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Individual dynamic lighting control in a daylit space

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SUMMARY
The objectives of the study are to observe individual preferences for dynamic lighting, individual control and possibly achieve energy savings in a daylit space. The dynamics in this study are modifications of light level and correlated colour temperature (CCT) from the electric lighting system in combination with daylight. Subjects performed office work for one day in a simulated office environment. Every 30 minutes the subjects were invited to use the dimmer controls to change the lighting conditions to their preferred level. Measurements were made of illuminance, luminance, CCT and energy use, whereas questionnaires were used to evaluate user satisfaction. The study shows that subjects tended to choose a preferred CCT level, which they maintained to some extent during the day; the subjects did not regulate according to a fixed light level throughout the day. Energy savings were not accomplished in this study and it is concluded that the field of dynamic lighting deserves more research.

KEYWORDS
Dynamic lighting, Individual control, Colour temperature, Office lighting, Daylit space

INTRODUCTION
Lighting affects individuals in different ways; it becomes important to individuals when they have preferences for a very dark or a very bright light for a specific situation (Butler and Biner, 1987). Biner et al. (1989) made a model that shows that the light level of a setting and the social situation can affect arousal. Tenner et al. (1997) found it clearly established that people have some difficulty in deciding how their preferred lighting scenarios appear and Boyce et al. (2006) showed that having a degree of individual lighting control tended to sustain motivation and alertness over the day for office workers. Knez and Enmarker (1998) and Knez and Kers (2000) found that the CCT of the electric lighting can affect the mood of individuals. Verderber (1986) and Leather et al. (1998) established that windows and the view to the outside are rated as important to individuals. Stone (1998) found that subjects perceived a room as being more motivating when the room has a window. Christoffersen et al. (1999) found that satisfaction with the view from an office was greater for views of natural scenes than of man-made scenes and Kaplan (2001) found that the view through windows to the outside affects satisfaction and a sense of well-being. By combining the fact that individuals are differently affected by light levels, CCT and appreciate a view to the outside, the need for some degree of lighting control is essential to the individual. Lighting controls can also be used to achieve energy savings (Roisin et al., 2008).

The primary goal of this study is to link these different aspects by providing individual control of the light level and CCT, daylight contribution and account for the energy use during the experiment. The hypotheses are that by providing daylight contribution with lighting control, energy savings will be achieved and that the controls will not be used to maintain a constant light level on the desktop. Furthermore there might be other photometric variables than the light level on desktops that are better at predicting the use of the controls.

METHODS

Test facilities

The experiment was conducted in the Daylight Laboratory at the Danish Building Research Institute (SBi) (see Figure 1) in Denmark (56°N and 12°E). Inside the laboratory there are two identical, side-by-side experimental rooms (width 3.5m, length 6m and height 3m), one room for subjects (Room A) and the other for researchers and measuring equipment (Room B). The façade faced SSE (7° from true south) and the glass area covered 44% of the façade. The window size and position was 3.5m wide and 1.4m high with a sill-height of 0.78m. Both offices had identical double-glazed windows of conventional clear glass with a low-e coating with a light transmittance of $\tau_\perp$= 72%. White venetian blinds (80 mm, convex, RAL 9016, ρ_{vis}=84%) were controlled by the researcher in both rooms simultaneously to prevent glare from windows. The experiment was carried out in the period from 20 December 2006 to 19 March 2007.
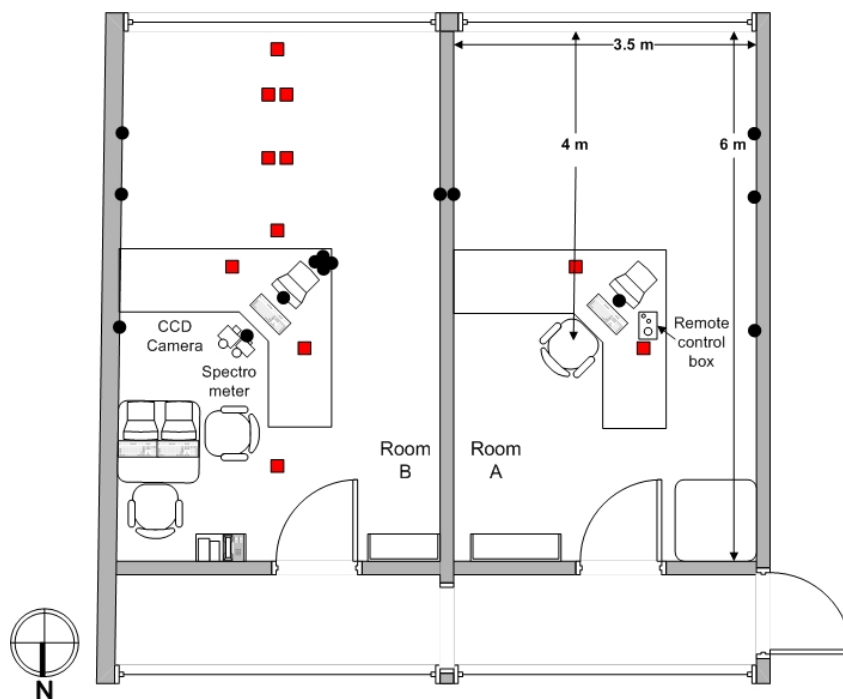

Figure 1. SBi's Daylight Laboratory. Room A used by subjects, Room B used for measurements and by the researcher. Black circles indicate a vertical illuminance meter and red squares indicate a horizontal illuminance meter.

Each office was furnished for one occupant only, with a desk arranged perpendicular to the window, and the main viewing direction at 45° and/or 90° (parallel) to the window. Each desk had a computer and flat 17" LCD monitor (screen luminance ~190 cd/m^2 measured on a white screen, the window being covered and no electric lighting). Table 1 summarizes the materials and reflectances of the furnishings. The subjects were placed at ~ 4m from the window façade in Room A. Room B was identical to Room A with additional photometric measurement equipment; the researcher's desk was placed at the back of the room. This allowed detailed lighting conditions data to be collected.

The lighting system was identical in both rooms, consisting of 3 Philips Savio luminaires (266 x 1259mm ceiling-mounted direct). Each luminaire contained 3 lamps, two were 6500 K (Master TL5 HO 54W/865) and one 2700 K (Master TL5 HO 54W/827). The lamps operated on electronic dimming ballasts by a commercial lighting control system (MultiDim). To

adjust the lighting conditions, the subjects used a remote control box placed on the desk in Room A. By means of the control box, the subject adjusted the electric lighting in both rooms simultaneously. The illuminance conditions in the two rooms were identical to within 3%. The maximum desktop illuminance from electric lighting was 1270 lux, and the minimum was 57 lux. The maximum desktop illuminance provided only by the 2700 K tubes was ~ 400 lux and the maximum desktop illuminance provided only by the 6500 K tubes was ~ 860 lux.

Table 1. Room surface materials and reflectances.

	Material	Colour	Reflectance
Desktop	Wood	Dark brown	0.15
Wall	Gypsum	Light grey	0.62
Carpet	Nylon	Dark grey	0.11
Ceiling	Acoustic tile	White	0.88

Interior and exterior measurements

The interior position of illuminance meters are shown in Figure 1. Global total and diffuse illuminance and irradiance measurements were recorded by an exterior meteorological station located on the roof of the laboratory. The photometric equipment in Room B was mounted on a tripod at the approximate location of the occupant's eyes (1.2 m). The equipment included a vertical illuminance sensor, a spectroradiometer and a digital camera calibrated as a luminance camera (yielding pixel-by-pixel luminance measurements). The energy use for lighting, luminance and CCT were recorded 23 times during the day, immediately before and after subjects changed the light setting by means of the remote control box.

Subjects and Office Tasks

There were 50 subjects (24 male, 26 female), mostly students, ranging in age from 20 to 35; one subject was 44 years of age. All subjects reported having normal or corrected-to-normal vision and only one subject attended the laboratory on each test day. Subjects brought their own work with them. The work included typical office tasks, such as reading, writing and/or working on a computer (on their own laptop or a stationary computer).

Procedure

The experimental session started in the laboratory between 8:45 and 9:15am. In this period the lighting equipment was introduced, subjects answered Part 1 of the questionnaire and learned to use the remote control box. Before subject arrival, the electric lighting was set by the researcher to provide a desktop illuminance of ~500 lx and CCT of ~3500 K. The subjects were told that they could only change the lighting scenario when invited to by the researcher and the invitation came every 30 minutes, beginning at 9:15. The researcher took luminance photos, measured the CCT and registered the energy use immediately before and after the subjects chose their preferred light setting. There were no breaks other than the lunch break (from 12:00 – 12:30). When subjects returned from lunch, the light level on the desktop was adjusted by the researcher to maintain a maximum of 500 lx and the CCT value was kept, as far as possible, at the same level as that chosen before lunch. The final control opportunity occurred at 15:15. At the end of the day, the subjects completed Part 2 of the questionnaire, which included questions on how they used the controls and on their satisfaction with various aspects of the indoor and lighting environment. Information on light sensitivity and chronotype was also collected, but these topics will not be addressed in this paper.

RESULTS

Illuminance Levels
Linear regression does not explain the correlation between individual light setting and dimmer control, as the experiment includes within-subject effects, but it gives an indication of what parameters are important. With that in mind, the results showed the highest correlation between dimmer setting and light level on the desktop and VDT.

The illuminance measured on the desktop is taken as a mean value of two horizontal values measured on both sides of the VDT (see Figure 1). Total desktop illuminance (daylight and electric lighting) had a mean value of 926 lux ($\underline{SD}$ = 538 lux), where electric lighting contributed with $\underline{M}$ = 577 lux ($\underline{SD}$=272 lux). Throughout the day, the total desktop illuminance varied between 129 and 5625 lux. Table 2 gives the descriptive statistics for all subjects and their choices of light levels on the desktop during the day are listed. The table shows variations in preferred light levels depending on different hours of the day and variation between subjects. In the right part of the table, the data for electric lighting only show a tendency to reduced output by increased daylight contribution (middle of the day). However this tendency did not result in a preferred light level during the day.

Table 2. Descriptive statistics of light level choice on the desktop at every measurement taken during the day. D+E = daylight and electric lighting, E = electric lighting only, $\underline{M}$ = mean value, $\underline{SD}$ = standard deviation, Med = median value.

Illuminance measured on desktop during the day	$\underline{M}$ [Lux] D+E	$\underline{SD}$ [Lux] D+E	Med [Lux] D+E	Confidence interval D+E		$\underline{M}$ [Lux] E	$\underline{SD}$ [Lux] E	Med [Lux] E	Confidence interval E	
				Lower 5 % [Lux]	Upper 95 % [Lux]				Lower 5 % [Lux]	Upper 95 % [Lux]
09:15	873	535	685	306	1800	593	298	518	213	1217
09:45	910	567	719	295	2071	567	293	502	173	1133
10:15	1016	889	828	223	2131	565	289	522	167	1091
10:45	922	492	832	376	1779	556	258	548	176	1039
11:15	956	515	772	322	1773	537	269	500	99	1058
11:45	968	515	760	383	1888	558	274	520	199	1020
12:45	898	444	738	436	1827	539	226	524	224	967
13:15	947	419	858	332	1700	572	246	556	187	1019
13:45	881	451	731	299	1762	564	279	550	157	1044
14:15	971	582	816	325	2094	603	272	544	233	1061
14:45	929	551	811	272	1869	618	286	627	154	1080
15:15	840	374	838	282	1401	651	275	653	286	1105

The VDT illuminance was measured at the top of the VDT (vertical). The daylight contribution was limited due to the VDT's position in the room and its orientation in relation to the window (see Figure 1). The mean illuminance value was $\underline{M}$ = 372 lux ($\underline{SD}$ = 234 lux) and a relatively wide variation in chosen light levels during the day. The majority of chosen illuminance values (63%) on the VDT ranged between 100 and 400 lux.

Correlated Colour Temperature (CCT)
The CCT was measured at a 45° viewing angle from the window at eye-level of a seated person (1.2m above the floor). CCT for daylight and electric lighting had a mean value of 4543 K ($\underline{SD}$ = 449 K) and the electric lighting had a mean CCT value of 3917 K ($\underline{SD}$ =

494 K). Table 3 shows that the mean value for the daylight and electric lighting is fairly stable throughout the day, but the variation between the subjects is substantial. In the experiment, CCT measurements varied between 3086 and 6325 K (daylight and electric lighting), but almost half of the subjects chose a CCT level ranging between 4300 and 4900 K. Table 3 (right side of table) lists the CCT choices from electric lighting which shows that the mean value is fairly stable, while variations between subjects is substantial. In the experiment, measurements varied between 2955 and 5350 K for electric lighting and 66% of the chosen values lie in the interval between 3400 and 4300 K.

Table 3. Descriptive statistics for CCT choice. D+E = daylight and electric lighting, E = electric lighting only, $\underline{M}$ = mean value, $\underline{SD}$ = standard deviation, Med = median value.

CCT measured at eye position during the day.	$\underline{M}$ [K] D+E	$\underline{SD}$ [K] D+E	Med [K] D+E	confidence interval D+E		$\underline{M}$ [K] E	$\underline{SD}$ [K] E	Med [K] E	confidence interval E	
				Lower 5% [K]	Upper 95% [K]				Lower 5% [K]	Upper 95% [K]
09:15	4274	488	4210	3623	5103	3956	404	3943	3274	4522
09:45	4474	460	4494	3646	5239	3897	509	3832	3205	4752
10:15	4528	495	4578	3639	5273	3915	557	3816	3171	5001
10:45	4544	492	4594	3593	5356	3854	503	3854	3083	4717
11:15	4593	538	4587	3834	5450	3875	484	3869	3192	4737
11:45	4632	471	4636	3894	5339	3894	480	3877	3162	4769
12:45	4641	490	4680	3738	5486	3934	532	3930	3124	4925
13:15	4612	476	4652	3820	5373	3949	489	3922	3335	4924
13:45	4638	503	4617	3967	5445	3913	543	3862	3178	5169
14:15	4544	487	4590	3771	5378	3938	506	3914	3215	4902
14:45	4529	493	4623	3748	5368	3941	469	3975	3196	4707
15:15	4498	528	4582	3595	5378	3934	477	3984	3153	4503

Figure 2 shows how each subject chooses a preferred CCT level from the electric lighting. When examining the intervals chosen, 36% showed a variation in the CCT setting ranging between 200 and 500 K, 40% ranged between 500 and 1000 K and 24% showed a variation between 1000 and 1700 K during the day. When estimating the effect of these intervals, the combination of daylight and electric lighting must be kept in mind.
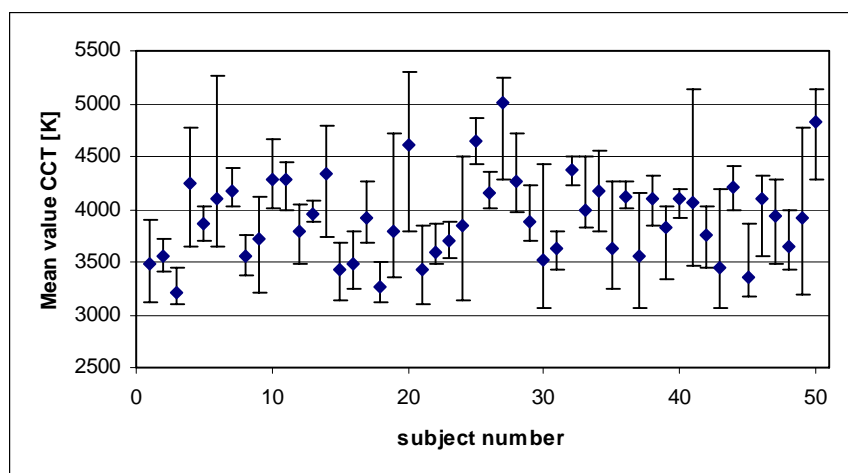

Figure 2. Mean value chosen per day by every subject (diamond) from electric lighting with the upper and lower 95% confidence interval.

Combination of chosen illuminance and CCT

The Kruithof curve for the daylight and electric lighting measurements is shown in Figure 3. The figure shows that the subjects tended to choose a combination of illuminance and CCT that should be perceived as a comfortable lighting environment according to the definition of the Kruithof curve. The thin line shown in the figure indicates the available combinations that could be chosen with the lighting equipment in this experiment.
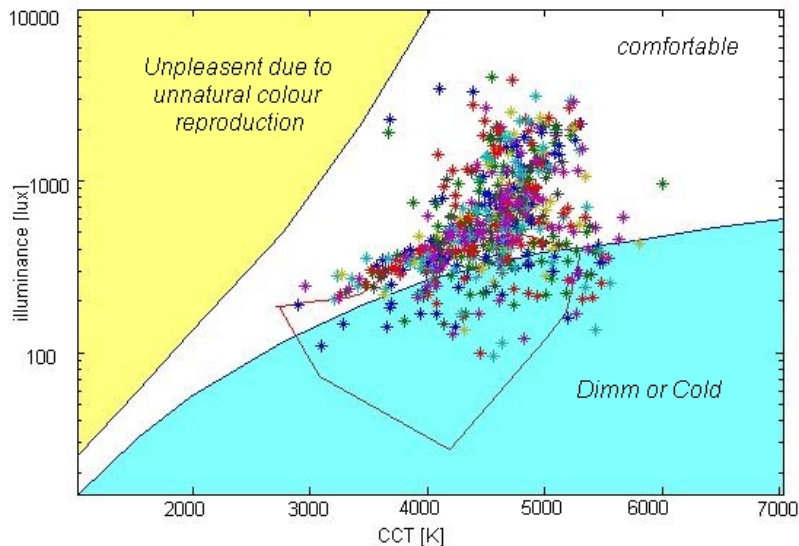

Figure 3. The figure shows a Kruithof curve indicating the subjects' choices as small colourful stars (daylight and electric lighting). A thin line in the figure represents the possible choice from the electric lighting alone. A lighting environment is perceived as comfortable in the white area, while it is perceived as unpleasant in the upper left area (yellow) due the unnatural colour reproduction. The lighting environment in the lowest area (blue) of the Kruithof curve represents the lighting environment that should be perceived as dim at low CCT and cold at high CCT (Kruithof, 1941).

Energy use

The average power of the lighting system per square meter could vary between $4.8W/m^2$ and $26.2W/m^2$. More energy was used in the morning and afternoon than at noon due to the higher output from electric lighting at these hours of the day (see Table 3) and less daylight contribution. For this setup the total average power per square meter was $\underline{M}$ = $12.5W/m^2$ which is more than the maximum average power of $10 \ W/m^2$ recommended by the Danish Electricity Saving Trust. On the other hand a constant level of 500 lux from electric lighting on the desktop (recommended in Denmark) cause the average power per square meter to be $11.2W/m^2$. Figure 4 shows the energy use/day for the experiment and some calculations to put the energy use in perspective to what was possible with the lighting system used in the experiment.
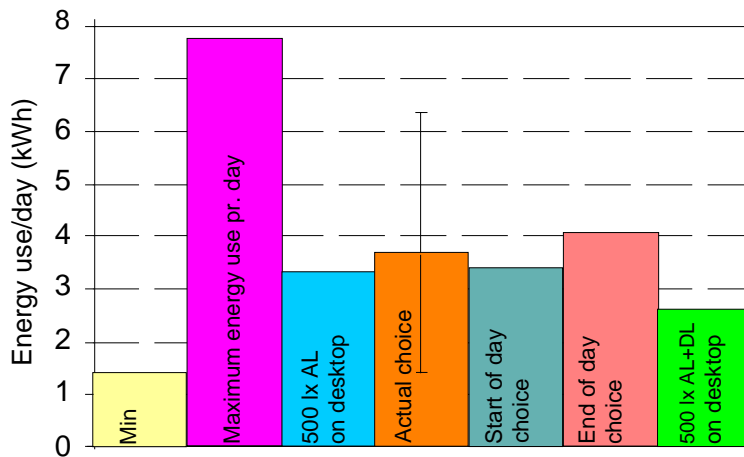
Figure 4. The Figure shows the energy use per day for minimum energy use, maximum energy use, calculated energy use for a constant level of 500 lux from electric lighting (AL) on desktop, the mean value (max, min) for chosen energy use during experiment, the energy use for the first measurement of the day and last measurement of the day and the calculated energy use for an ideal automatically regulated system.

DISCUSSION AND CONCLUSION

This project aims to identify an acceptable approach of dynamic lighting control for office environments in Denmark with focus on user acceptance and energy efficiency.

According to previous research in the field (Tenner et al., 1997), results for chosen light levels from electric lighting depend on daylight contribution and personal preferences with a mean value extending the recommended practice value (500 lux on task). In this study the lighting controls were not used to maintain a constant light level on the desktop in the way that many control systems operate today. The photometric variables that seem to predict the use of the controls were light level on desktop and on computer VDT. The CCT values chosen depended on a personal preference for CCT and 50% of the subjects chose to stay within close range to that preferred value. A combination of chosen CCT and illuminance shows that the subjects tended to choose what can be considered as a comfortable lighting environment (Kruithof, 1941). However, care should be taken to use the Kruithof curve as a design guideline, since more research is needed to validate the curve with today's lamps and lighting systems. The questionnaire data implied that subjects were generally satisfied with the lighting conditions as a whole in the experiment. Most of the subjects registered that they had controlled the lighting depending on daylight condition and task. It was considered important to be able to adjust the light level as well as the colour of the light. The subjects also answered that they would have found it highly acceptable if the electric lighting was automatically controlled with the option of manual override.

With the many possibilities arising with new and advanced lighting control, it is important to respect users' wishes and preferences and therefore be aware of what parameters are important for the users to be able to adjust and at what intervals. This work has given a hint of how dynamic lighting control can be used for individual preferences in winter season in Denmark but has somewhat failed to do so in an energy-efficient way. However the results are very similar to what the lighting community has found previously. Further research will be conducted intending to achieve energy efficiency in combination to user satisfaction and preferences by performing measurements with different desk placements in the room and adding with a desk lamp. The variation in the use of the dynamic lighting concept will be explored according to different seasons of the year in order to optimize energy use.

REFERENCES
Biner P.M., Butler D.L., Fischer A.R., Westergren A.J. 1989. An Arousal Optimization Model of Lighting Level Preferences an Interaction of Social Situation and Task Demands, *Environment and Behavior*, 21(1), 3-16.

Boyce P.R., Veitch J.A., Newsham G.R., Jones C.C., Heerwagen J., Myer M., and Hunter C.M. 2006. Lighting quality and office work: two field simulation experiments, *Lighting Research and Technology,* 38, 191-223.

Butler D., Biner P.M. 1987. Preferred Lighting Levels Variability Among Settings, Behaviors, and Individuals. *Environment and Behavior*, 19(6), 695-721.

Christoffersen J., Petersen E., Johnson K., Valbjorn O., and Hygge S. 1999. Windows and daylighting – a post-occupancy evaluation of offices, *Statens Byggeforskningsinstitut* SBi Report 318.

Fotios S.A. 2006. Chromatic adaptation and the relationship between lamp spectrum and brightness, *Lighting Research and Technology*, 38(1), 3-17.

Kaplan R. 2001. The Nature of the View from Home: Psychological Benefits, *Environment and Behavior*, 33(4), 507-542.

Knez I. and Enmarker I. 1998. Effects of Office Lighting on Mood and Cognitive Performance and a Gender Effect in Work-Related Judgment. *Environment and Behavior*, 30(4), 553-567.

Knez I. and Kers C. 2000. Effects of Indoor Lighting, Gender, and Age on Mood and Cognitive performance. *Environment and Behavior*. 32(6), 817-831.

Kruithof A.A. 1941. Tubular Luminescence Lamps for General Illumination. P*hilips Technical Review*, 6 (3) 65-96.

Leather P., Pyrgas M., Beale D., and Lawrence C. 1998. Windows in the Workplace: Sunlight, View, and Occupational Stress, *Environment and Behavior*, 30(6), 739-762.

Roisin B., Bodart M., Deneyer A., D'Herdt P. 2008. Lighting energy savings in offices using different control systems and their real consumption, *Energy and Buildings*, 4, 514-523.

Stone N.J. 1998. Windows and Environmental Cues on Performance and Mood, *Environment and Behavior*, 30(3), 306-321

Tenner A.D., Begemann S.H.A., and van den Beld G.J. 1997. Acceptance and Preference of Illuminaces in Offices, *Proceedings of The 8th European Lighting Conference Amsterdam, Lux Europa* 1997.

Verderber S. 1986. Dimensions of Persons- Window Transactions in the Hospital Environment, *Environment and behavior*, 18(4), 450-466.