical model in cognitive ergonomics is the man-machine-environment system, in which the man's cognition is affected by various environments. In recent years, more and more attention has been paid to lighting, one of the most important environments, aiming to disclose its effect on cognitive ergonomics.

Most of the existing research on lighting ergonomics has been focusing on hard-copy documents. Most of the existing research on lighting ergonomics has been focusing on hard-copy documents. The previous studies have

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shown that cognitive ergonomics is negatively correlated with illumination and colour temperature of environmental lighting (Yan *et al*., 2012). The brain has a strong cognitive ability, thus a good short-term memory, at low illuminance and low colour temperature, and is susceptible to fatigue at high colour temperature (Yan *et al*., 2012). For a fatigued brain, the most suitable lighting environment should have a moderate colour temperature. Taking classroom lighting for example, the colour temperature of 4,000K helps students achieve the best learning efficiency. However, the optimal illuminance varies with colour temperatures. For instance, the best illuminance is 300lx at the colour temperature of 2,700K, and 750lx at 4,000K. Besides, it is not recommended to set the colour temperature to 6,500K, or adopt the illuminance of 750lx at 2,700K, 500lx at 4,000K, or 500lx at 6,500K (Yan *et al*., 2010). Probing into the ergonomics of paper reading, Hu *et al*. determined the optimal lighting conditions for different reading times: 750lx and 4000K for 30min, 750lx and 6,500K for 1h, and 500lx and 4,000K for 2h (Hu *et al*., 2016). It is proved in their research that high illuminance suits short-term reading with heavy brain fatigue, and that moderate colour temperature and illuminance fits in with long-term reading. The above studies reveal the significant impact of illuminance and colour temperature on cognitive ergonomics (Sleegers *et al*., 2013).

Thanks to the progress information and intelligence technologies, information interaction has been increasingly transferred from hard-copy documents to visual display terminal (VDT), making the latter the dominant form of work in modern times. To ensure the working efficiency of VDT, it is necessary to ascertain the effect of lighting condition, a key determinant of cognitive ergonomics, on the cognition of VDT information (Min *et al*., 2013; Xu and Wang, 1992). It has been reported that VDT working mode produces a mild brain fatigue after 8h of LED lighting (Wang *et al*., 2017). According to Lin *et al.* and Shieh *et al.,* the best cognitive ergonomics can be obtained under the VDT working mode of a moderate colour temperature, 450~500lx illuminance and a blue background(Lin and Huang., 2013; Shieh and Lin, 2000).

To sum up, the lighting condition is a major influencing factor of the cognitive ergonomics of both hard-copy documents and VDTs. Thus, lighting factors must be taken into consideration when designing the workplace. Of course, the hard-copy documents and VDTs are not entirely independent of each other. In social activities, there are frequency interactions between the two working modes. In this paper, a working mode involving only the hard-copy documents or VDTs is defined as the single working mode, while that integrating both the hard-copy documents and VDTs is defined as the multi-working mode. In view of the above analysis, this paper aims to disclose how environmental lighting conditions affect the cognitive ergonomics in the single and multi-working modes, and identify the best lighting parameters of multi-working mode. To this end, cognitive efficiency experiments were carried out at different lighting conditions under different working modes, taking illuminance and colour temperature as independent variables and reaction time and accuracy as dependent variables. During the research, the subjective questionnaire survey and eye movement indices were treated as corroborating data.

Experiment Design

Basic conditions of subjects

Twenty college students aged between 21 and 26 were selected for the experiments. All of them are 147.6~190.0cm tall and 41.5~80.9kgin weight, with a corrected visual acuity higher than 1.0. None of the subjects suffer from colour weakness, colour blindness and any other eye diseases. The subject did not drink coffee, drink tea or smoke for 24h before the experiments, and slept for at least 7h on the night preceding the experiments.

Experimental method

For the experiments, illuminance and colour temperature were taken as independent variables, and reaction time and accuracy were adopted as dependent variables. The VDT saturation was set to 102, and 75% contrast positive text and images were employed. Due to the poor cognitive ergonomics on hard-copy documents or VDTs at low colour temperature and low illuminance (Lin and Hao, 2007; Lin and Huang, 2013), the colour temperature of 2,700K and the illuminance of 300lx were not taken into account. So, the experiment sets 4000 K and 6500 K as the two levels of colour temperature, 500 lx and 750 lx as the two levels of illumination. The experiments were carried out in a comprehensive manner.

The subjective questionnaire contains two scales: the Cooper–Harper (CH) scale and the Profile of Mood States (POMS). The former enables the subjects to evaluate the exact workload, while the latter is a 5-point scale reflecting the subjects' mood changes before and after the experiments. The pupil diameter variation coefficient and the per-second blinking rate were extracted from eye movement data for physiological analysis, and the degree of fatigue of the subjects was also analysed. The eye movement data was captured by a Tobii X2-30 eye tracker.

Experimental process

The experimental group and VDT single working mode were set up in the experiment. The main experimental process is shown in Figure 1.

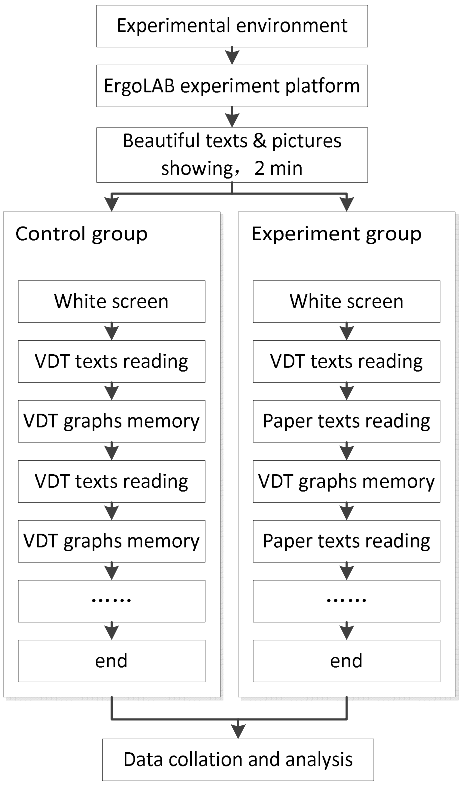

Figure 1. Experimental process

Data Analysis

Cognitive performance comparison between single and multi-working modes

(1) Comparison of reaction time

First, the reaction time of the hard-copy documents was removed from the total reaction time of the multi-working mode. Then, the VDTs was contrasted with the multi-working mode to see if there is any difference in reaction time. The reaction times of the test group and control group were analysed through the independent-samples t test. According to the test results in Table 1, the average reaction time of the multi-working mode (270,7.7908) was significantly longer (p=0.000<0.01) than that of the VDT single working mode (2,063.7922).

(2) Comparison of accuracy

The accuracies of the test group and control group were also analysed through the independent-samples t test. According to the test results in Table 2, the two groups differed in the accuracy variance. After correction, the test results were T=4.228, P=0.000<0.01. The results show that the average accuracy of the multi-working mode (0.9933) was much better than that of the single working mode (0.9819).

(3) Comparison of pupil diameter variation coefficient

The pupil diameter variation coefficients of the VDT single working mode and multi-working mode were compared through the independent-samples test. The test results in Table 5 reveal the difference between the test group and the control group in the variance of the pupil diameter variation coefficient. Hence, the test results were corrected as T=-4.145, P=0.000<0.01. It can be seen that the average pupil diameter coefficient of the multi-working mode (0.19053) was less than that of the VDT single working mode (0.2365).

(4)Comparison of per-second blinking rate

The per-second blinking rates of the VDT single working mode and multi-working mode were compared through the independent-samples t test.

Table 1. T-test results of reaction time comparison between single and multi-working modes

		Levene's test for Equality of variances		t-test for Equality of means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
RT	Equal variance assumed	90.632	0	15.791	7198	0	643.99856	40.78151
	Equal variance not assumed			16.232	7191.825	0	643.99856	39.6748

Table 2. T-test results of accuracy comparison between single and multi-working modes

		Levene's test for Equality of variances		t-test for Equality of means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Accuracy	Equal variance assumed	79.723	.000	4.446	7198	.000	.01138	.00256
	Equal variance not assumed			4.228	5050.716	.000	.01138	.00269

Table 3. T-test results of pupil diameter variation coefficient comparison between single and multi-working modes

		Levene's test for Equality of variances		t-test for Equality of means				
		F	Sig.	t	df	Sig.(2-tailed)	Mean Difference	Std. Error Difference
Variation coefficient of pupil diameter	Equal variance assumed	95.516	.000	-4.145	158	.000	-.045994	.011095
	Equal variance not assumed			-4.145	88.917	.000	-.045994	.011095

Table 4. T-test results of per-second blinking rate comparison between single and multi-working modes

		Levene's test for Equality of variances		t-test for Equality of means				
		F	Sig.	t	df	Sig.(2-tailed)	Mean Difference	Std. Error Difference
Blink rate	Equal variance assumed	12.388	.001	-7.764	158	.000	-.158875	.020464
	Equal variance not assumed			-7.764	146.991	.000	-.158875	.020464

The test results in Table 4 show the difference between the test group and the control group in the variance of the per-second blinking rate. Hence, the test results were corrected as T=-7.764, P=0.000<0.01. It is clear that the average per-second blinking rate of the multi-working mode (0.1597) was less than that of the VDT single working mode (0.31863).

Comparative analysis of the effect of lighting conditions in single and multi-working modes

The data of the hard-copy documents were removed from that of the multi-working mode before discussing the effect of lighting conditions of VDTs in different working modes.

(1)Comparing the effect of lighting conditions on reaction time in different working modes

Repeated measurements were performed for the variance analysis of working mode, illuminance and colour temperature. The analysis results are as follows: the working mode F(1,799)=209.863, P=0.000<0.01; the illuminance F(1,799)=315.060, P=0.000<0.01; the colour temperature F(1,799)=97.896, P=0.000<0.01; F(1,799)=1.751, P=0.186>0.05; the working mode*colour temperature F(1,799)=2.089, P=0.147>0.05; F(1799)=269.973, P=0.000<0.01; the working mode*illumination*colour temperature F(1,799)=1.866, P=0.172>0.05. It can be concluded that the reaction time relies heavily on working mode, illuminance, colour temperature and illuminance*colour temperature, but has little to do with work mode*illumination, working mode*colour temperature, and working mode*illumination*colour temperature.

Then, the illuminance and colour temperature were discussed separately due to the significant interaction effect between the two factors. Through the individual analysis on VDT single working mode and multi-working mode, it is learned that the illuminance of 500lx or 750lx and the colour temperature of 4,000K or 6,500K directly bears on reaction time under whichever working mode, and vice versa. Figure 2 illustrates how illuminance and colour temperature individually affects cognitive ergonomics in different working modes. As shown in the figure, the illuminance for the optimal reaction time of VDTs remains the same under the single or multi-working mode.

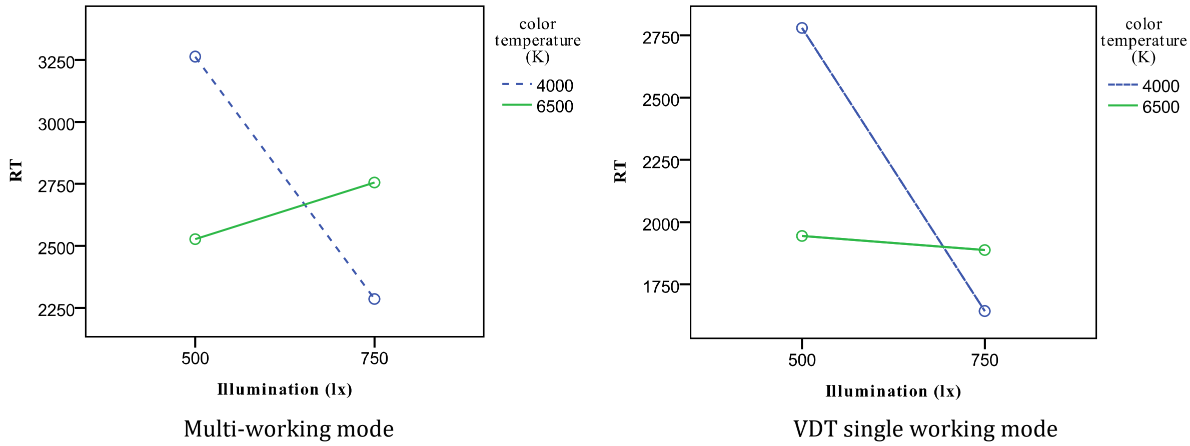

Figure 2. Individual effect of illuminance or colour temperature on cognitive ergonomics in different working modes

(2) Comparing the effect of lighting conditions on accuracy in different working modes

After repeated measurements and analysis, it is observed that the accuracy is not significantly impacted by illumination, colour temperature, mode*illumination, mode*colour temperature, illuminance*colour temperature, or mode*illumination*colour temperature. However, the working mode is a main influencing factor of accuracy. Therefore, the lighting conditions have no impact on accuracy, eliminating the need for further comparison.

(3) Comparing the effect of lighting conditions on eye movement indices in different working modes

The variance of the pupil diameter variation coefficient was analysed through repeated measurements. The results are as follows: mode $F(1,19)=7.009$, $P=0.016<0.05$; illuminance $F(1,19)=1.517$, $P=0.233>0.05$; colour temperature $F(1,19)=0.001$, $P=0.970>0.05$; mode*illuminance $F(1,19)=4.674$, $P=0.044<0.05$; mode*colour temperature $F(1,19)=0.115$, $P=0.738>0.05$; illuminance*colour temperature $F(1,19)=4.719$, $P=0.043<0.05$; mode*illumination*colour temperature $F(1,19)=3.745$, $P=0.068>0.05$.

First, the author contrasted the effects of illumination and colour temperature on the pupil diameter variation coefficient in single and multi-working modes. Considering the limited effect on the coefficient and interaction between the two factors, the illuminance and colour temperature were examined separately. Under the colour temperature of 6,500K, the pupil diameter variation coefficient plunged deep from the illuminance of 500lx to that of 750lx in the single working mode ($P=0.024<0.05$). There was no significant difference in the coefficient under any other conditions.

The effects of working mode, illuminance and colour temperature on per-second blinking rate were also investigated via repeated measurements. The investigation shows that the working mode is the only major influencing factor of per-second blinking rate ($F(1, 19)=54.773$, $P=0.000<0.01$). Furthermore, the interaction between illuminance, colour temperature and the other factors has no significant effect on the per-second blinking rate.

Lighting ergonomics analysis in multi-working mode

(1) Analysis of reaction time

In the multi-working mode, the lighting efficiency was analysed under the mixed working mode of hard-copy documents and VDTs. Table 5 displays the results of variance analysis through repeated measurements. It can be seen that illumination, colour temperature and the interaction effect between the two factors all have pronounced effect on reaction time, making it necessary to discuss the individual effect of illuminance and colour temperature. As can be seen from Figure 3, the minimum reaction time, that is, the fastest reaction speed, appeared at the illuminance of 750lx and the colour temperature of 4,000K.

(2) Analysis of accuracy

The analysis results are as follows: illumination ($F(1,1999)=0.024$, $P=0.876$), colour temperature ($F(1,1999)=0.510$, $P=0.475$), and illuminance*colour temperature ($F(1,1999)=1.801$, $P=0.180$). Thus, the accuracy in multi-working mode is not heavily affected by illuminance, colour temperature or the interaction between them.

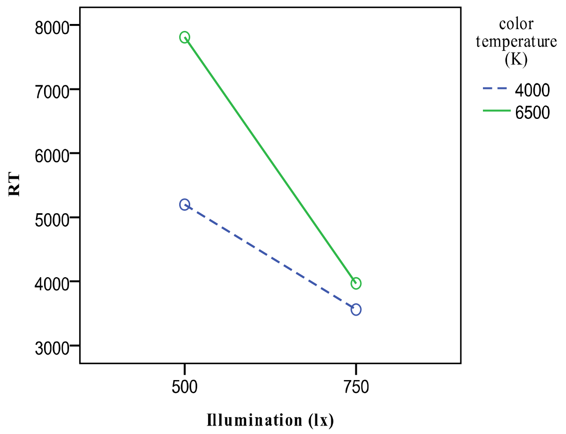

Figure 3. Individual effect of illuminance or colour temperature on reaction time in multi-working mode

(3) Analysis of eye movement indices
The analysis results are as follows: illumination (F(1,3)=0.698, P=0.414), colour temperature (F(1,3)=0.544, P=0.470), and illuminance*colour temperature (F(1,3)=0.000, P=0.985). From the results, it can be inferred that none of the three factors exert any significant effect on the pupil diameter variation coefficient in multi-working mode. Similarly, none of illuminance (F(1,19)=1.550, P=0.228), colour temperature (F(1,19)=0.489, P=0.493), and illuminance*colour temperature (F(1,19)=0.370, P=0.550) has any significant effect on per-second blinking rate.

Subjective scale analysis

(1) CH scale analysis
A total of 80 questionnaires were issued, all of which were effectively recovered. The experimental task was graded on a 10-point scale. The grades obey normal distribution (P=0.000<0.05), with the average working load being 5.41 and the standard deviation being 3.096. Among the subjects, 22.5% considered the task as difficult (7 points), requiring huge mental efforts to lower the errors to moderate levels; 21.25% viewed the task as relatively easy (2 points); 20% believed that the task was difficult (8 points), requiring huge mental efforts to avoid large or numerous errors. On average, the experimental task has a moderate difficulty, and needs high mental concentration to be completed successfully.

(2) POMS scale analysis
The POMS, consisting of a pre-experiment part and a post-experiment part, reflects the mood changes arising from the experiments. Thus, the test group and the control group were individually compared before and after the

Table 5. Results of variance analysis on lighting efficiency in the multi-working mode

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Illumination	Sphericity Assumed	1.502E10	1	1.502E10	67.919	.000
	Greenhouse-Geisser	1.502E10	1.000	1.502E10	67.919	.000
	Huynh-Feldt	1.502E10	1.000	1.502E10	67.919	.000
	Lower-bound	1.502E10	1.000	1.502E10	67.919	.000
Error (illumination)	Sphericity Assumed	4.420E11	1999	2.211E8		
	Greenhouse-Geisser	4.420E11	1999.000	2.211E8		
	Huynh-Feldt	4.420E11	1999.000	2.211E8		
	Lower-bound	4.420E11	1999.000	2.211E8		
Color temperature	Sphericity Assumed	4.554E9	1	4.554E9	20.252	.000
	Greenhouse-Geisser	4.554E9	1.000	4.554E9	20.252	.000
	Huynh-Feldt	4.554E9	1.000	4.554E9	20.252	.000
	Lower-bound	4.554E9	1.000	4.554E9	20.252	.000
Error (color temperature)	Sphericity Assumed	4.496E11	1999	2.249E8		
	Greenhouse-Geisser	4.496E11	1999.000	2.249E8		
	Huynh-Feldt	4.496E11	1999.000	2.249E8		
	Lower-bound	4.496E11	1999.000	2.249E8		
Illumination* color temperature	Sphericity Assumed	2.434E9	1	2.434E9	10.506	.001
	Greenhouse-Geisser	2.434E9	1.000	2.434E9	10.506	.001
	Huynh-Feldt	2.434E9	1.000	2.434E9	10.506	.001
	Lower-bound	2.434E9	1.000	2.434E9	10.506	.001
Error (illumination * color temperature)	Sphericity Assumed	4.632E11	1999	2.317E8		
	Greenhouse-Geisser	4.632E11	1999.000	2.317E8		
	Huynh-Feldt	4.632E11	1999.000	2.317E8		
	Lower-bound	4.632E11	1999.000	2.317E8		

experiments. The results reveal no major change in the mentality of the subjects across the experiment (P=0.300>0.05).

As mentioned above, the POMS scale can capture the mood variation of the subjects before and after the experiments. Here, the mood variation is captured against colour temperature and illuminance. The mood scores were tested by the average variance of the dependent variables. Prior to the experiment, the variables were treated as one layer, and the colour temperature and illuminance were taken as another layer. The results show that moderate colour temperature and illuminance have no significant effect on the mood before and after the experiments (P=0.300>0.05).

Table 6. One-way analysis of variance(ANOVA) of the POMS

	Sum of Square	df	Mean Square	F	Sig.
Between Groups	406.406	1	406.406	1.081	.300
Within Groups	59374.788	158	375.790		
Total	59781.194	159			

Results and Discussion

Main influencing variables

(1) Comparison of working modes

The working mode has a major impact on the reaction time of information identification. The multi-working mode differs greatly from the VDT single working mode in information identification. The average reaction time in multi-working mode was 3,136.11, much longer than that in the VDT single working mode (2,182.90).

The working mode also has a significant effect on accuracy. The multi-working model boasts a higher average accuracy than the VDT single working model (0.9929 vs. 0.9819). Note that the working mode of hard-copy documents has no significant difference from the VDT working mode (Jiang, 2008). Thus, it is possible to eliminate the speed improvement in the information identification of hard-copy documents.

The difference in reaction time may arise from the following two reasons. First, it takes time to move the line of sight between the hard-copy documents and the VDTs; second, the eyes need to adapt to the new environment when the line of sight is moved from the hard-copy documents to the VDTs or in the opposite direction. The experimental results show that the reaction is time-consuming and highly accurate in the multi-working model, and time-saving but low in accuracy in the VDT single working mode. Thus, it is possible to enhance the accuracy of the VDT operation despite the slowdown in progress.

The pupil diameter variation coefficient and per-second blinking rate vary from working mode to working mode. On average, the two factors are greater in the single working mode than the multi-working mode. The pupil diameter variation coefficient is positively correlated with the degree of fatigue (Xue-song and Li, 2015), while the per-second blinking rate is negatively correlated with the latter (Fu, 2011). Therefore, the degree of fatigue derived from the pupil diameter variation coefficient contradicts that from the per-second blinking rate.

There are two kinds of blinking: the natural reaction of the body, and the protective measure against external stimuli. In general, blinking is very susceptible to external influences. Thus, the per-second blinking rate is not so stable and scientific as the pupil diameter variation coefficient. So far, there is no report comparing the per-second blinking rates needed to identify the information on hard-copy documents and the VDTs. It is not yet clear if hard-copy documents caused the lower per-second blinking rate of hard-copy documents than that of VDTs in our experiments. However, previous studies have shown that VDT reading is very likely to cause eye burn, pain, irritation, and strain (Dainoff *et al.,* 1981), and that the eyes may blink frequently during VDT reading to alleviate discomfort. Therefore, the author held that the VDT single working mode is easy to cause visual fatigue, and so it is with continuous working with computer.

(2) Environmental lighting ergonomics in multi-working mode

In the multi-working mode, the illuminance has a significant effect on the reaction time. Specifically, the reaction time of moderate illuminance (500lx) is longer than that of the high illuminance (700lx). In other words, the information is identified at a much faster speed at high illuminance than moderate illuminance. Meanwhile, it is observed that the two illuminance levels have no obvious difference on the pupil diameter variation coefficient or per-second blinking rate, causing no significant changes to eye fatigue. Therefore, the illuminance has no significant effect on eye fatigue in short-term information identification (about 30min), and the difference in information identification speed is mainly attributable to the effect of illuminance on cognitive efficiency.

In the multi-working mode, the colour temperature has a significant effect on the reaction time. Specifically, the reaction time at high colour temperature (6,500K) is longer than that of medium colour temperature (4,000K). In other words, the information is identified at a much faster speed at medium colour temperature than high colour temperature. Similar to illuminance, the colour temperature does not have any major impact on the pupil diameter variation coefficient or per-second blinking rate. The conclusion agrees well with Hu's finding that the VDT information recognition is faster at 4,000K than 6,500K.

Through the above discussion, it is possible to drawn the following conclusions: the single working mode of hard-copy documents, the single working mode of VDTs and the multi-working mode have the same performance on colour temperature, and the optimal colour temperature is 4,000K. The value is not only the colour temperature of natural light, but also the recommended colour temperature for office lighting in man-machine engineering manuals. The lamp tubes in most classrooms and offices, too, have a colour temperature of 4,000K.

Variables with little impact

The illuminance has no significant effect on VDT working ergonomics in the single or multi-working modes. For VDTs, the optimal illuminance remains constant regardless of the working mode, i.e. the VDT lighting ergonomics is stable and independent of the working mode. Despite the efficiency difference, the single and multi-working modes share the same optimal illuminance. Thus, the working mode is negligible in future work on illumination.

The experimental results show that illuminance and colour temperature have no significant effect on accuracy in multi-working mode. Considering the previous research, it is concluded that the information identification cannot be more accurate by changing the illuminance or colour temperature in the VDT single working mode or the multi-working mode.

In addition, the illuminance has no significant effect on the pupil diameter variation coefficient or per-second blinking rate, and the mood before and after the experiments has nothing to do with the working mode and lighting conditions.

Conclusions

First, the single working mode differ greatly from the multi-working mode in cognitive performance. In spite of the high speed, the VDT single working mode is low in accuracy and easy to cause eye strain. Therefore, the working mode could be optimized by integrating hard-copy documents like paper task lists and paper records in VDTs. In this way, the staff will identify information more accurately and experience less eye fatigue.

Second, the illuminance has no significant effect on the cognition ergonomics of VDT working, whether in VDT single working mode or multi-working mode. VDT lighting efficiency is independent of the working mode, and the effect of lighting environment on multi-working mode is no different from that of VDT single working mode. However, the colour temperature of 6,500K and the illuminance of 500lx tend to cause eye fatigue in VDT single working mode.

Third, in multi-working mode, the optimal lighting conditions for the best cognitive ergonomics are: high illuminance (700lx) and white light (4000K).

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