Publication V(B)

Juslén H. (2006) Influence of the colour temperature of the preferred lighting level in an industrial work area devoid of daylight. Ingineria Iluminatului, 8,18, 25-36.

INFLUENCE OF THE COLOUR TEMPERATURE OF THE PREFERRED LIGHTING LEVEL IN AN INDUSTRIAL WORK AREA DEVOID OF DAYLIGHT

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The first objective of the study was to find out if preset colour temperature and illuminance level affects the preferred lighting levels in an industrial work environment. The second objective was to measure if the illuminance or colour temperature has an effect on productivity. A dimmable task-lighting system was installed above eight individual industrial assembly workstations. Four preset "switch-on" settings were employed (4400 K/350 lux, 4400 K/820 lux, 3500 K/350 lux, 3500 K/820 lux). The system allowed the workers to change the illuminance but not the colour temperature using IR-controllers after the lighting was switched on. The values selected by the (regular) workers were recorded. It was found that slightly lower task-lighting illuminances were selected when the colour temperature was higher, and a much higher illuminance was selected when the preset switch-on illuminance was higher. The productivity of the workers was significantly higher (5.7 per cent) when the higher colour temperature was in use. The switch-on illuminance did not affect productivity.

Keywords: lighting, productivity, colour temperature, preferred illuminances

1 Introduction

In most cases, lighting is designed to meet the minimum norms and up until now most of the lighting research has neglected to study the lighting preferences of industrial workers. It is worthwhile to build up knowledge with respect to the preferences of workers regarding lighting level and light colour and to establish whether there are any differences between workers. This information could help to create lighting conditions that workers prefer, thus increasing their well-being and indirectly influencing productivity.

Inside Europe there are differences between the colour temperatures preferred. More lamps with a warmer colour temperature are sold in northern Europe and more lamps with a cooler colour temperature in the south. This is typically explained by the differences in weather and temperature conditions. In areas with a lot of daylight, the colour temperature of the artificial lighting is not so evident because of the contribution of the daylight. In office-lighting studies, where people's control behaviour has been studied (Maniccia et al. 1999; Escuyer and

Fontoynont, 2001; Moore et al. 2003; Love, 1998; Boyce, 1980; Jennings et al. 2000; Begemann et al 1997), daylight has been available. In industry, the daylight contribution is quite often missing. Control-behaviour studies (Juslén et al. 2005) in industrial environments not encompassing changes in colour temperature show that workers have their individual preferences for the level of the lighting, but the difference between individuals is large.

Recent findings of non-image-forming, psycho-biological effects of light via a photo-biological pathway in the brain (Brainard et al. 2001, Hattar et al. 2002, Berson et al. 2002) and the increasing demands for higher productivity have made the issue of lighting and productivity in industrial environments topical once again. As shown by melatonin-suppression tests, the sensitivity of intrinsically photosensitive retinal ganglion cell (ipRGC) has a peak in the area of 420 nm - 490 nm. (Qiu et al. 2005, Panda et al. 2005, Melyan et al. 2005, and Newman et al. 2003). This could mean that higher colour temperatures might be more effective for alertness and productivity.

2 Methods

2.1 General

In this work, two aspects were studied. Firstly, by installing a dimmable task-lighting system (illuminance and colour temperature), the aim was to see what kind of illuminances workers would select and whether the switch-on colour temperature or illuminance would influence their choice. Secondly, by monitoring productivity figures, it would be observed whether the illuminance or colour temperature had any effect on productivity.

2.2 Lighting and work in the test area

2.2.1 The situation before the test installation

The study was conducted in two types of workstations in a German luminaire factory. Before the lighting change, general lighting (4000 K) was always on when people were working in the area. It produced 500 lux horizontal illuminance on the working plane and 200 lux vertical illuminance at eye height over the total floor area, without shadows.

Type 1 workstation (Figure 1a)

Work

In this area, the workers were assembling control gear, lamps, end caps and wires in the luminaire housings. Materials were mainly white in colour, and the visually most demanding part was the wiring. The tasks were mainly on the horizontal plane. In the European standard for this kind of work, namely EN 12464-1 (2.6 electrical industry, 2.6.2 assembly work, medium), the minimum maintained illuminance required is 500 lux.

Breaks

Workers in this area were working in one or two shifts, depending on the work load (0600-1400 and 1400-2200 hours). There were three scheduled breaks: 0900-0915, 1200-1230 and 1800-1830 hours.

Workers

During the productivity measurement period (8 months), 26 female workers (average age 45 years) were working in the area. Before the productivity measurements (5 months) and after them (3 months), workers' presence was not monitored. This

meant that during the total period the number of workers was actually slightly higher (around 30) and the average age somewhat lower (summer workers).

Lighting

Prior to the test installation, there was no task lighting in these workstations. General lighting provided 300-400 lux horizontal at the middle of the table. (2*58 W TLD 840 lamps, open reflector). There was no daylight available.

Type 2 workstation (Figure 1b)

Work

In this area, luminaire optics were assembled manually. The material was relatively glossy aluminium. Workers put together lamellae to side reflectors. The tasks were mainly on the horizontal plane. In the European standard for this kind of work, namely EN 12464-1 (2.6 electrical industry, 2.6.2 assembly work, medium), the minimum maintained illuminance required is 500 lux.

Breaks

Workers in this area were working one shift (0600-1400 hours) incorporating two scheduled breaks: 0900-0915 and 1200-1230 hours. Normally only two or three workers were present at these workstations per shift.

Workers

Six female workers (average age 41 years) were working in these workstations. The presence of individual workers was not monitored.

Lighting

The old task-lighting system before the change delivered 400 lux horizontal illuminance at the middle of the table (1*58 W TLD 840 lamps, prismatic optics). General lighting provided 400 lux horizontal at the middle of the table (2*58 W TLD 840, open reflector). There was no daylight available.

Figure 1, a) (top): Type 1 workstation before the lighting change. b) (bottom): Type 2 workstation before the lighting change.

2.2.2 The situation during the study period

The work and workers remained the same before and during the study. Only the lighting installation was changed. Figures 2a and 2b show the workstation after the change (during the study period.) New dimmable lighting was installed in both types of workstations. There were two lamps (Philips 54 W T5) with different colour temperatures (2700 K and 6500 K) in this the task-lighting luminaire, and the balance between them could be changed to achieve different colour temperatures. To make colour temperature differences more visible and to limit the effect of the task lighting on the other adjacent workstations, a white canopy and a partial-separation wall were added. The general lighting remained unchanged, but these new screening structures reduced the amount of general lighting available at the workstation.

Type 1 workstation (Lighting installation during the study - Figure 2a)

The luminaires were installed at a height of 225 cm above the floor, and the table height was 70 cm. The general lighting provided a constant illuminance of 200-300 lux at the middle of the tables, while the task lighting provided a maximum of 700 lux in addition to this.

Type 2 workstation (Lighting installation during the study - Figure 2b)

The luminaires were installed at a height of 218-230 cm above the floor and the table height was 93-98 cm. The general lighting provided a constant illuminance of 200-300 lux at the middle of the tables, while the new task lighting provided a maximum of 900 lux in addition to this.

Figure 2, a) (top): Type 1 workstation during the study. b) (bottom): Type 2 workstation during the study

2.3 Data logging and changing the control possibilities of the workers

In order to induce the workers select their preferred illuminances, the dimmable task lighting was regularly switched off automatically. Table 1 shows the switching schedule. Part of the automatic switching

was during the official breaks. Those switch-off moments described as being 'extra' were discontinued after the first eight months of monitoring, since the workers were bothered by them. The short 'on' period in the morning was to warm up the lamps before the workers entered the area.

Time	Command	Remarks
5.50	On	Warming the lamps before work
6.00	Off	Warming the lamps before work
7.30	Off	extra off
9.10	**Off**	**break**
10.30	Off	extra off
12.25	**Off**	**break**
14.00	**Off**	**break**
15.15	Off	extra off
16.30	Off	extra off
18.15	**Off**	**break**
19.30	Off	extra off
21.00	Off	secure switch-off after work
22.00	Off	secure switch-off after work

Table 1. Switching schedule in the study area

In order to restore the lighting after switch-off, the workers had to switch it on again using their infrared transmitters. They could then set the lighting level to their preference. The switch-on level of the lamps was varied between four different situations, which are shown in Table 2. Changing of the switch-on situation was normally done on Friday evening. During the 16-month measuring period, the settings were changed 44 times. Each time, one of the four settings was on for an average of somewhat less than two weeks. The workers were able to readjust the lighting level whenever they felt like it, but they could not change the colour temperature. To increase or decrease the level, the workers had to press the button until the lighting level was the level they wanted. From the lower presets it took more than four seconds to reach maximum. The luminaires' DALI ballasts were connected to a LON bus system (Local Operating Network), and the selected output of the lamps was monitored between March 2004 and June 2005. For every 10-minute period, the dimming values of both lamps in the luminaire were recorded. The illuminances under the different dimming voltages at the middle of the different tables were measured. Based on these measurements, data-logged dimming levels have been transformed to the illuminances presented in this paper.

Table 2. Switch-on levels. The values in workstations types 1 and 2 are a combination of the task lighting and the general lighting and averages of values on similar tables. The table-top colour temperature is measured from white paper placed in the middle of the table, while the wall value is measured from the middle of the vertical screening wall between working areas. Illuminance values are measured from the same places.

		Lamp dimming		Test area 1 (General + Task lighting)				Test area 2 (General + Task lighting)			
	Task luminaire	Warm	Cold	Table		Wall		Table		Wall	
	CT (K)	%	%	CT (K)	E (lux)	CT (K)	E (lux)	CT (K)	E (lux)	CT (K)	E (lux)
High warm	3500	85	55	3500	740	3500	350	3600	990	3700	460
High cold	4400	52	88	3900	760	4100	360	4000	970	4300	500
Low warm	3500	12	8	3700	310	3700	90	3800	410	3700	120
Low cold	4400	7	13	3700	310	3800	90	3800	400	3800	120

3 Results

3.1 Selected Illuminances

The workers used practically the whole illuminance scale available. The values selected ranged from 250 lux to 1200 lux, peaking at around 800 lux (horizontal illuminance at the table). Since the presence of workers at a given workstation was not followed continuously, it is difficult to say exactly how often task lighting was used. Based on the workers' verbal comments, it is clear that some workers did not always use task lighting. However, based on the data gained during the productivity measurement period, when presence was also partially monitored, it can be said that during more than 75 per cent of the working time these lights were in use. There were differences among the individuals: some used task lighting nearly all the time, while others used it only rarely. The amount of data regarding the illuminances selected at the different colour temperatures correlates with the number of days that a given preset was in use. This indicates that colour temperature did not markedly influence the frequency of use of the task lighting.

The influence of preset colour temperature and illuminance on employee's choice has been studied by considering all the selections made by the workers. The statistical means of the illuminances selected depending on the preset value are shown in Figure 3. Factorial ANOVA (analysis of variance) was used for the analysis of the data.

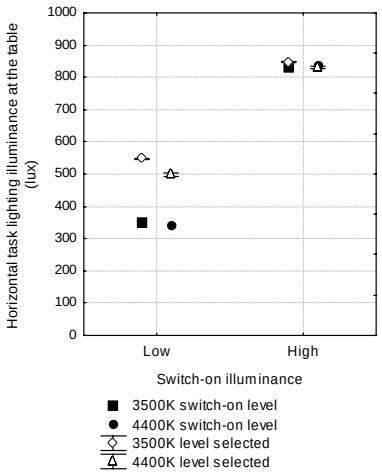

Figure 3. The influence of the colour temperature and the switch-on illuminance on the illuminances selected (task lighting + general lighting for all selections made on both workstation types).

For the task-lighting illuminance (dependent variable: task lighting illuminance; factors: colour temperature and switch-on illuminance), the ANOVA showed a significant main effect for the factor colour temperature ($F(1, 48213)= 295.8$, $p<0.01$). Also the main effect for for the factor switch-on illuminance was significant ($F(1,48213)=26294$ $p<0.01$). And the interaction between colour temperature and switch-on illuminance was also significant ($F(1, 48213)=62.8$, $p<0.01$).

The preset colour temperature at switch-on had a significant effect on the illuminance selected by the worker. When the colour temperature of the task-lighting luminaire was 3500 K, workers selected illuminances that were 5 per cent higher than when it was 4400 K. The influence of the switch-on illuminance of the task lighting was considerably more noticeable. When this was high, workers selected task-lighting illuminances that were

60 per cent higher than when the switch-on illuminance was low.

When preset illuminance values were high, the difference in the selected illuminances was small under different colour temperatures (Figure 3). When lower preset illuminance values were in use, workers tended to increase the task-lighting illuminance, so influencing the mixed colour temperature on the table and wall. However, the average colour change on the table was less than 100 K towards a colder value when the starting value of the illuminance was low and the colour temperature of the luminaire was 4400 K, and less than 100 K towards a warmer value when the starting value of the illuminance was low and the colour temperature of the luminaire was 3500 K.

The effect of the time of the day on the illuminance selected was tested by using the data type 1 workstations - in these workstations, employees also worked in the evening. The results of one-way ANOVA (independent variable: illuminances; factor: time) showed very small differences. During the morning shift, average illuminance values per hour varied between 621 lux and 643 lux. During the evening shift, the variation was from 603 lux (1800-1900 hours, this time the evening shift included a meal break) to 670 lux (2100-2200 hours - last working hour). Evening-shift differences in selected illuminance were statistically significant ($p<0.05$) but still small.

The data from the Type 1 workstations were also employed to find out if selections during bright months (May, June, July and August) differed from other periods. When the switch-on value was high, there were no real differences. The same was true for the low switch-on value when the colour temperature was 3500 K. However, when the colour temperature was high and the switch-on level was low, there were statistically significant differences in selected illuminances (bright months on average 580 lux; other months on average 380 lux).

3.2 Productivity

The influence of the preset colour temperature and illuminance on productivity was studied by collecting productivity figures from type 1 workstations between August 2004 and April 2005. A total of 26 individuals were working in the area during that period. Productivity of the assembly work is calculated by comparing planned and real working time. The nominal value is 60 minutes, so if a worker does 150 minutes work in 100 minutes, the productivity value is 90 minutes. If the same work were to take 200 minutes, the value would be 45 minutes. So the higher the value, the higher the productivity. Values in Figure 4 are average daily values and they have been shown for the different switch-on colour temperature and switch-on illuminance values. Factorial ANOVA (analysis of variance) was used for the analysis of the data.

For the productivity (dependent variable: productivity; factors: colour temperature and switch-on illuminance), the ANOVA showed a significant main effect for the factor colour temperature ($F(1, 323)= 4.9$, $p<0.05$). The main effect for the factor switch-on illuminance was not statistically significant ($F(1,323)=0.32$, $p=0.57$).
The interaction between colour temperature and switch-on illuminance was not significant ($F(1, 323)=0.33$, $p=0.57$).

The colour temperature of the task-lighting luminaire had a significant effect on productivity. When the colour temperature was 4400 K, productivity was 5.7 per cent higher compared to when it was 3500 K. The switch-on illuminance did not significantly affect the productivity.

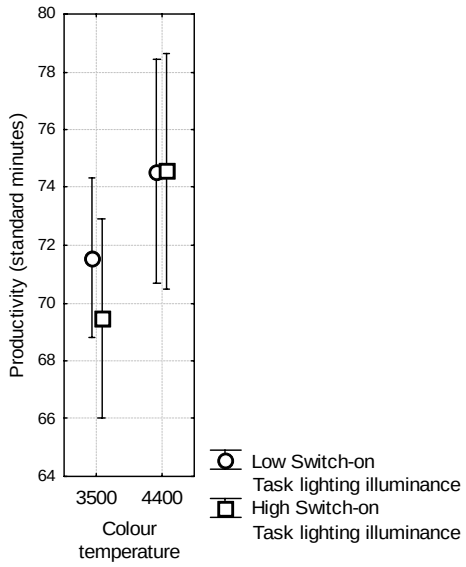

Figure 4. The influence of the colour temperature and the switch-on illuminance on the productivity. Higher value means higher productivity. Vertical bars denote 95 per cent confidence intervals.

4 Discussion

The possible errors in the illuminance values that are presented in this paper are caused mainly by the temperature behaviour of the lamps and the differences between the workers. T5 lamps are very temperature sensitive. When the worker switches on the cold lamps and chooses a lighting level, the lamps will warm up (slowly) and after some time the light output will increase. This is especially true at low dimming levels. The main difference between workstations was their location with respect to the general lighting, which was therefore slightly different at each workstation. Part of the results presented here are therefore averages for all eight workstations. The most important "error" factor was most probably the individual worker - way of working, hairstyle, colours of the clothing, etc., influence the lighting level on the task area. Also, shadows cast by the worker result in a lower lighting level in the task area than that measured on the empty table, which was the value employed in this work.

The presence of the workers at workstations was not monitored during the whole test period. It is known (Juslén et al. 2005) that workers in similar situations might select very different task-lighting illuminances. But since employees' positions are not exactly known, no firm conclusions can be drawn regarding seasonal or hourly differences between the lighting levels employed or the frequency of use of the lighting.

It is interesting that the higher colour temperature seemed to result in a lower preferred illuminance. However, the 5 per cent difference mentioned earlier (Sec. 3.1) is not large enough to be discernible (perceived by the eye). The 5 per cent differences in illuminance could also be attributable to measurement errors. But since every workstation was measured individually and in the same way, it is not likely that any errors would be in favour of one colour temperature. So even if a 5 per cent error in illuminance were possible, the

direction and size of the error should be the same for both colour temperatures.

It is not possible to say why colour temperature influenced the selected illuminance. However, when controlling luminaires by IR remote control it is usual to look at the luminaires whilst doing so - is something happening? does the pushbutton work? It might be that the luminaire with the 4400 K setting was seen as being brighter than the same luminaire set to 3500 K. This "brightness" difference might have created the illuminance difference when workers were actually aiming for more or less same the same value. Some early studies provided evidence that the higher the colour temperature of a lighting, the higher is its perceived brightness (Harrington, 1955; Alman, 1977). But also some more recent studies have been carried out that show that this connection does not exist (Boyce and Cuttle, 1990; Hu et al. 2006). It might be that the connection is more complicated than just colour temperature - colour rendering might also have an effect (Fotios, 2001)

The differences in selected illuminances under different colour temperatures are interesting, especially since the higher colour temperature resulted in higher productivity. So for productivity as well as for energy reasons, these results seem to indicate that a higher colour temperature (4400 K) is a better solution for task lighting than a lower colour temperature (3500 K). Colour-temperature differences are small at the workstation (400 K at the table between higher illuminance presets). On the wall, in front of the workers, differences are a little bit higher (600 K between higher illuminance presets), because less general lighting and more task lighting enters that area. Illuminance differences at the workers' eyes are probably greater since wall and canopy cut off most of the direct general lighting. Light entering the workers' eyes comes directly from the task-lighting luminaire or via reflection from the wall (mainly task lighting) or from the table. Laboratory studies have shown that bright light influences the alertness and cortisol suppression of people (Scheer and Buijs, 1999; Leprout et al. 2001). It is also stated that bright light improves vitality and alleviates distress in healthy people (Partonen and Lönnqvist, 2000). When we examine the results of recently-found action spectra of the photo-biological effects (Brainard et al. 2001), we see that the productivity results of this present study might be explained by this. A higher colour temperature might have resulted in higher productivity by increasing the alertness of the workers. However, the temperature difference is quite small (3500 K/4400 K) and it is unlikely that the result is purely biological. Another possible reason for higher productivity could be improved visual acuity. There is some evidence that a higher colour temperature improves near-visual acuity (Berman et al. 2006). However, since employees used 5 per cent lower illuminances in the higher colour temperature situation compared to those used in the lower colour temperature situation, this is not likely to be the only reason.

The illuminance selection results were different in this work compared to that described in the study by Juslén et al. (2005), where the subjects were using more or less the same lighting level whatever the preset values or dimming speeds. In this case, the preset value clearly influences the illuminance selected. With a high preset

level, the workers just switch on the light, whereas with low presets they increase the lighting, but not to such a high value as with high preset levels. However, the difference was only 300 lux. The total range in this study (300–1000 lux) was small compared to the 200–3000 lux range that was employed in the study of Juslén et al. (2005).

5 Conclusions

The results of this study suggest that for a lower use of energy as well as for higher productivity, the colour temperature of the dimmable task lighting system should be around 4400 K rather than around 3500 K. The results indicate that for increased productivity, the colour temperature increase of 3500 K to 4400 K is a more important factor than the illuminance increase from 500 lux to 800 lux. It can be concluded that in these circumstances:

- The 4400 K preset colour temperature resulted in a 5.7 per cent higher productivity than did the 3500 K preset value of the task lighting.
- Illuminance (520/820 lux) did not influence productivity.
- The 4400 K preset colour temperature led to 5 per cent lower illuminance selection than did the 3500 K preset value of the task lighting.
- The lower preset illuminance led to significantly lower selected illuminances than did the higher preset illuminance.
- Dimmable task lighting was actively employed.
- Selected illuminances of the dimmable task lighting varied considerably.

Acknowledgements

I am grateful to management and all personnel of Philips Springe, and especially to all the workers who participated in this study. My special thanks go to Minje Afheld for helping out in many practical issues during the research. I also wish to thank Toni Kobs for handling productivity measurements, Dirk Maennicke for his help with the measurement computer, Marius Wouters and Ariadne Tenner for commenting on the study design, and Liisa Halonen and Ariadne Tenner for improving the manuscript. The assistance of the Philips' Lighting Controls department has been essential in being able to data log the values used. My thanks to Henk Verstegen and Noël Bonné, and their colleagues.

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Received 16 November 2006,
Revised 19 February 2007
Reviewers: Dr. David CARTER,
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