Lighting Res. Technol. 2015; Vol. **47**: 192–209

Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood

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Received 7 September 2013; Revised 14 March 2014; Accepted 21 March 2014

Lighting conditions in workplaces contribute to a variety of factors related to work satisfaction, productivity and well-being. We tested whether different photometric variables also influence visual perception and the comfort of the lighting, as well as subjective non-visual variables such as mood, alertness and well-being. Twenty-five young subjects spent two afternoons either under electric light or daylighting conditions (without view from the window). Subjects overall preferred the daylighting for visual acceptance and glare. Changes of photometric variables modulated changes in visual light perception, alertness and mood in the course of the afternoon. Finally, we found several associations of visual and non-visual functions, indicating a potential relationship of visual comfort with other circadian and wake-dependent functions in humans, which consequently could impact office lighting scenarios in the future.

1. Introduction

An optimal indoor environment can increase comfort, productivity, health and well-being in office workers.[1,2] Several studies have shown that a higher evaluation of the work environment is related to overall job satisfaction and contributes to organizational outcomes such as fewer absences due to illness and longer employee commitment.[3,4] Indoor lighting conditions, as one aspect of the work environment, impact on occupants' mood, well-being, task performance[5] and work engagement.[6] Greater satisfaction with lighting conditions at work is usually associated with a higher work plane illuminance, lighting uniformity, absence of glare, light directionality (ratio of horizontal and vertical illumination), as well as the presence of a window.[7] Access to daylight generally improves satisfaction with lighting and is preferred to electric lighting (EL) alone.[7–10] It is well known that daylight is more desirable for the psychological dimensions of visual comfort, environmental appearance and amenity.[9,11,12]

International standards for some of the factors mentioned earlier, such as glare, light directionality, light uniformity and work plane illuminance have existed for many years.[13,14] Nevertheless, a wide range of inter-individual differences in subjectively preferred illuminance has been reported; Newsham and Veitch found that no more than 50% of occupants were satisfied within 100 lx of a given work plane illuminance.[15] It was reported that the preferred work plane illuminance on a horizontal plane was either greater[16,17] or lower[18–20] than the standard of 500 lx,[13,21] but the reasons for

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10.1177/1477153514531518

such differences are not well understood. Fotios and Cheal[22] reviewed the ranges of preferred illuminance from existing literature: they found that the average preferred illuminance was often close to the mean of the available illuminance ranges, which they confirmed also by their own studies.[22] Reports from Logadóttir *et al*.[23] confirmed these findings: The authors also noted that the initial illuminance which was used at the beginning of the studies did affect the overall preferred illuminance.[23]

In the last decade it has been recognized that light also modulates many non-visual functions such as the biological clock that drives our approximate 24-hour (circadian) rhythms of alertness, core body temperature, hormonal secretion,[24–27] and affects sleep.[28–31] Bright polychromatic light during daytime increases alertness and cognitive performance.[32,33] Moreover, exposure to bright polychromatic light also enhances mood and vitality in healthy office workers during winter time in the northern hemisphere.[34] The physiological base for these modulations has been recently elucidated by the discovery of a third class of photoreceptors that specifically account for many non-visual functions through light perception via the eyes. The greatest sensitivity of these photoreceptors is in the bluish part of the visible light at around 480 nm.[35–37] This explains why besides illuminance and irradiance, other physical properties, such as the correlated colour temperature (CCT) and the spectral composition of light during daytime are important. Lighting conditions with lower CCT (warm colour) and illuminance (2700 K, ~100 lx) are subjectively more relaxing than higher CCT and illuminance (4000 K, ~1300 lx; cooler colours) at certain times of the day.[38] Higher illuminance stimulates the alerting system more efficiently with 'daylight' fluorescent tubes (5500 K) than with 'warm white' (3000 K) polychromatic fluorescent tubes.[39] Two applied office studies over several weeks showed that with blue-enriched polychromatic white light (17 000 K) during daytime, office workers reported higher subjective alertness and performance, and less sleepiness, when compared to polychromatic white light (4000 K and 2900 K).[40–41] Several laboratory studies in which the lighting, room temperature, body posture and other variables were well controlled showed that exposure to electric light sources with higher CCT resulted in greater melatonin suppression (in the evening or during the night), greater subjective alertness and better cognitive performance.[42–43] However, not all studies could find an influence of higher CCT or full spectrum fluorescent lighting on task performance and arousal (as reviewed in McColl and Veitch[44–45]).

So far, many office lighting studies have been performed under steady EL conditions; there is still a lack of investigations which consider the dynamics of daylight, especially under different sky conditions. Surprisingly few studies have investigated the effects of daylight on non-visual functions. It was shown that half an hour exposure to a bright daylight near windows (between 1000 lx and 4000 lx) was almost as effective as a short nap in reducing normal post-lunchtime drowsiness in healthy subjects.[46] A recent study showed a strong association for longer sleep duration (46 minutes on average per night) and quality of life patterns in office workers with daylight at their workplaces, when compared to office workers without windows.[47] There are still many workplaces around the world without any access to daylight. The fact that most office workers spend at least 8 hours a day at their workplaces, illustrates the need to identify and optimise interior lighting conditions, with respect to both visual and non-visual functions.

To summarize, there are several questions, which remain unanswered: What might be the reasons for the observed daylight preference and visual comfort, besides the window view? Do different photometric variables also play a role? What are the differences in subjective and non-visual variables (over time) between windowless rooms and offices with daylight? In order to test whether it is one of the inherent daylight properties, and not the (positive) bias of the window view which makes subjective perception of daylight superior to pure EL, we prevented any outside view in both lighting conditions. We therefore extended existing reports which did not disentangle between daylighting (DL) with and without window view. Our first hypothesis was that a greater visual comfort will be perceived with daylight than with pure EL, even when an outside view is prevented. In order to test if any of the monitored photometric properties account for changes in visual comfort, subjective alertness, mood and well-being over time, the following two other hypotheses were formulated: (i) changes of photometric properties such as illuminance, CCT and colour rendering index (CRI) will induce modulations of visual comfort, alertness, mood and well-being in DL conditions and, (ii) those changes will occur at different times during the afternoon for the EL and DL conditions.

2. Subjects and methods

2.1. Study participants

Subjects were recruited at the Swiss Federal Institute of Technology in Lausanne (Switzerland). We only considered healthy subjects between 20 and 30 years, without any medical, psychiatric or sleep disorders, as assessed by two different questionnaires and a personal interview. Only men and women without any medication (except for oral contraceptives) or drug abuse were included, and none of them was an extreme morning or evening chronotype (as assessed by the Horne–Östberg questionnaire). Subjects who had performed night shifts or had travelled across more than two time zones within the last three months were excluded. Twenty-nine subjects completed the entire study.[48] Because repeated visual comfort scales (VCSs) were not given to the first four subjects, a subgroup of 25 subjects was included in the analysis (nine women, 16 men; age = 23.5 ± 2.3 years; mean ± standard deviation (SD)). Seven days prior to beginning the study, subjects were asked to maintain a regular sleep–wake cycle of approximately 8 hours at a self-selected target bed- and wake-time, within a range of 30 minutes. Compliance was controlled by means of a wrist activity monitor (Daqtix® Süttdorf, Germany) and sleep diaries. Habitual wake time was on average at 7:31 am ± 45 minutes and bedtime at 11:25 pm ± 43 minutes (mean ± SD). Subjects were also asked to consume alcohol and caffeine moderately during the 7 days before the study and to completely abstain on study days. All subjects gave their written informed consent during an interview prior to the study beginning; they were not informed about the hypotheses of the study. The study protocol was approved by the local ethical commission in Lausanne (Switzerland); the study procedures were in agreement with the Declaration of Helsinki.

2.2. Study design

All study participants spent two consecutive afternoons and early evenings from noon to 8 pm in a test room (Figure 1(a) and (b)) at the Solar Energy and Building Physics Laboratory (LESO solar experimental building) at the Swiss Federal Institute of Technology in Lausanne (EPFL, Switzerland) located at 46°32′N latitude and 6°38′E longitude. The test room (7 m × 5 m) comprised a large table located in the middle of the room, and a large window front, which almost covered one side of the room (window-to-wall ratio of 0.5). Subjects were seated at one end of the room, facing the wall on the other side of the room; the window was located to

Figure 1 Photograph of the study room with the two different lighting conditions: (a) mainly daylighting conditions (DL); (b) electric lighting conditions (EL). The picture reproduces the view from the subject's position. The tilted board on the table ensured a more horizontal gaze direction

their left side. Subjects came twice around noon (i.e. 4–5 hours after their habitual wake time) and spent the afternoons (from 12 pm to 6 pm) under two different lighting conditions, in a balanced crossover design during autumn–winter (from September to February).

During the afternoon hours, one or two subjects remained seated in the test room; they were allowed to read, work or listen to music, but not to perform any computer work. In order to ensure vertical gazing, subjects had to work on vertically tilted table boards. Regularly (every 30–60 minutes), the subjects had to assess their visual comfort, subjective alertness, mood and well-being using visual analogue scales (VAS) (see below). A trained assistant was present in the test room and ensured compliance with the study procedures. For the evening tests (6 pm–8 pm), the subjects went to a room with dim light (<6 lx). Hormonal and performance results from the evening part in dim light have been reported previously.[48] In summary, subjects were more alert at the beginning of the dim light condition when they had daylight during the preceding afternoon. They showed better cognitive performance in dim light after an exposure to daylight in the afternoon, when compared to electrical light conditions without differences in two salivary hormone concentrations (cortisol and melatonin). Here, we report the findings from the afternoon part on visual comfort, alertness, mood and well-being under two different lighting conditions.

2.3. Room set-up and lighting conditions

The LESO building is equipped with anidolic DL systems on the southern facade, located on the upper part of the windows.[49,50] The anidolic DL system re-directs the collected daylight flux towards the ceiling and to the rear of the room; it provides a larger light flux deeper into the room and optimizes the indoor daylight flux distribution.[49,51] The EL system consisted of eight polychromatic white light luminaires, mounted on the ceiling (58 W, fluorescent tube, 4000 K). A digital addressable lighting interface was used to control the work plane illuminance.[50] For the DL condition, the translucent blinds located in front of the lower window parts were closed in order to prevent any direct outside view; daylight entered the room only via the upper window parts and the anidolic DL system (Figure 1(a)). IIluminance at the subjects' eye (vertical illuminance) was targeted between 1000 lx and 2000 lx for the DL condition. Whenever vertical illuminance levels exceeded this target range and/or direct sunlight entered the room, the upper blinds were partially closed. If the measured vertical illuminance dropped below the target range (due to an overcast sky or later in the afternoon), a complementary EL system was switched on (polychromatic white light). The pure EL condition was set up in the same room by using opaque curtains, which prevented any daylight entering the room (Figure 1(b)).

The horizontal illuminance at desk level in the middle of the room was set to 400 lx (i.e. similar to standard office lighting conditions between 300 lx and 500 lx on a horizontal plane). Horizontal illuminance was measured every 60 minutes (Luxmeter; LMT Pocket Lux 2, Germany); vertical illuminance at the subjects' eyes (E_v; vertical illuminance) was continuously recorded in 5-minute intervals throughout the study, using a spectroradiometer (Specbos 1201, JETI, Germany). The device was placed as close as possible to the subjects' eyes and pointed in a direction parallel to the subjects' visual axis. During both lighting conditions, the spectral light composition (between 380 nm and 780 nm), the CCT and CRI as well as the irradiance provided by the lighting were simultaneously assessed using the same spectroradiometer. In order to determine the light distribution in the room, several snapshots of the room were taken at the beginning of each study session. Light distribution was determined by high dynamic range imaging techniques, as previously reported.[52,53]

2.4. Subjective assessments

During both study sessions, subjects had to assess visual comfort and subjective alertness, mood and well-being on paper-based VAS. VAS had been validated by different groups to reliably assess changes in subjective alertness, mood and well-being.[54,55] The VAS requires evaluation between two extremes (for example extremely alert and extremely sleepy) on a horizontal line (0–100 mm).[54–56] Subjects were instructed to indicate with a small vertical tick on the horizontal line their current subjective rating. The VAS was used for assessments of visual comfort and subjective alertness, mood and well-being. The single items of those scales are described in the next two sections.

2.4.1. Visual comfort

Two questionnaires for visual comfort assessments were applied: At hourly intervals subjects had to rate seven items on the VCS. The items were extracted from the larger office lighting survey (OLS)[57,58] and modified to be used on a continuous VAS. Items 1–7 had to be answered between two extremes: 'Yes' (0 mm) and 'No' (100 mm); The assertions were: (1) 'I like the light in this room'; (2) 'Overall, the light in this room is comfortable'; (3) 'The light in this room seems too bright'; (4) 'The light in this rooms seems too dark'; (5) 'There is not enough light to work/read correctly'; (6) 'There's too much light to work/read correctly'; (7) 'How do you feel the glare in this room?' The last item was ranging between 'Imperceptible' (0 mm) and 'Intolerable' (100 mm). Some of the items are related to each other and showed a high intra-reliability score (Cronbach's alpha), we therefore combined six questions to three scores (item 7 about glare perception stands alone) in the following way:

- *Visual acceptance*: 'I like the light in this room'/'Overall, the light in this room is comfortable' (averaged items 1 and 2; Cronbach's alpha = 0.97).

- *Luminous perception of brightness*: 'The light in this room seems too bright'/ 'There's too much light to work/read correctly' (averaged items 3 and 6; Cronbach's alpha = 0.75).

- *Luminous perception of darkness*: 'The light in this rooms seems too dark'/'There is not enough light to work/read correctly' (averaged items 4 and 5; Cronbach's alpha = 0.95).

At the end of the afternoon, subjects had to fill in once a slightly modified version of the complete OLS[50]: the corresponding items are listed in Table 3.

2.4.2. Non-visual functions assessments

In the course of the afternoon, subjects assessed every 30 minutes their subjective alertness, mood, physical well-being and relaxation on VAS (0–100 mm). The items were (i) extremely alert–extremely sleepy; (ii) in very bad mood–in very good mood; (iii) physically comfortable–physically uncomfortable and (iv) extremely relaxed–extremely tense.

3. Results

3.1. Photometric measurements

In order to characterize the meteorological weather conditions during the study days with daylight conditions by using three different sky conditions (clear, intermediate and overcast), the Swiss Norm 150 911[59] was used to determine the average sunshine duration from 12 pm to 5 pm. For this purpose, meteorological data of a local weather station were obtained (Meteosuisse, Pully/VD, Switzerland).[60] A clear sky refers to 0–25% of cloud covering during day time (e.g. 45–60 minutes of sunshine per hour); an overcast sky reflects 75–100% of cloud covering (e.g. 0–15 minutes of sunshine per hour).[59] We considered a sky with a cloud covering between 25% and 75% as an intermediate sky (e.g. 15–45 minutes of sunshine per hour). Since there was no daylight after 5 pm in any case, we excluded the last hour from our weather data file. The average vertical illuminance, vertical irradiance, CCT and CRI observed during the study under DL (for the three different skies) and the EL lighting condition are summarized in Table 1. In order to account for not equally distributed sample sizes between weather conditions (clear, intermediate and overcast sky), log-transformed photometric variables were analysed with a mixed linear regression model (proc mixed; SAS version 9.3; SAS Institute Inc., Cary, NC) comprising the fixed factors 'weather' (clear, intermediate and overcast sky) and the repeated factor 'time' (hourly bins from noon to 6 pm) and the random effect 'subject'. The p-values were adjusted for multiple comparisons using the Tukey–Kramer rank test; degrees of freedom were adjusted after Kenward–Rogers.

The DL conditions were highly dynamic and photometric variables significantly changed over time (Figure 2(a)–(d); means ± SD are listed in Table 1). Since the study was conducted during autumn and winter, we found that all values significantly decreased after 5 pm, due to the natural fading of daylight. Table 2 presents details from the statistical analyses with the mixed linear regression model. All the photometric variables were significantly lower under overcast sky conditions than under clear skies (main effect of 'weather'). We also found significant interactions between the factors 'time' and 'weather' for illuminance and irradiance: both were significantly lower under overcast skies at 1 pm and 3 pm, compared to clear sky conditions (Figure 2(a) and (b)). Under clear sky conditions, CCT was significantly higher at 4 pm (Figure 2(c)) and CRI was higher from noon to 1 pm and also at 4 pm, than under overcast sky conditions (Figure 2(d)); Table 2 presents F- and p-values as well as effect sizes (η^2).

Table 1 Mean values (±SD) for vertical illuminance (lx), irradiance (W/m^2), correlated colour temperature (K), colour rendering index (–) are shown for EL and DL

Photometric light variables	Electric light (EL) (n = 25) (mean ± SD)	Daylight (DL)			
		Total DL only (n = 25) (mean ± SD)	Overcast (n = 14) (mean ± SD)	Intermediate (n = 6) (mean ± SD)	Clear (n = 5) (mean ± SD)
Illuminance (lx)	173.6 ± 4.3	1086 ± 1031	875 ± 1124	1167 ± 723	1578 ± 911
Irradiance (W/m^2)	0.5 ± 0.01	4.5 ± 4.6	3.5 ± 5.0	5.0 ± 3.3	7.0 ± 4.1
CCT (K)	3708 ± 23	4420 ± 389	4309 ± 380	4446 ± 389	4701 ± 253
CRI (–)	83.4 ± 0.1	91.8 ± 4.6	89.9 ± 4.2	93.1 ± 4.5	95.4 ± 3.3

For DL, the mean values of overcast, intermediate and clear sky are shown separately. The numbers in brackets indicate the number of subjects in the respective DL weather condition.

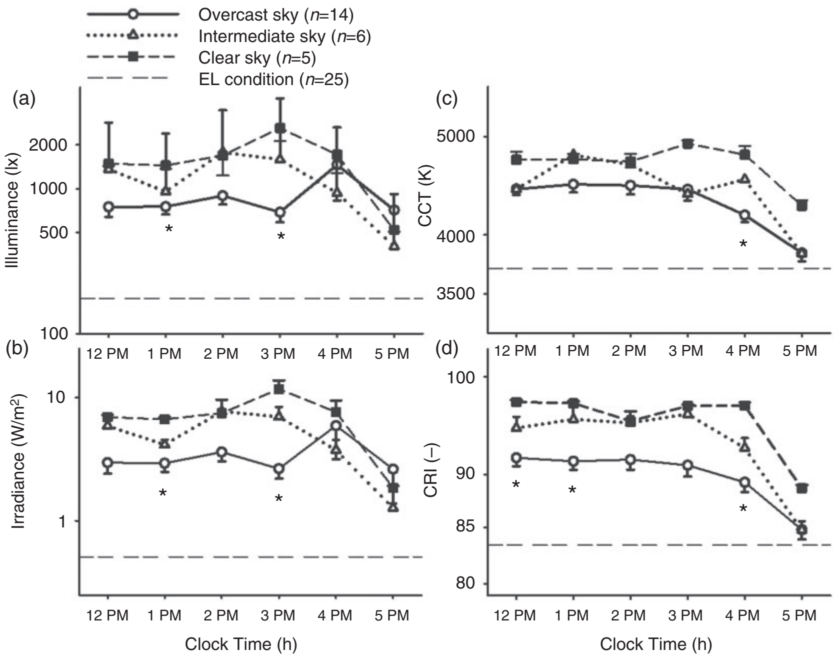

Figure 2 Photometric properties for three different daylighting conditions (on log-scales), e.g. clear sky (black rectangles); intermediate sky (white triangles) and overcast sky (white circles), as well as for electric lighting (EL; dashed horizontal line): (a) Vertical illuminance (lx); (b) irradiance (W/m^2); (c) correlated colour temperature (K) and (d) colour rendering index; mean + or − SEM; * = $p < 0.05$ indicates the differences between clear and overcast skies. The numbers in brackets indicate the numbers of subjects in the respective weather conditions

3.2. Visual acceptance, luminous and glare perceptions

Data for DL and EL conditions were analysed with four-way repeated analysis of variance (ANOVA), using a general linear regression model (Statistica, version 9, Tulsa, OK); ‘condition’ (DL, EL) and ‘time’ (12–5 pm) were repeated variables and ‘gender’

Table 2 Results from the repeated mixed linear regression

	Weather p-value (η^2)	$F_{2,22}$	Time p-value (η^2)	$F_{5,18}$	Weather × time p-value (η^2)	$F_{10,25}$
Illuminance	0.004 (0.30)	7.3	<0.001 (0.17)	15.8	<0.001 (0.16)	6.2
Irradiance	0.002 (0.30)	8.6	<0.001 (0.19)	20.6	<0.001 (0.16)	6.1
CCT	0.003 (0.29)	7.9	<0.001 (0.25)	45.9	0.003 (0.13)	3.8
CRI	<0.001 (0.31)	11.4	<0.001 (0.27)	58.1	0.004 (0.14)	3.7

'Weather' (p-values and effect sizes (η^2) second column; F-values third column); 'time' (p-values and effect sizes (η^2) fourth column; F-values fifth column) and 'time × weather' (p-values and effect sizes (η^2) sixth column; F-values seventh column).

and 'order' (begin with DL or begin with EL) categorical factors. The visual acceptance score became worse in the course of the afternoon (main effect of 'time'; $F_{5,\ 105} = 4.47$; $p = 0.001$; partial eta squared (η^2) = 0.18) and was overall better for DL than EL (main effect of 'condition' $F_{1,21} = 43.01$; $p < 0.0001$; $\eta^2 = 0.67$; mean ± SD for EL = 41.1 ± 21.6 and DL = 20.6 ± 15.2; Figure 3(a)). The luminous perception score for brightness was similar for EL and DL condition (luminous perception score for brightness; main effect of 'condition' $F_{1,\ 21} = 2.5$; $p = 0.1$; mean ± SD for EL: 76.1 ± 19.2 and DL: 81.2 ± 17.4) and over time (main effect of 'time'; $F_{5,\ 110} = 1.5$; $p = 0.2$). They rated DL as significantly less bright when they started the study with the DL condition (main effect of 'order' $F_{1,\ 21} = 8.8$; $p = 0.007$; $\eta^2 = 0.3$). Subjects rated simultaneously the DL condition as less dark than the EL condition (luminous perception score for darkness; main effect of 'condition'; $F_{1,\ 21} = 5.1$; $p = 0.04$; $\eta^2 = 0.2$; mean ± SD for EL: 73.5 ± 25.0 and DL: 82.5 ± 20.2; Figure 3(b)). Subjective glare ratings were significantly higher under EL compared to DL (Figure 3(c); 'condition'; $F_{1,\ 21} = 4.8$; $p = 0.04$; $\eta^2 = 0.2$; mean ± SD for EL: 35.0 ± 16.4 and DL: 30.0 ± 17.7).

In order to closer investigate the specific impact of the dynamic DL conditions on visual acceptance (which varied over time), 'weather' was used as a categorical factor in our analysis for DL only. A significant interaction was found with the factors 'weather' and 'time' for the visual acceptance score (two-way repeated measures ANOVA; $p = 0.01$; $F_{8,88} = 2.6$; $\eta^2 = 0.2$ Figure 4; mean ± SD: for overcast sky (n = 14): 16.7 ± 10.9; for intermediate sky (n = 6): 24.8 ± 15.5 and for clear sky (n = 5): 26.5 ± 21.3). The interaction was such that subjects assessed lower visual acceptance under clear sky conditions at the end of the afternoon (4–5 pm), when compared to overcast sky conditions; they had lower visual acceptance at 4 pm under clear sky conditions, when compared to the intermediate sky conditions (Duncan's multiple range test; $p < 0.05$).

For the modified version of the OLS questionnaire given once towards the end of the two afternoons (Table 3), we applied a three-way ANOVA with the repeated factor 'condition' and the categorical factors 'sex' and 'order'. Subjects rated the luminous distribution significantly higher under DL than under EL condition ($F_{1,21} = 10.6$; $p < 0.01$; $\eta^2 = 0.34$); they assessed having less reflections ($F_{1,21} = 9.4$; $p < 0.01$; $\eta^2 = 0.31$), light flickering ($F_{1,21} = 7.1$; $p < 0.05$; $\eta^2 = 0.25$) and shadows ($F_{1,21} = 4.9$; $p < 0.05$; $\eta^2 = 0.19$). Subjects also estimated the appearance of the lighting to be 'colder' under EL than the DL condition ($F_{1,21} = 7.7$; $p < 0.05$; $\eta^2 = 0.27$). They found that the lighting under DL was better than in their existing offices ($F_{1,21} = 11.0$; $p < 0.01$; $\eta^2 = 0.34$); they

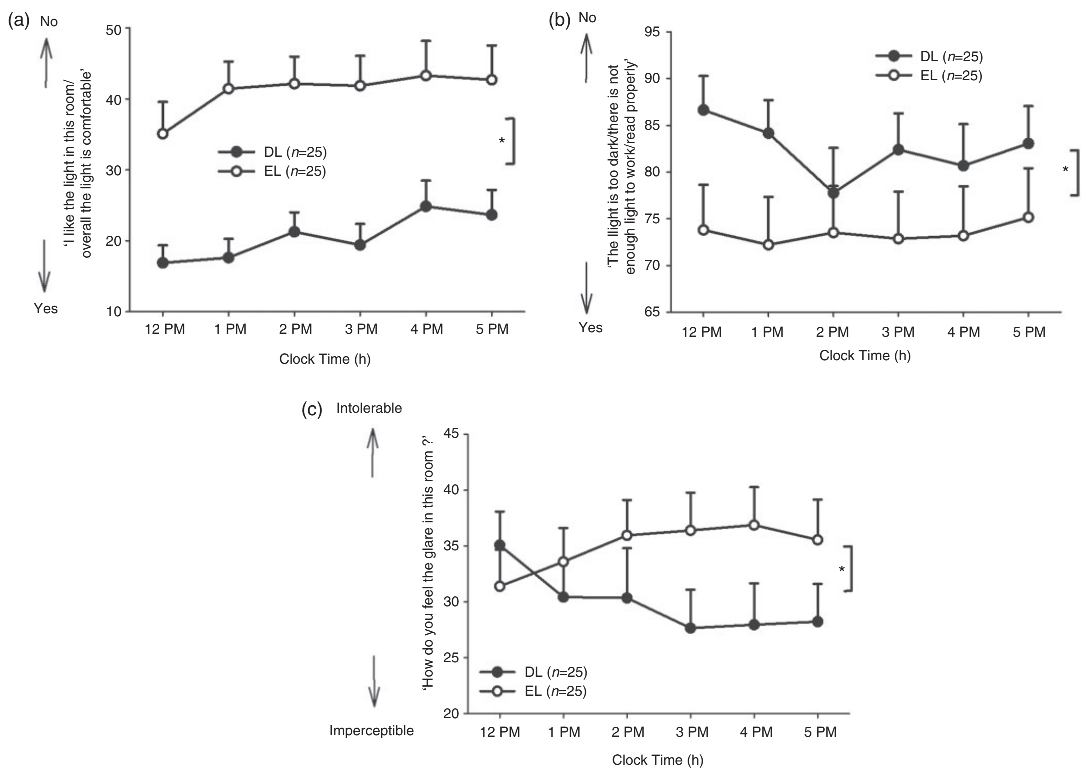

Figure 3 Subjective assessments of the visual acceptance score ('I like the light in this room/overall the light is comfortable'; 0 = 'Yes'; 100 = 'No' (a); luminous perception for darkness (the light in this room is too dark; 0 = 'Yes'; 100 = 'No' (b) and (c) subjective glare perception (0 = imperceptible; 100 = intolerable) for EL and DL lighting conditions. DL = black circles and EL = white circles. * = $p < 0.05$ (mean + SEM, n = 25)

estimated to be able to work for a longer time episode under DL than under EL lighting conditions ($F_{1,21} = 18.0$; $p < 0.01$; $\eta^2 = 0.46$). The latter was also dependent on whether the subjects had DL on their first or second study day (main effect of 'order'; $F_{1,\ 21} = 7.2$; $p < 0.05$; $\eta^2 = 0.26$). When subjects started their sessions under DL condition, they found the lighting under EL condition more poorly distributed and judged that they would spend less time in that lighting environment than subjects who started the session with EL (main effect of 'order'; $F_{1,\ 21} = 6.23$; $p < 0.05$; $\eta^2 = 0.23$).

3.3. Non-visual functions assessments: Subjective alertness, mood and physical well-being

We analysed the data of DL and EL conditions with four-way repeated measures ANOVA by using a general linear regression model (see Section 3.2). For further analysis of the dynamics, we determined for each moment in the afternoon whether it was different from the beginning of the study (t-tests with adjusted p-values for multiple comparisons by using the false discovery rate[61]). Subjective assessments showed significant variation over time for alertness, physical

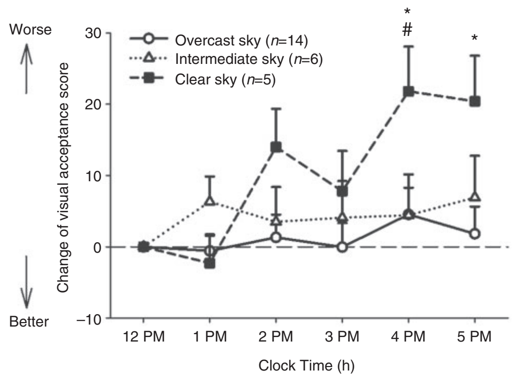

Figure 4 Time course of the visual acceptance score for different skies (expressed as difference from the values obtained at noon, mean + SEM) during DL conditions: clear sky = black squares (n = 5); intermediate sky = white triangles (n = 6) and overcast sky = white circles (n = 14). The dashed horizontal line indicates the first assessment at the beginning of the study at noon. * = significant differences between clear and overcast skies ($p<0.05$). # = significant differences between clear and intermediate skies ($p<0.05$)

well-being and mood, such that these outcomes became worse towards the end of the afternoon (main effect of 'time'; alertness: $F_{5,105}=14.8$; $p<0.01$; $\eta^2=0.41$; physical well-being: $F_{5,\ 105}=5.3$; $p<0.01$; $\eta^2=0.21$; mood: $F_{5,105}=2.6$; $\eta^2=0.12$; $p<0.05$). Subjects felt less alert in the course of the afternoon when they started the first day of study with DL, than when they started with EL (main effect of 'order'; $F_{1,\ 21}=5.38$; $p<0.05$: $\eta^2=0.20$), even though there was no significant difference at the beginning of each study day (t-test between DL and EL at noon for day 1: $p=0.29$; $t=1.07$ and day 2: $p=0.24$; $t=-1.2$).

We further analysed the relative time course of those subjective assessments by comparing their variations to values at noon. There was an earlier decrease of alertness during the EL than DL condition (Figure 5(a); EL: $p<0.001$ and $t<-2.56$ from 1 pm to 5 pm; 37.9 ± 17.4 mean ± SD for EL; DL: $p<0.001$ and $t<-3.70$ from 2 pm to 5 pm; 35.4 ± 16.0 mean ± SD for DL). After the first hour, subjects felt significantly less well under the EL condition, when compared to the beginning of the study (Figure 5(b); $p<0.025$ and $t<-2.41$ 4 pm; 25.7 ± 13.9 (mean ± SD during the afternoon)). Under the DL condition their physical well-being did not significantly change in the course of the afternoon ($p>0.05$ for adjusted p-values; 22.9 ± 12.6; mean ± SD for all).

3.4. Inter-correlations between dependent variables

Inter-correlations for DL condition between the dependent visual variables (visual acceptance, luminous perception, glare perception) and the dependent non-visual variables (alertness, mood, physical well-being, relaxation) were determined with Pearson's correlations (t-values are indicated in Table 4). Worse visual acceptance scores correlated with higher perception of brightness ('yes, the light is too bright') at 1 pm ($r=-0.64$), and from 3 pm ($r=-0.47$) to 4 pm ($r=-0.60$), and with higher perception of darkness ('yes, the light is too dark') from 2 pm to 5 pm ($r<-0.56$). Worse visual acceptance scores were also related to lower physical well-being at 4 pm ($r=0.48$), and lower alertness from 1 pm to 2 pm ($r>0.43$) and at 4 pm ($r=0.67$). These results indicate associations between visual variables, physical well-being and alertness during the afternoon which all went in the same (negative) direction.

Lower luminous perception ('the light is not too bright') was related to more relaxation and better physical well-being from 2 pm to 5 pm ($r<-0.46$), and greater alertness at 1 pm ($r=-0.42$), 4 pm and 5 pm ($r=-0.46$), as well as better mood from 2 pm to 3 pm ($r>0.51$), and at 5 pm ($r=0.45$). From 3 pm to 4 pm, lower darkness perception ('the light is not too dark') was associated with greater alertness ($r<-0.44$). Less physical well-being was associated with

Table 3 OLS questionnaire, given once per afternoon during DL and EL. The exact wording is stated (means ± SD; n = 25)

			Main effect of							
			Condition				order			
Answers: 0 = Yes / 100 = No	Total		DL		EL		DL/EL		EL/DL	
(Item 9: 1 = better / 5 = worse)	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
1. The lighting is poorly distributed here*,#	83.8	21.5	90.4	11.1	77.2	27.0	74.9	26.7	92.0	10.3
2. The light causes deep shadows*	78.5	25.3	83.7	19.0	73.2	30.0	71.4	28.2	85.0	20.7
3. Reflections from the light fixtures hinder my work*	71.3	30.4	77.9	27.2	64.7	32.5	72.8	26.2	69.8	34.3
4. The ceiling light fixtures are too bright	77.6	21.1	79.9	18.8	75.2	23.4	79.9	14.9	75.4	25.7
5. My skin has an unnatural tone under the lighting	69.9	27.5	71.0	29.6	68.8	25.9	63.5	29.7	75.9	24.4
6. The lights flicker throughout the day*	83.1	22.3	88.1	18.2	78.0	25.0	78.6	24.9	87.2	19.1
7. The lighting is too warm in colour for an office	89.3	10.1	88.1	11.3	90.4	8.8	87.7	11.2	90.7	9.0
8. The lighting is too cool in colour for an office*	57.3	30.5	67.9	26.2	46.6	31.3	50.1	29.6	63.9	30.5
9. How does the lighting of this office compare with the lighting of other offices you* have worked in? (1 = better...5 = worse)	2.8	1.0	2.4	0.9	3.2	1.0	3.0	1.1	2.6	0.9
10. For a working day, I imagine that I can work in this light environment for x hours*,#	3.0	1.0	3.4	0.9	2.5	1.0	2.6	0.9	3.3	1.0

* = main effect of 'condition'; # = main effect of 'order'; $p<0.05$.

less relaxation throughout the afternoon ($r > 0.59$), lower alertness ($r > 0.49$) and worse mood ($r < -0.40$). At 3 pm we found that higher subjective glare sensations were correlated with worse mood ($r = -0.47$), and at 4 pm with less relaxation ($r = 0.41$). Less relaxation was also associated with lower alertness at the beginning of the study ($r = 0.51$) and correlated with worse mood from 12 pm to 4 pm ($r < -0.47$). During most of the afternoon, we found that more sleepy subjects were in a worse mood ($r < -0.40$).

3.5. Multiple regression analysis

In order to identify the photometric variables (e.g. vertical illuminance, CCT and CRI) which could have modulated the assessments of visual and non-visual functions during the afternoon, multiple regression analysis was performed hourly for each of those variables, with the respective hourly mean of the independent (log-transformed) photometric variables. Table 5 summarizes the significant results (as well as standard error of the mean (SEM), t- and p-values). The goodness of fit for adjusted R^2 was greater than 0.2 for all models ($p < 0.05$), and F-values ($F_{3;21}$) were all greater than 3.0. In the first part of the afternoon we found that lower visual acceptance was significantly related to higher vertical illuminance, higher CCT and lower CRI (at 12 pm). Better luminous perception ('the light is not too dark; not too bright') was explained by lower CCT (at 12 pm and 2 pm). Higher illuminance, CCT and lower CRI at 1 pm were accounting for higher sleepiness at this time of day. In the second part of the afternoon, better luminous perception ('not too dark') was modulated by lower illuminance at 3 pm. We found that improvement of mood was associated with higher CCT at 4 pm, indicating a large blue component in light, most likely on days with greater daylight availability. At 5 pm, lower CRI was related to higher subjective glare perception.

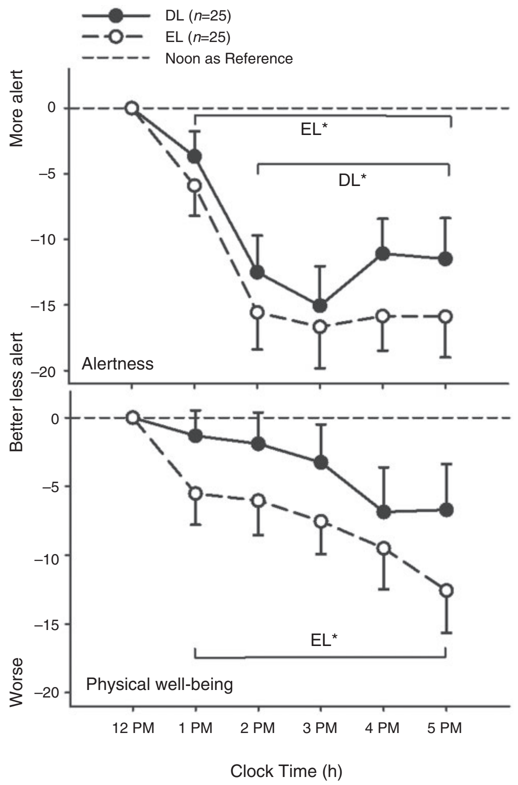

Figure 5 Time course for variations of subjective alertness and physical well-being (expressed as change since the beginning of the study = dashed horizontal line). Values were hourly binned and averaged across subjects (DL = black circles; EL = white circles; mean + or − SEM, n = 25; * = p < 0.05, indicate significant changes since 12 pm)

4. Discussion

In two realistic office lighting environments we found significantly higher visual acceptance scores under DL than EL conditions, despite the lack of a direct outside view. Subjective glare was lower under DL than under EL condition. While subjective alertness and physical well-being decreased for both lighting conditions in the course of the afternoon, subjects felt sleepy earlier under EL than DL. Physical well-being became worse in the course of the afternoon only

Table 4 Inter-correlations (Pearson's correlation coefficients r) for significant correlations (p < 0.05) between all dependent visual and non-visual variables for each moment between 12 pm and 5 pm (t-values in brackets)

Pearson's correlation coefficient (DL only)			12 pm	1 pm	2 pm	3 pm	4 pm	5 pm
Visual acceptance	vs	Brightness perception	–	−0.64 (−4.0)	–	−0.47 (−2.5)	−0.60 (−3.6)	–
		Darkness perception	–	–	−0.56 (−3.3)	−0.65 (−4.1)	−0.61 (−3.7)	−0.72 (−5.0)
		Physical well-being	–	–	–	–	0.48 (2.6)	–
		Alertness	–	0.43 (2.3)	0.44 (2.3)	–	0.67 (4.3)	–
Brightness perception	vs	Relaxation	–	–	−0.52 (−2.9)	−0.72 (−5.0)	−0.56 (−3.2)	−0.51 (−2.9)
		Physical well-being	–	–	−0.47 (−2.6)	−0.46 (−2.5)	−0.57 (−3.3)	−0.55 (−3.1)
		Alertness	–	−0.42 (−2.2)	–	–	−0.46 (−2.5)	−0.46 (−2.5)
		Mood	–	–	0.51 (2.8)	0.60 (3.6)	–	0.45 (2.4)
Darkness perception	vs	Alertness	–	–	–	−0.46 (−2.5)	−0.44 (−2.4)	–
Relaxation	vs	Subjective glare	–	–	–	–	0.41 (2.2)	–
		Physical well-being	0.70 (4.7)	0.76 (5.7)	0.70 (4.7)	0.59 (3.5)	0.70 (4.6)	0.85 (7.7)
		Alertness	0.51 (2.8)	–	–	–	–	0.55 (3.1)
		Mood	−0.72 (−5.0)	−0.61 (−3.7)	−0.52 (−2.9)	−0.58 (−3.4)	−0.47 (−2.5)	–
Physical well-being	vs	Alertness	0.50 (2.7)	0.54 (3.1)	0.49 (2.7)	0.57 (3.4)	0.60 (3.6)	0.56 (3.2)
		Mood	−0.75 (−5.5)	−0.69 (−4.6)	−0.60 (−3.6)	−0.48 (−2.6)	−0.50 (−2.8)	−0.40 (−2.1)
Alertness	vs	Mood	−0.61 (−3.7)	−0.60 (3.6)	−0.40 (−2.1)	–	−0.47 (−2.6)	−0.57 (−3.3)
Mood	vs	Subjective glare	–	–	–	−0.47 (−2.6)	–	–

Table 5 Multiple regression analysis of the dependent variables: visual acceptance score, luminous perception scores (too bright–too dark), alertness, mood and glare; the independent (log-transformed) photometric variables: illuminance, irradiance, CCT and CRI. Analysis was performed hourly from 12 pm to 5 pm

*b	SEM * b	t-value	p-value	Dependent variable	Time	Independent variable
1.177	0.46	2.560	0.018	Visual acceptance		Illuminance
0.994	0.27	3.650	0.001	Score ('I like the light in this room'/overall the light is comfortable)	12 pm	CCT
−1.796	0.56	−3.210	0.004	0 = Yes 100 = No		CRI
−0.737	0.28	−2.652	0.015	Luminous perception Score ('the light is too bright') 0 = Yes 100 = No	12 pm	CCT
−0.775	0.28	−2.763	0.012	Luminous perception	12 pm	CCT
−1.380	0.61	−2.258	0.035	Score ('the light is too dark')	2 pm	CCT
−0.590	0.25	−2.401	0.026	0 = Yes 100 = No	3 pm	Illuminance
1.513	0.41	3.683	0.001	Subjective	1 pm	Illuminance
0.792	0.37	2.134	0.045	Alertness	1 pm	CCT
−1.844	0.58	−3.203	0.004	0 = very alert; 100 = very sleepy	1 pm	CRI
1.036	0.40	2.568	0.02	Mood 0 = very bad; 100 = very good	4 pm	CCT
−1.122	0.47	−2.394	0.03	Glare 0 = imperceptible; 100=intolerable	5 pm	CRI

The first column shows the standardized regression coefficient *b, indicating the direction of the explained variance. The second column shows the standard error of *b, and the third and fourth columns depict, respectively, the t-value and the p-value (n = 25).

under EL. These variations were at least in part predicted by three different photometric variables (vertical illuminance, CCT and CRI) in the DL condition in the course of the afternoon.

The larger visual acceptance score under DL is supporting our first hypothesis; it is in good agreement with previous studies,[8,9,62,63] even though (as stated in Section 1) the outside view in those studies was not considered as a bias for assessments. Likewise, glare sensations were overall more tolerated under daylight, when compared to EL conditions,[64–66] suggesting a greater tolerance for glare under daylight. This might be due in certain cases to a pleasant view out of the window[64–66] which was shown to positively influence glare ratings.[67,68] In our study however, any direct outside view was prevented and could not lead to higher light preference, visual comfort and lower subjective glare ratings. For non-visual functions such as relaxation, physical well-being, subjective alertness or mood, we found similar associations with the lighting conditions, even though the dynamics of physical well-being and subjective alertness during the afternoon were different: They both decreased relatively earlier under EL than DL (compared to noon values). This is in agreement with a previous report where sleepiness was reduced after bright daylight exposure from a nearby window for half an hour in the afternoon.[46] Other studies showed that higher vertical illuminance during daytime led to greater alertness and thus served as countermeasure for increased sleepiness during the day.[32,69]

According to our first hypothesis, we found that photometric variables modulated some of the visual and non-visual functions in the course of the afternoon; interestingly, these variations did not always go in the same direction (see multiple regression results). Increases in vertical illuminance, for example, were related to greater sleepiness and worse visual acceptance at the beginning of the afternoon ('post-lunch dip'), whereas a decrease of illuminance at 3 pm accounted for a more comfortable luminous perception ('the light in this room is not too dark'). As another example, higher CCT values in the first half of the afternoon were associated with lower visual acceptance and luminous perception scores and less alertness, but better mood towards the end of the afternoon. Since higher CCT reflects a 'cooler' light, which is in our situation linked to daylight availability, there is a risk of a too high illuminance (and CCT) occurring at least at the beginning of the afternoon, when daylight availability is high. The CCT variation later in the afternoon fits well in the known context, a bluer light component can acutely act stronger on non-visual functions such as mood.

It seems also that prior experience of bright DL conditions had an impact on visual acceptance between 5 pm and 6 pm, when only low DL was available, in the case of overcast or intermediate skies. The order of prior light experience, i.e. DL condition on the first or the second study day, also had an impact on visual comfort, as shown by the different OLS and subjective alertness scores. The two lighting conditions also influenced early evening hours, when all subjects remained in dim light conditions for 2 hours. The DL group was more alert at the beginning of the evening; the EL group became significantly sleepier towards the end of the study. Cognitive performance was improved for the DL group compared to the EL group.[48]

We also showed that visual acceptance scores worsened over time, confirming a previous report by Boyce *et al.*[70] It is to note that the scores for both lighting conditions were still within the 50% range of satisfaction. Because the DL condition in our study was dynamic, we could only in part disentangle, whether the variations over time were explained by the modifications of the photometric variables (by means of the results from the regression analysis), or due to changes in the subjects' internal state (i.e. time of day-dependent changes), or both. Not all subjective assessments changed over time: subjective glare ratings, for example, remained stable over the course of the afternoon for both lighting conditions, indicating that a decrease of visual acceptance at the end of the afternoon cannot be solely explained by subjective glare sensations, unless participants became more glare sensitive the less relaxed they were. Causes and mechanisms for the decrease of visual acceptance over time remain to be elucidated; it may come from other behavioural variables, such as variations in subjective alertness, mood, etc. as pointed out by the inter-correlations of these dependent variables. Our results suggest that visual acceptance and luminous perception were partly related with non-visual functions, such as mood, alertness and well-being, and that there is an integration of these perceptual networks in the brain.

Altogether, different lighting conditions, particularly daylight availability, can also be one of the indicators of occupants' work satisfaction, which includes visual and non-visual functions. These effects depend not only on the lighting environment, but also on the time of day and the photometric properties. Whether visual acceptance and glare sensation also undergo other circadian and/or wake-dependent variations needs further investigation and may have consequences for future office lighting environments.

Funding

M. Münch and A. Borisuit were financially supported by the VELUX Foundation

Switzerland; F. Linhart received financial support from the Swiss Federal Office of Energy (SFOE).

Acknowledgements

We are grateful to the LESO-PB mechanic Pierre Loesch for his valuable help with the electric lighting equipment. We also thank REGENT Beleuchtungskörper AG (Switzerland) for providing us with the luminaires in the testing room, and OSRAM (Switzerland) for the DALI control gear system.

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