Indoor Lighting Conditions and Inter-individual Light Preferences: Effects on Subjective Alertness, Physical Wellbeing and Electrical Energy Consumption

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Abstract

The worldwide need to lower energy consumption from electrical lighting has also challenged discussions of new lighting requirements at work places. Since electrical lighting requirements vary not only across climate zones and building related variables but also between individuals, it is difficult to define a 'golden standard' for humans, especially with regards to non-visual light effects. To further investigate this topic we chose extreme morning and evening types as 'natural models' to monitor lighting preference under their different habitual work hour's schedules. So far, 26 subjects completed the study in a controlled experimental office environment. All subjects underwent three different lighting conditions: 1) dim light (<5 lx), and 2) bright light (1000 lx). In the third condition, subjects were asked to choose their preferred illuminance and light source (including daylight). We monitored electrical energy consumption from lighting, as well as subjective alertness and physical wellbeing from questionnaires across 16 hours. Preliminary results showed significantly lower illuminance and electrical energy consumption under self-selected lighting conditions than under constant bright lighting. Subjective sleepiness increased and physical wellbeing dropped in the course of the study. These changes occurred earlier in morning than evening types, and were earlier during self-selected lighting conditions than under constant bright light. Both chronotypes showed no difference in energy consumption from electrical lighting in both conditions. Our preliminary results suggest that inter-individual aspects of light requirements could be integrated when designing lighting at work spaces, without draw backs from electrical energy consumption.

Keywords - extreme chronotype; energy consumption; lighting preference; non-visual light perception, circadian

1. Introduction

Improved thermal performance in buildings and building envelopes has led to reduced energy consumption caused by heating ventilation air-conditioning systems in buildings. As a consequence, the portion of electrical energy used for electrical lighting has increased within the total building energy consumption [1-2]. Ongoing attempts to reduce energy consumption due to electrical lighting in buildings have also raised the discussion how to adapt standards for indoor light quantity and quality with respect to human needs. Extensive chronobiological research of the last decade(s) revealed the important role of non-visual light perception for a variety of biological functions, such as entrainment of the internal circadian clock by light to the external 24-h day [3]. It has further been shown that light acutely affects alertness, physical wellbeing, cognitive performance, sleep and mood [4-8]. In addition, there are known physiological and behavioral differences in response to light between individuals and age groups which are not well understood. It still remains to be elucidated how indoor lighting scenarios could be optimized for both, energy efficiency in buildings and biological non-visual functions in different populations [9-10].

We aimed to investigate, whether inter-individual differences in lighting preferences are linked to changes of alertness and physical wellbeing between two subject groups. We chose extreme morning and evening types (‘Larks’ and ‘Owls’; also referred as chronotypes) with known behavioral differences [11-12]. Extreme morning types prefer wake- and bedtimes which are approximately 4-5 hours earlier than in extreme evening types and thus, the two groups vary in their individual work schedules and exposure duration to (day-) light. We addressed the question, whether self-selected lighting conditions go along with differences of subjective alertness and physical wellbeing across habitual working days between these two groups. We simultaneously assessed energy consumption from lighting in order to compare it between lighting conditions and the two chronotypes.

2. Subjects

We chose extreme morning types (MT) and extreme evening types (ET) based on their extreme diurnal sleep-wake preferences, as assessed by two validated questionnaires (Horne & Östberg Morningness-Eveningness Questionnaire, Munich Chronotype Questionnaire). We only included healthy subjects without any medications (except for oral contraceptives). So far, 13 MT and 13 ET completed the study (11 men and 15 women; age 22.7 ± 3.4 years; mean ± SD). The study procedures were approved by the local ethical review board and are in agreement with the Declaration of Helsinki. All subjects gave their written informed consent before the study.

3. Study Design

Seven days before the study, subjects were asked to maintain a very regular sleep-wake rhythm, with approximately 8 hours of sleep, initiated at their habitually chosen bed times. Compliance was controlled by a wrist activity monitor (Daqtix®, Oetzen-Süttorf, Germany) and sleep logs. The study was performed in the testing room at the Solar Energy and Building Physics Laboratory (LESO-PB), at the Swiss Federal Institute of Technology in Lausanne (Switzerland). The testing room is equipped with upper and lower windows. The upper windows are part of the anidolic daylighting system [13] which provides daylight deep into the room. In order to avoid any vertical outside view, the lower windows were covered with semi-translucent blinds. The room temperature was kept constant for the entire study duration.

The three study sessions were scheduled to begin one hour after habitual wake time and lasted for 16 hours. The study begin was for MT at 7:17±0:37, and for ET 11:10±1:06 (clock times, mean ± SD). During the study sessions, subjects remained seated in the testing room. They were allowed to read, work or listen to music (including one hour of scheduled computer work). A trained assistant stayed in the testing room throughout the study. All subjects underwent three different lighting conditions: 1) Dim light (DIM), with less than 5 lx on a vertical plane at the subjects' corneal level; 2) constant bright light (BL) with approximately 1000 lx on a vertical plane at the subjects' corneal level. The BL condition consisted of both, daylight and electrical light (ceiling polychromatic white light source, 4000K). The target threshold of 1000 lx was chosen (based on the literature) [14] to provide saturating stimulation for the non-visual system. 3) The third condition was self-selected lighting (SSL): light intensity and color temperature depended on the subject's choice. Subjects could choose daylight and/or electrical light with direct and indirect portions; and/or a desk lamp (electrical light could be set to reach maximally 1200 lx in a vertical direction at the subjects' corneal level). Subjects were asked to assess their lighting preference every 60 min which was then adapted accordingly. Vertical illuminance at the eyes' level was continuously recorded in 5 min intervals throughout the study by using a spectroradiometer (Specbos 1201, JETI, Jena, Germany). The study always started with the DIM condition, followed by the BL and SSL conditions in a cross-over design. The study days were balanced across all seasons. Subjective alertness, mood and physical wellbeing were assessed on visual analogue scales (between 0-100 mm) every 30 minutes. For the analysis, we averaged subjective assessments in hourly bins and calculated the difference since the start of the study for each subject before averaging across chronotypes. Electricity consumption for the electrical lighting was monitored for each study session.

4. Preliminary Results

4.1 Illuminance

In this report, we will focus on preliminary results from the BL and SSL conditions. The lighting consisted in both conditions of daylight (if available) and electrical light. On average, we found significantly lower illuminance during the SSL than the BL condition (BL: 1034±5 lx SSL: 774±98 lx; mean ± SEM; 2-way rANOVA; main effect of condition; $p<0.05$). The time course of self-selected illuminance in the SSL session varied for both chronotypes differently, such that for MT the illuminance was significantly lower during the first hour of the study and significantly higher after 5 h and 6 h, when compared to ET (2-way rANOVA; condition x time; Duncan's multiple rank test; $p<0.05$; Figure 1).

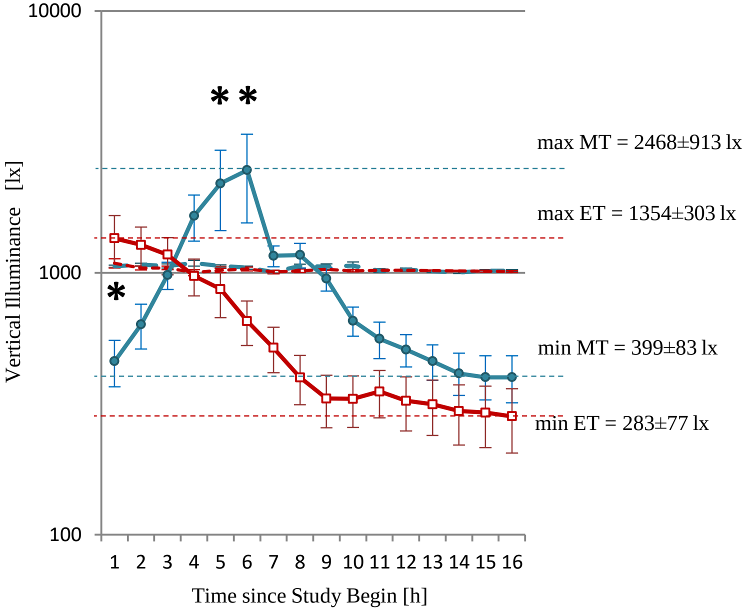

Figure 1: Illuminance for morning types (MT; n=13; blue filled circles) and evening types (ET; n=13; red open squares) under bright light (BL; horizontal lines around 1000 lx) and self-selected lighting conditions (SSL). The dotted lines indicate minimum and maximum illuminance for both chronotypes. Illuminance (lx) is shown on a log-scale and was measured every 5 min on a vertical plane at the approximate eye's level, averaged in hourly bins (means ± SEM). The x-axis represents elapsed time since study begin (h). *= significant differences between both chronotypes ($p<0.05$).

4.2 Energy Consumption

Electricity consumption from electrical lighting was significantly lower during the SSL (8.98±4.86 kWh; mean±SD) than the BL condition (15.21±2.35 kWh; 2-way rANOVA; main effect of condition; $p<0.05$). It reached on average 59±29% (mean±SD) of the electricity consumption during the BL condition. Between MT and ET, there was no significant difference in energy consumption from electrical lighting ($p>0.47$; Figure 2).

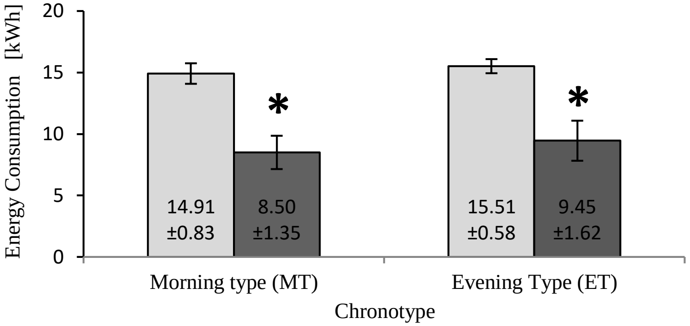

Figure 2: Energy consumption (kWh) from electrical lighting for both lighting conditions: left side: Morning Types (MT; n=13); right side: Evening Types (ET; n=13; means ± SEM); light grey = bright light condition (BL); dark grey= self selected light condition (SSL).
* indicates significant differences between BL and SSL ($p<0.05$).

4.3 Subjective Sleepiness

Evening types felt overall sleepier than MT (2-way rANOVA; main effect of chronotype; $p<0.05$, analyzed with absolute values, data not shown).

In a next step, we wanted to further analyze the dynamics of subjective sleepiness. We calculated the change of subjective sleepiness over time for every hour as difference since beginning of the study (separately for both chronotypes and lighting conditions). We found that MT became significantly earlier sleepy in both lighting conditions than ET (comparisons to the first hour; t-tests; $p<0.05$; Figure 3). In BL, MT felt significantly sleepier after 13 hours than at the beginning (which equals 14 hours after habitual wake time). Evening types showed no significant increase of sleepiness in the BL session. During the SSL condition, MT became significantly sleepier after 7 study hours, whereas the increase of sleepiness in ET occurred only in the second last study hour, i.e. 16 hours after habitual wake time (t-test comparisons to the first hour; $p<0.05$; Figure 3).

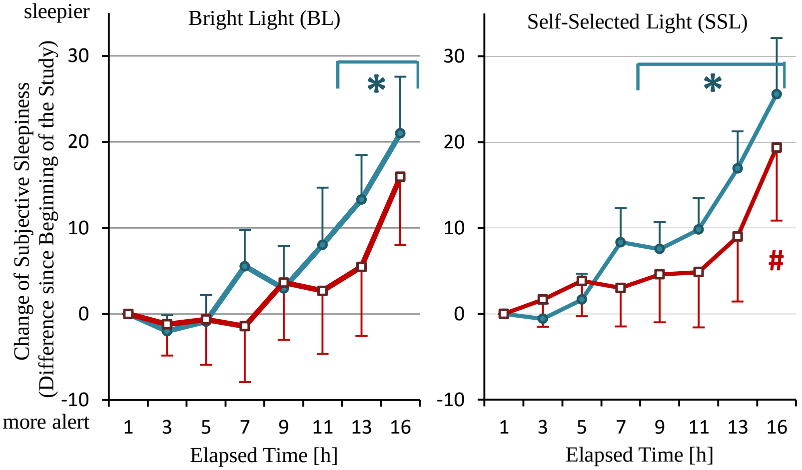

Figure 3: Time course of the relative change in subjective sleepiness since the beginning of the study, for bright light (BL; left) and self-selected lighting (SSL; right); averaged in 2-h bins for both chronotypes separately (mean values + or - SEM). Morning types (MT) = blue filled circles and evening types (ET) = red open squares (both n=13). Significant changes since the beginning of the study are indicated with: * for MT and # for ET ($p<0.05$).

4.4 Physical Wellbeing

Subjective physical wellbeing decreased for both chronotypes over time (2-way rANOVA; main effect of time; $p<0.05$; n=26). There was no significant difference of physical wellbeing between both groups (2-way rANOVA; $p>0.16$, absolute data not shown).

To analyse the time course within each chronotype in more detail, we calculated the difference of physical wellbeing since the beginning of the study (separately for both chronotypes and lighting conditions). Our results suggest an earlier drop of physical wellbeing in MT (BL: after 5 hours; SSL: after 11 hours) than in ET (BL: after 13 hours; SSL: no significant drop of subjective physical wellbeing since the beginning of the study; t-test comparisons to the first hour; $p>0.05$; Figure 4).

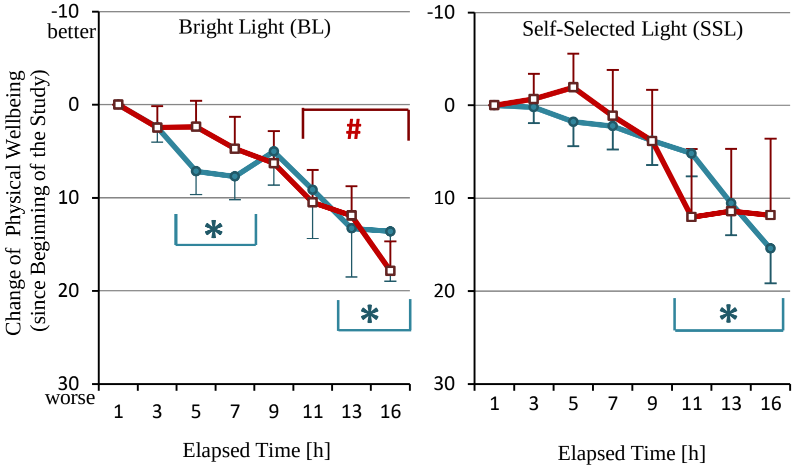

Figure 4: Time course of the relative change in subjective physical wellbeing since the beginning of the study, for bright light (BL; left) and self-selected light (SSL; right), averaged in 2-h bins for both chronotypes separately (mean values + or - SEM). Morning types (MT) = blue filled circles; evening types (ET) = red open squares (each group n=13). Significant changes since the beginning of the study within chronotypes are indicated with: * for MT and # for ET ($p<0.05$).

5. Discussion

Our preliminary findings suggest an earlier increase of sleepiness and an earlier drop of physical wellbeing during the study sessions in MT than in ET. The raise of subjective sleepiness occurred earlier in the SSL than the BL condition which can be explained by lower illuminance in the second half of the SSL sessions, when (lower) lighting conditions were chosen according to the subjects' preference. Thus, bright light counteracted the increase of sleepiness and the drop of physical wellbeing in the course of the study, at the costs of more than 40% of energy consumption from electrical lighting.

The illuminance levels in the SSL condition showed that both subject groups were exposed to bright daylight at different clock times, especially in the later morning hours but also in the afternoon. This is in accordance with studies where real life light exposures were monitored [15, 16].The earlier increase of subjective sleepiness in MT confirms previous results with subjective sleepiness but also objective data (obtained by electroencephalographic methods [12, 17]). These reports demonstrated a faster raise of sleepiness in MT than ET under prolonged wakefulness but also during 'normal' wake periods, reflecting a faster build-up of homeostatic sleep pressure. The new finding of our study is that even when subjects could choose higher illuminance (for example to counteract their decrease of alertness in the evening), they did not. As a consequence, other non-visual variables need to be considered (such as melatonin, performance or sleep) to fully understand possible reasons for these behavioural choices.

We consider the significant energy consumption savings from electrical lighting, when both chronotypes could self-select their light preferences as a clear advantage, compared to the energy consumption during constant bright light. On the other hand, when we compared energy consumption from lighting under the SSL condition with current standard lighting conditions (500 lx on a horizontal plane, at desk height), there was significantly higher energy consumption in the former than the latter condition (data not shown). This suggests that the higher illuminance chosen in the SSL condition also comprises higher energy consumption, than a standard lighting situation. The challenge for the future will be to design lit work spaces which account for both, energy savings **and** human needs.

6. Conclusion

Since light can impact on our physiology and behavior and even health, it becomes crucial to tailor light quality and quantity at work places and homes for optimal functioning and perception. It will be important to consider individual non-visual light effects when designing new buildings and new standards for electrical light and daylight.

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