Hubalek, Sylvia; Brink, Mark; Schierz, Christoph:

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URN: urn:nbn:de:gbv:ilm1-2014210273

Published OpenAccess: November 2014

Original published in:

Lighting research and technology. - London [u.a.] : Sage (ISSN 1477-0938). - 42 (2010) 1, S. 33-50.
DOI: 10.1177/1477153509355632
URL: http://dx.doi.org/10.1177/1477153509355632
[Visited: 2014-10-14]

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Lighting Research and Technology 2010 42: 33 originally published online 5 January 2010
DOI: 10.1177/1477153509355632

Lighting Res. Technol. 2010; **42**: 33–50

Office workers' daily exposure to light and its influence on sleep quality and mood

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Received 26 July 2008; Revised 18 September 2009; Accepted 30 October 2009

To study the amount of light entering the eye and its effects on office workers, measurements were taken from 23 office workers over a period of seven consecutive days. Two parameters of visible light were recorded: (i) illuminance and (ii) irradiance of the blue spectral component. Every evening before going to bed, a questionnaire had to be filled out, containing scales relating to the mood dimensions of pleasure and arousal, questions about the previous night's sleep and a rough time table with information about the person's whereabouts during the day. The exposure to light on workdays is regular but it varies strongly on days off. No evidence could be provided for the influence of age, sex or seasonal affective disorder (SAD) scores on the daily exposure to light of office workers. The amount of light entering the eye during the day appears to have a positive impact on sleep quality the following night. Pleasure and arousal were not significantly associated with daily light exposure.

1. Introduction

In 1948, Hollwich hypothesised that light entering the eye is not only responsible for vision, but also for various non-visual biological effects.[1] Sixty years later, accepted applications for the non-visual effects of light are, for example, to shift the circadian rhythm to avoid jetlag, to increase alertness at night and to treat seasonal affective disorder (SAD; also known as winter depression).[2–8] While these applications pertain to selected portions of the population only, there are two interesting non-visual light effects that might affect large portions of the population: The effect of light on sleep quality and on mood. These potential effects of daily exposure to light have so far been argued from varying viewpoints.[3]

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1.1 Daily exposure to light

In general, little is known about the daily exposure to light of humans.[9] Before new devices[10–12] for measuring the blue spectral component irradiance were available, data could only be collected for illuminance. Some measurements were taken with devices fixed on the wrist,[13–17] but other, more relevant ones, were taken with devices fixed on the forehead.[18–21]

According to the literature, no significant differences in daily exposure to light have been found for differences in age, sex,[15,16] income level and family status[15] nor for light on workdays compared to days off.[15,19] Significant differences in the daily exposure to light have been found for differences in geographic latitude and season[16,22–24] as well as occupation.[17,25] Findings are inconclusive for SAD scores: while Espiritu *et al.*[15] found that healthy persons with higher SAD scores spent less time at higher illuminances compared to healthy ones with lower SAD scores

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Guillemette *et al.*[22] could not find differences between these groups.

1.2 Effects of light on sleep quality, mood and alertness

The effects of light on sleep quality need to be separated into light exposure during the day and light exposure at night. A higher light exposure during the day may have a positive influence on sleep quality.[17,26,27] An increased blue spectral component may possibly enhance this effect.[28,29] During the night and prior to bedtime, it is beneficial for increased quality of sleep to try to avoid too much light.[17,30]

The effect of light on mood is controversial. Goel and Etwaroo[31] refer to nine studies showing a positive impact of light on mood and eight studies which were not able to show a relationship. However, the positive impact on mood was stronger with persons suffering from subsyndromal seasonal affective disorder.[31–33] Aan het Rot *et al.*[24] were able to show in 2008 that short-term light exposure to more than 1000 lx was positively associated with a good mood, more agreeableness and less quarrelsomeness in subsyndromal SAD people (S-SAD).

While it is well accepted that light exposure at night has an effect on alertness, it seems to be far more difficult to show this effect for light exposure during the day.[34,35] An alerting effect of light during the day could be shown for about 65% of the subjects only,[36] for shift-workers[37] and for persons with subsyndromal seasonal affective disorder (S-SAD).[38] Revell *et al.*[39] found an increasing alerting effect with shorter wavelengths. Hence, the authors conclude that the spectral sensitivity for alerting effects may be different from the spectral sensitivity function for melatonin suppression.[11,12,40,41] All the results mentioned above were obtained in laboratory experiments. It has also been shown in a field experiment that there is a negative correlation between illuminance at the eye and fatigue of office workers.[42] Furthermore, blue-enriched white light in the workplace is related to an improved self-reported alertness during daytime.[29]

1.3 Aim of the study

This study aims to elucidate whether light exposure has an influence on sleep quality, mood and arousal alertness which is strong enough to show up in everyday life. Since most of the studies mentioned above were carried out in laboratories, field data needed to be collected.

Furthermore, data for (i) daily exposure to light and (ii) exposure to light during time spent in the office should be collected for future use. As soon as the necessary light exposure – from the chronobiological point of view – is known, these data can be used to examine the difference between ‘target’ and ‘actual’. If ‘actual’ (e.g. the measured daily exposure to light in everyday life) is different from ‘target’ (the necessary light exposure from a chronobiological point of view), there is a need for intervention. Modality and extent can be defined with the collected data. The results would be beneficial for designing lighting as well as the individual handling of light.

2. Method

2.1 Subjects

Twenty-three volunteers between the ages of 18–57 (mean = 38.4, SD (standard deviation) = 10.6) took part in the experiment. They were selected to meet the following criteria:

– No diseases or medications which are known to influence photosensitivity
– Normal or corrected to normal visual acuity
– No special experience with the non-visual effects of light
– Full time office employment with an office located in or close to Zurich, Switzerland (47.38° North, 8.54° East).

In order to measure the subjects’ susceptibility to seasonal affective disorder, the

Seasonal Pattern Assessment Questionnaire (SPAQ)[43] was used. Specific descriptive data for the subject group are shown in Table 1.

Thirteen subjects were permanently working at their individual office desks, five worked at different desks in the same building and five others had additional outside appointments. All work stations were day-lit with a maximum distance to the façade of 3.50 m (mean = 1.45 m, SD = 0.91 m).

2.2 Instrumentation

Two parameters of visible irradiance with different spectral sensitivities were recorded: (i) illuminance with the CIE spectral luminous efficiency function for photopic vision $V(\lambda)$ and (ii) irradiance of the blue spectral component with the action spectrum for melatonin suppression, which is currently also used for other non-visual biological effects. For the blue spectral component we used a spectral sensitivity $c(\lambda)$ defined by Gall,[44] which is based on a combination of laboratory results and the transmission properties of the human eye media. The illuminance ranges up to 5000 lx and the blue spectral component irradiance ranges up to 7.5 W/m^2. Values are alternately recorded every 100 milliseconds.

The head-mounted device – named LuxBlick – consists of two light sensors, which are fixed on the participant's spectacle frames or lenses, and a control unit and data-recording mini-computer worn in a bag around the waist.[11,12] Suitable to be worn in everyday life, the parts at the head are light and inconspicuous as shown in Figure 1. Subjects with normal visual acuity wore the sensors on empty spectacle frames. The device was worn from the time of awakening to bedtime. If the subjects had to remove the device, for example, when taking a shower or doing sports, they put a black cloth on the sensors to make sure that no irradiance was recorded.

2.3 Meteorological data

Additionally, we obtained the total daily sky radiation energy density (in Wh/m^2) – a rough indicator of the weather conditions that prevailed during the measurement days – from the nearest weather station of the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). Full graphic data sets were documented.[12]

2.4 Questionnaires

Every evening before going to bed, a questionnaire had to be filled out containing

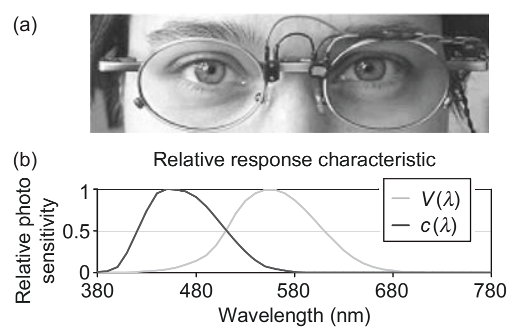

Figure 1 (a) The two light sensors are fixed in the middle of the spectacle frame. (b) The spectral sensitivities of $c(\lambda)$ and $V(\lambda)$

Table 1 Subjects' sex, age, vision and SAD distributions

Sex	Male (♂)		Female (♀)
	16		7
Age	18–29 years	30–44 years	45–57 years
	5 (3♂/2♀)	11 (7♂/4♀)	7 (6♂/1♀)
Vision	Normal	Spectacles	Lenses
	3 (♂)	17 (12♂/5♀)	3 (1♂/2♀)
Result	Healthy	S-SAD	SAD
SPAQ-test	(0–7 scores)	(8–10 scores)	(≥11 scores)
	14 (11♂/3♀)	5 (2♂/3♀)	4 (3♂/1♀)

scales of the mood dimensions pleasure (as an expression of contentment) and arousal (as an expression of alertness or activation), questions about the previous night's sleep and a rough time table giving information about the person's whereabouts during the day.

Pleasure and arousal: For the basic emotional dimensions pleasure and arousal the Pleasure–Arousal–Dominance (PAD) model of Mehrabian *et al.*[45] was used. Each of the two emotional dimensions is summed up from six bipolar semantic differentials. For 'pleasure' the six semantic differentials sorted in ascending order are: Unglücklich–glücklich (unhappy–happy), genervt–erfreut (annoyed–pleased), unzufrieden–zufrieden (unsatisfied–satisfied), schwermütig–zufrieden (melancholic–contented), verzweifelt–hoffnungsvoll (despairing–hopeful), gelangweilt–entspannt (bored–relaxed). For 'arousal' the six semantic differentials sorted in ascending order are: entspannt–stimuliert (relaxed–stimulated), ruhig–aufgeregt (calm–excited), träge–rasend (sluggish–frenzied), lahm–nervös (dull–jittery), schläfrig–hellwach (sleepy–wide awake), unerregt–erregt (unaroused–aroused). German adjectives were chosen from a pool of possible translations in order to get similar independent factors by factor analysis. The score for each scale ranged from one to seven, resulting in a sum for each dimension of between 6 and 42 points. To avoid habituation effects the list of adjective scales on a form varied in direction of scores and in a daily rotation.

Sleep quality: While questions on pleasure and arousal were asked by means of a standardised test, sleep quality was ascertained by simply using the two following questions: (i) 'Wie haben Sie letzte Nacht geschlafen, verglichen mit einer durchschnittlichen Nacht?' (How did you sleep last night compared to an average night?) (ii) 'Wie unruhig haben Sie geschlafen?' (How restless was your sleep?). The answers were given on five-point scales with the end points schlecht–gut (bad–good) and ruhig–unruhig (restful–restless). Scale values were translated into integer values from 1 to 5. A score was calculated by subtracting the value of the second scale from the value of the first scale. A minimum sum of -4 equates to low sleep quality, whereas a maximum sum of $+4$ equates to high sleep quality. As sleep quality pertaining to the preceding night (and possibly influenced by conditions that prevailed during the previous day) was assessed in the questionnaire, the obtained value was shifted backwards 1 day in the data file so that it corresponds to the light exposure measurements of the previous day.

2.5 Experimental procedure

Before the start of the experiment, the irradiance measurement device, questionnaires and procedure were explained to each individual participant and the sensors were fixed on the spectacles. The experiment was conducted over three weeks in April and June 2005 with up to nine subjects being measured in parallel. For each participant the experiment ran for seven consecutive days. The device was operating during awake time only. Every evening before going to bed the daily questionnaire mentioned above had to be filled out. After 7 days, the subjects returned to the laboratory to remove the sensors and allow us to measure the transmission values of their glasses. Finally, the subjects were given a remuneration of € 50.

2.6 Data preparation

For people wearing glasses, all measured values had to be corrected for the transmittance of the spectacle lenses. Then, data were cleaned conservatively: Days on which the subjects stopped wearing the device for more than two hours were excluded from the data set. The data set was thus reduced from 156 to 97 days for the analysis of (i) daily exposure to light. The data were then prepared to show the course of the day and the cumulative frequency distributions of illuminance and blue spectral component. Full graphic data sets were documented together with outdoor global irradiance during the course of all measurement days.[12]

Even fewer data sets were accepted for the time spent in the office: Data sets were only accepted when subjects spent between seven and nine hours in the office. Thus, a data set consisting of 56 days from 22 subjects was available for the analysis of (ii) exposure to light during time spent in the office.

Subsequently, parameters were calculated for illuminance as well as for blue spectral component irradiance: Exposure, intensity and duration over thresholds. The maximum data were limited through the apparatus' sensitivity so the chosen measure for the central tendency was the median, which is robust against erroneous maxima.

Furthermore, morning/evening ratios were calculated. In contrast to Iwata,[17] morning and evening exposure data were taken independently of individual sleeping time: One hour in the morning from 10:00 to 11:00 hours and one hour in the evening from 21:00 to 22:00 hours, respectively. Only time periods with less than 5% of data missing were used. This way, the data set for further analysis – regarding the influence of the morning/evening ratios on sleep quality, pleasure and arousal – was again shortened to between 37 and 49 days. Additionally, a new spectrum parameter called vis–nonvis was introduced to describe the relation between illuminance and blue spectral component irradiance – measured in identical time intervals. The name vis–nonvis is an abbreviation for vision (vis) and non-visual biological effects (nonvis). The spectrum parameter vis–nonvis is defined as:

$$\begin{aligned}\text{Vis}-\text{nonvis} &= \log\,(\text{median of illuminance})\\ &\quad - \log\,(\text{median of blue spectral}\\ &\quad \text{component irradiance})\end{aligned}$$

The logarithm was chosen because of the assumed logarithmic stimulus–response relationship of the non-visual system.[4,46] Vis–nonvis decreases with increased irradiance by the short wavelengths of the visible spectrum.

3. Results

3.1 Light exposure

Example data from a workday and a day off are shown in Figure 2(a) and (b), respectively. Both data sets are from participant 005. In addition to illuminance (E in lux) and the irradiance of the blue spectral component (B in W/m^2), sequences of the rough time table, with information about the person's whereabouts during the day, are presented. Due to the fact that the sampled time intervals used a minimum of 30 minutes, shorter time intervals, for example, outdoors from home to the office and from the office back home, are not visible in the time lines, but only via the high values in the graphs.

Since the participant's office is facing west, the values were increasing in the afternoon on a sunny day (April 14). Towards sunset at 20:14 hours, the values are decreasing. During the lunch break, from approximately 12:45 to 13:15 hours, more light entered the participant's eyes. Peaks are caused by views towards the office window or towards other sources of bright light. Altogether, the daily luminous exposures were 5649 lxh and 11.3 Wh/m^2.

The day off (April 16; mixed weather) is remarkable due to the small intensities of light that entered the participant's eyes during the time at home. Only around lunchtime some time spent outdoors led to higher values. Altogether, the daily luminous exposures were 1 650 lxh and 3.0 Wh/m^2.

Figure 3 shows the daily luminous exposures from all 96 data sets. A large variability in light exposure is evident from day to day for the same participant and between participants. Furthermore, the difference between the minimum and maximum light exposures is noticeable. A minimum of 217 lxh for participant 023 was the result of a day spent at home with electronic media. Because a pathway is situated directly in front of the window, the Venetian blinds were closed to screen from view. A maximum of 21 815 lxh was recorded with participant 001. Around midday, the participant spent several hours outdoors.

Tables 2 and 3 show the descriptive data for 'time in office' and 'daily exposure to light'. For the illuminance and the blue spectral irrandiance, the different parameters 'luminous exposure' and 'exposure', 'illuminances' and 'irradiances' as well as 'duration over thresholds' are shown. For each datum not only the median, but also the 25th and 75th percentile (data in brackets) are

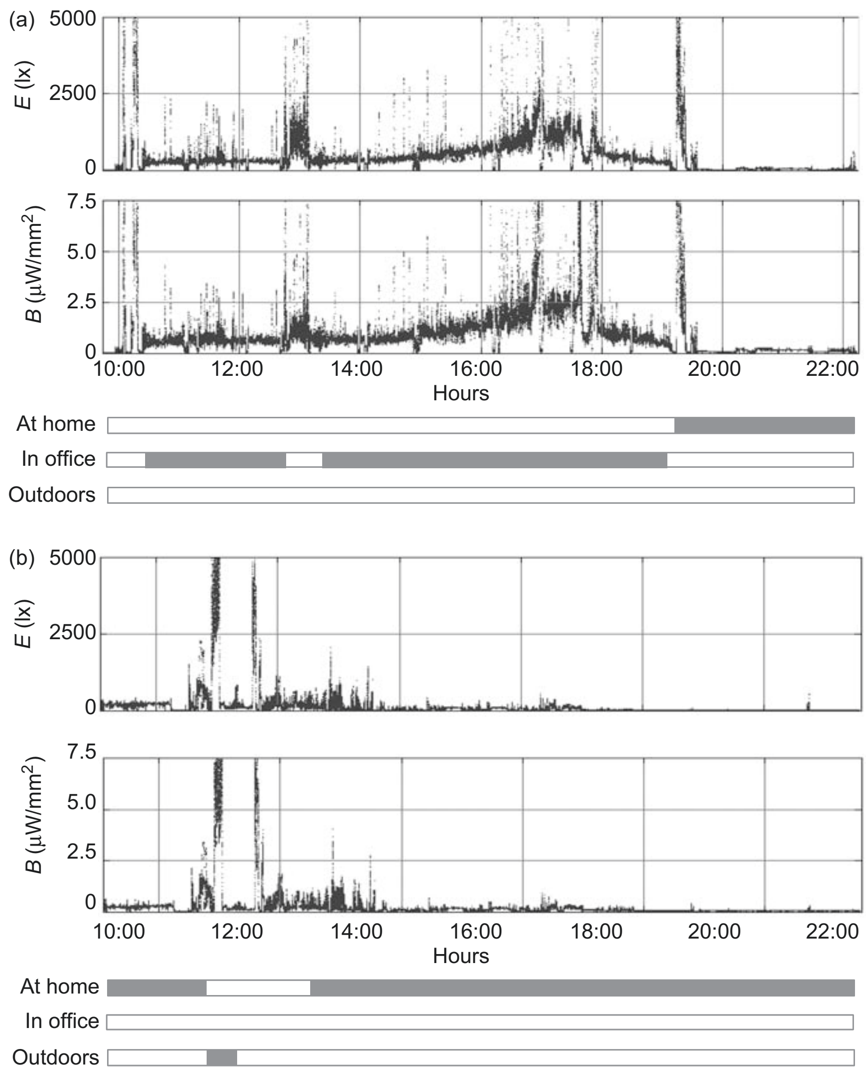

Figure 2 Examples of recordings of a workday (a) and a day off (b). Shown are the illuminance E, the blue spectral component irradiance B and the time lines giving the whereabouts of the subject. Data were measured on April 14th and 16th 2005 from participant 005

shown to give information about the variability.

For orientation: first, a luminous exposure of 5000 lxh is recommended for light therapy to treat SAD.[47,48] While the median luminous exposure during time in office is 2244 lxh, the median daily luminous exposure is about three times greater at 7394 lxh. Second, the median illuminance of 308 lx during time in office decreases to a median of 183 lx for daily illuminance. This is due to the fact that illuminances in the evenings were far lower than during the working days. Third, a duration over threshold of 100 lx for 6.5 hours at night is sufficient for a 50% impact threshold of a light-induced shift of the circadian rhythm, melatonin suppression and subjective alertness.[4,46] For daily exposure to light, the duration over a threshold of 100 lx is significantly longer. The median duration of 534 min (just less than 9 hours) is obviously related to time with daylight. Fourth, an illuminance at the eye of 1000 lx for working men was proposed in 2003 by the Nederlandse Stichting voor Verlichtingskunde.[49] Up to now, however, it has not been explained for how long, in what rhythms, at what time, etc. this value should be available. In any case, the median subject was exposed to illuminance $\geq$1000 lx for 105 minutes per day and 16 minutes during the time in office. Twenty five percent of the data for time in the office show less than 2 minutes spent at more than 1000 lx at the eye. Fifth, a minimum illuminance of 2500 lx for 2 hours is recommended for light therapy. The median subject was exposed to illuminance $\geq$2 500 lx for 43 minutes per day and 1 minute during the time in office.

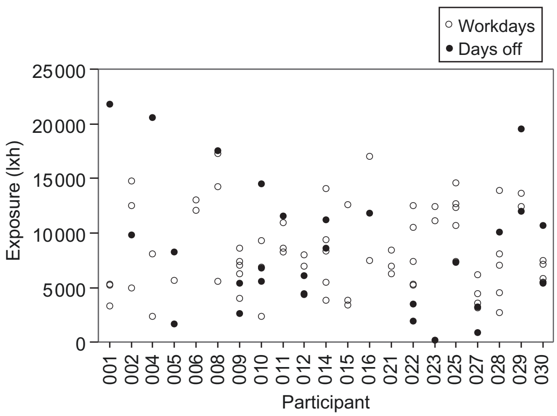

Figure 3 The daily luminous exposure to light. The data points are from 97 data sets provided by 21 subjects for both workdays and days off

While the illuminances shown in Table 2 are comparable to values from the literature, no values have yet been reported to which our blue spectral component irrandiances

Table 2 Illuminance data for time spent in the office and the daily exposure to light. Shown are luminous exposure, the median illuminance and the illuminance at different percentiles of the distribution and the duration of exposure above thresholds of 100 lx, 1000 lx and 2500 lx. For each datum not only the median, but also the 25th and 75th percentiles (data in brackets) are shown to give information about variability

	Time in office	Daily exposure to light
Luminous exposure	2244 lxh (1199–3392 lxh)	7394 lxh (5237–11 683 lxh)
Illuminance		
10th percentile	113 lx (66–173 lx)	15 lx (8–24 lx)
25th percentile	201 lx (135–369 lx)	56 lx (29–87 lx)
Median	308 lx (202–572 lx)	183 lx (118–249 lx)
75th percentile	569 lx (298–815 lx)	488 lx (263–870 lx)
90th percentile	840 lx (451–1246 lx)	1203 lx (786–2 706 lx)
Duration over thresholds		
Threshold 100 lx	240 minutes (204–283 minutes)	534 minutes (436–626 minutes)
Threshold 1000 lx	16 minutes (2–48 minutes)	105 minutes (61–187 minutes)
Threshold 2500 lx	1 minute (0–8 minutes)	43 minutes (16–92 minutes)

Table 3 Blue spectral component irradiance data for time spent in the office and the daily exposure to light. Shown are the exposure, the median irradiance and the irradiance at different percentiles of the distribution and the duration of exposure above thresholds of 0.1 W/m^2, 1.0 W/m^2 and 2.5 W/m^2. For each datum not only the median, but also the 25th and 75th percentiles (data in brackets) are shown to give information about variability

	Time in office	Daily exposure to light
Exposure	3.08 Wh/m^2 (1.83–5.07 Wh/m^2)	11.85 Wh/m^2 (7.75–17.90 Wh/m^2)
Irradiance		
10th percentile	0.19 W/m^2 (0.11–0.27 W/m^2)	0.05 W/m^2 (0.03–0.07 W/m^2)
25th percentile	0.31 W/m^2 (0.20–0.56 W/m^2)	0.11 W/m^2 (0.06–0.13 W/m^2)
Median	0.51 W/m^2 (0.31–0.82 W/m^2)	0.29 W/m^2 (0.17–0.41 W/m^2)
75th percentile	0.85 W/m^2 (0.44–1.19 W/m^2)	0.83 W/m^2 (0.40–1.20 W/m^2)
90th percentile	1.12 W/m^2 (0.72–1.74 W/m^2)	1.85 W/m^2 (1.06–3.70 W/m^2)
Duration over thresholds		
Threshold 0.1 W/m^2	259 minutes (217–307 minutes)	667 minutes (542–744 minutes)
Threshold 1.0 W/m^2	41 minutes (12–114 minutes)	175 minutes (93–246 minutes)
Threshold 2.5 W/m^2	3 minutes (0–18 minutes)	65 minutes (36–119 minutes)

could be compared. Different to illuminance, median daily exposure to light with a blue spectral component of 11.84 Wh/m^2 is not only three times, but about four times higher than during time in office, which is at 3.08 Wh/m^2. This effect could be explained by both the limited range of the measurement device, LuxBlick, which has maxima of 5000 lx and 7.5 W/m^2, and the fact that higher values are rare, as illustrated in Figure 2. It can thus be assumed that the amount of short wavelength light of the visible spectrum is higher. This assumption seems reasonable because high values are predominantly measured outdoors and the amount of short wavelength light of the visible spectrum outdoors is much higher than indoors.[44] Similarly to illuminance, the median blue spectral component of 0.51 W/m^2 during time in office decreases to a median of 0.29 W/m^2 for the whole day. This is due to the fact that blue spectral component levels in the evenings were far lower than during days. Thresholds of 0.1 W/m^2, 1.0 W/m^2 and 2.5 W/m^2 were chosen following the grading of the thresholds for illuminance, with an emphasis on smooth numbers. Thus, a factor 1000 was chosen in between the illuminance and blue spectral component, instead of using the factor 683 (maximum photometric radiant equivalent: 683 lm/W), the duration over thresholds in Table 3 is considerably longer than in Table 2. Similarly to illuminance, the duration over the highest threshold, 2.5 W/m^2, is short with three minutes during time in office.

The same parameters for illuminance and blue spectral component irradiance are strongly correlated (Table 4). This was to be expected as they are both related to the spectral power distribution. The squared correlation coefficient (= coefficient of determination) is the percentage of explained variance. For example, this means for the median of the time in office ($r = 0.942$, $p < 0.001$; $r^2 = 0.887$) that 88.7% of the variance of the blue spectral component irradiance can be explained by illuminance variation (and vice versa). Luminous exposure has an even stronger correlation.

3.2 Influence of age, sex and SAD scores

Figure 4 shows the cumulative frequency distributions for illuminance separated by the subjects' different ages, sexes and SAD scores.

Three age groups were formed: 18–29 years, 30–44 years and 45–57 years. Only minor differences were found among those

Table 4 Correlations (Spearman) between illuminance and blue spectral component irradiance parameters. One-sided statistically significant results are shown in bold

	Time in office		Daily exposure to light	
	r	Sig.	*r*	Sig.
Exposures	0.951	**<0.001**	0.971	**<0.001**
Illuminance and irradiance				
10th percentiles	0.934	**<0.001**	0.145	0.077
25th percentiles	0.931	**<0.001**	0.368	**<0.001**
Medians	0.942	**<0.001**	0.903	**<0.001**
75th percentiles	0.947	**<0.001**	0.912	**<0.001**
90th percentiles	0.937	**<0.001**	0.963	**<0.001**
Duration over thresholds				
Thresholds 100 lx and 0.1 W/m^2	0.904	**<0.001**	0.726	**<0.001**
Thresholds 1000 lx and 1.0 W/m^2	0.849	**<0.001**	0.906	**<0.001**
Thresholds 2500 lx and 2.5 W/m^2	0.882	**<0.001**	0.915	**<0.001**

groups. The graphs of all three groups cross at 100 lx at a cumulative frequency of 58%. This means that they spent an average 58% of the wake time at an illuminance of 100 lx and more. With an illuminance of less than 100 lx, the graphs depart from each other systematically. While the youngest spent 31% of their wake time with an illuminance of less than 30 lx, it was barely 23% for the oldest. This might be due to the fact that older people need more light for similar vision.

3.3 Daily exposure to light on workdays and days off

The exposure to light on workdays is regular whereas it varies strongly on days off (Figure 5(a) and (b)), which is reflected in the increased SD. Furthermore, office workers' (OW) daily exposure to light on workdays differs clearly from days off (Figure 5(c)). This finding is not in line with earlier findings based on measurements made with daytime guards (DG).[19] For daytime guards there is barely a difference between workdays and days off (Figure 5(c)).

3.4 Influence of light on sleep quality, pleasure and arousal

One of our main hypotheses was that there would be an association between daily exposure to light and sleep quality (according to self-rating), and pleasure and arousal (according to the PAD model[45]). We further hypothesised that the weather that prevailed during the measurements might influence the subject's mood independent of the particular (partly indoor) light exposure at the eye. Therefore, we obtained the total daily sky radiation energy density (in Wh/m^2) – a rough indicator of the weather conditions that prevailed during the measurement days – from the nearest weather station of the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss).

To perform the analyses, a data set of 86 cases (days) was available for sleep quality (Min $= -2$; Max $= 4$; Median $= 2.00$; Mean $= 1.23$; SD $= 1.38$). Ninety seven cases were available for pleasure (Min $= 17$; Max $= 42$; Median $= 28.0$; Mean $= 28.2$; SD $= 5.4$) and arousal (Min $= 7$; Max $= 29$; Median $= 22.0$; Mean $= 21.0$; SD $= 4.7$), respectively. No correlation could be found between pleasure and arousal (two-sided Spearman: $r = 0.036$; $p = 0.656$). This verifies that both emotional dimensions can be treated separately.

The collected data are of a hierarchical nature incorporating both fixed and random factors which demands appropriate statistical modelling techniques. Exposure to light as well

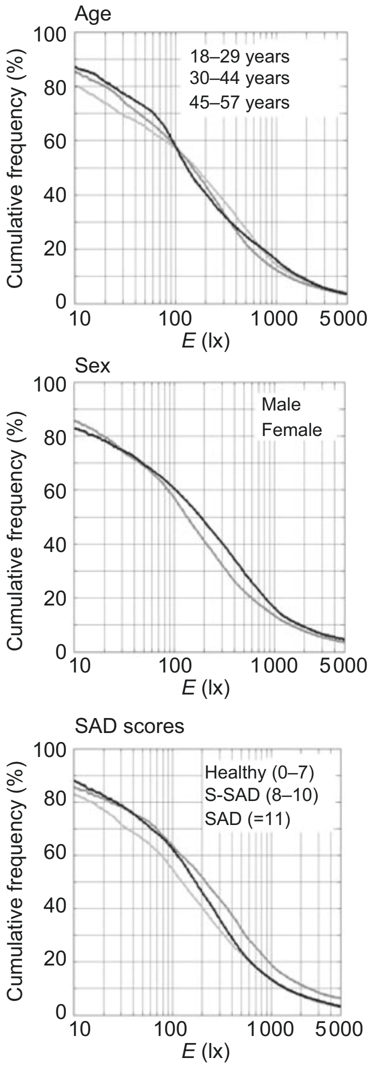

Figure 4 Cumulative frequency distributions of illuminance separated by age, sex and SAD scores. No evidence could be provided for their influence on the daily exposure to light

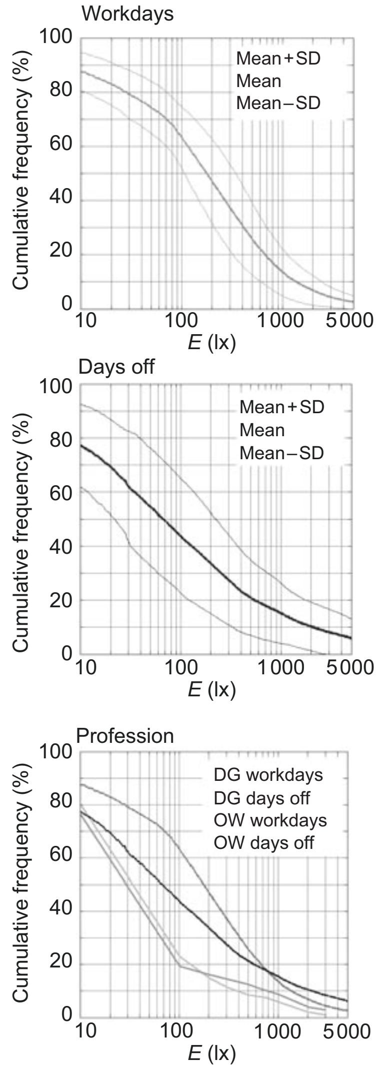

Figure 5 Cumulative frequency distributions of illuminance separated into workdays (mean and standard deviation (SD)), days off (mean and standard deviation (SD)) and different professions (daytime guards = DG, office workers = OW). The exposure to light on workdays is regular but varies strongly on days off. While a clear difference can be seen between workdays and days off with the office workers, there is barely a difference with the daytime guards

as its effects was measured for each subject during several consecutive days, thus the factor 'day' is nested within the higher level factor 'subject'. Each day is furthermore characterised by the weather that prevailed and whether it is an office day or a day off. The weather is hereby called a covariate since it possibly co-varies with the measured dependent variables (e.g. mood, sleep quality, etc.) and must be controlled. Also the fact whether the day was a day spent at the office or not might be of importance for the result. Finally, each subject is considered a random pick from a much larger population (e.g. all office workers in Zurich). Subjects are therefore called random factors. Subjects are not a factor of primary interest within the study, but the exposure to light is, the latter being called a fixed factor. Since the data thus are made up of both fixed and random factors, the statistical model to describe them is called a mixed model. Pursuing this mixed model approach, data were analysed using the MIXED procedure of SAS Version 9.1 (SAS Institute, Cary, NC, USA) with restricted maximum likelihood estimation.

We investigated the influence of the daily exposure to light in several mixed models where the subject (nested within sex) was treated as a random factor; sex and whether the subjects spent the day in the office or not (day in office) were treated as fixed factors; and age, SAD score (according to SPAQ questionnaire[43]), number of the day (day number) within the individual study period, the weather, and the daily exposure to light were treated as covariates. Several measures of daily exposure to light were available. Given the fact that there are no standard measures for light exposure, we had to run several models using different indices of light exposure. Preliminary regression analyses showed that daily luminous exposure, the time spent above 1000 lx in minutes, the time spent above 2500 lx in minutes and the vis–nonvis spectrum parameter best predicted the outcome measures. Other measures of daily exposure to light where thus not considered. The corresponding blue spectral component parameters were, as described above, highly correlated with the illuminance parameters and therefore no separate models were calculated with these variables.

Differences due to varying daily exposure to light were calculated for the three outcome measures and tested for significance at a critical level of $p < 0.05$. In the models, the four covariates age, SAD score, day number, and weather were entered first, followed by the subject and daily light exposure as main effects. Separate models were calculated for sleep quality, pleasure and arousal.

Of the main outcome measures considered, only sleep quality was significantly related to any measure of daily light exposure. Other factors and covariates were not significantly related to either sleep quality, pleasure or arousal (modelling the subject as a fixed effect revealed that pleasure and arousal are basically determined by the factor subject and much less so by light exposure). These predictors were thus ignored in the further analyses. However, we considered the fact whether the day was spent in the office as relevant within the scope of this investigation and the factor day in office was thus retained in all models. The results of the models are outlined in Table 5.

Where the main effect for the daily light exposure was statistically significant, estimated least-squares means and standard errors are reported separately for the minimum, the median, and the maximum daily light exposure value across the sample. The corresponding figures are given in Table 6. The least squares means in the column denoted 'estimate' are predictions of the sleep quality score for a given combination of levels of the explaining variables, here the daily luminous exposure and day in office. For example, if the daily luminous exposure is 7394 lxh and the subject is in the office during such a day, the model predicts that the sleep quality the following night would be subjectively rated as 1.13 on the five-point scale. From Table 6 it also becomes obvious that sleep quality increases with increasing daily luminous exposure.

4. Discussion

4.1 Light exposure

Compared to other long-time light exposure data, our data fit well into the scope of other investigations concerning illuminance. The median daily luminous exposure of our office workers is 7394 lxh; Iwata[17,21] reports values from 1860 to 12 000 lxh measured close

Table 5 Results of the mixed models analyses. The table shows individual model results of the fixed effects for the three dependent variables (sleep quality; pleasure and arousal) and four exposure-related predictors (daily luminous exposure; spectrum parameter vis–nonvis; duration above a threshold of 1000 lx in minutes; duration above a threshold of 2500 lx in minutes). The factor 'Day in office' indicates whether the day was spent in the office or elsewhere was retained in all models. Statistically significant results are shown in bold

Dependent	Predictor	*DF*	*F*	*p*
Sleep quality	Day in office	1; 74.5	0.11	0.74
	Daily luminous exposure	1; 81.1	6.84	**0.01**
Pleasure	Day in office	1; 80.1	0.22	0.64
	Daily luminous exposure	1; 90	0.16	0.69
Arousal	Day in office	1; 78.1	0.1	0.75
	Daily luminous exposure	1; 85.4	1.22	0.27
Sleep quality	Day in office	1; 75.2	0.09	0.77
	Vis–nonvis	1; 76.7	5.02	**0.03**
Pleasure	Day in office	1; 79.2	0.19	0.66
	Vis–nonvis	1; 90.2	0.06	0.81
Arousal	Day in office	1; 77.9	0.17	0.68
	Vis–nonvis	1; 85.9	0.02	0.89
Sleep quality	Day in office	1; 74.2	0.08	0.78
	Duration over threshold 1000 lx in minutes	1; 76.2	4.22	**0.04**
Pleasure	Day in office	1; 80.5	0.27	0.60
	Duration over threshold 1000 lx in minutes	1; 92.8	0.24	0.63
Arousal	Day in office	1; 77.9	0.13	0.72
	Duration over threshold 1000 lx in minutes	1; 88.3	0.27	0.60
Sleep quality	Day in office	1; 77.4	0.82	0.37
	Duration over threshold 2500 lx in minutes	1; 81.3	6.82	**0.01**
Pleasure	Day in office	1; 81.6	0.04	0.84
	Duration over threshold 2500 lx in minutes	1; 88.7	0.8	0.37
Arousal	Day in office	1; 79.2	0.01	0.93
	Duration over threshold 2500 lx in minutes	1; 84.6	0.88	0.35

to the eye. Measured at the wrist – she reports a median of 3339 lxh for students, 5421 lxh for office workers and 35 086 lxh for bus drivers. Duration over a threshold of 100 lx is with 534 minutes comparatively longer than that shown in other investigations. So far, data in the literature is for measurements made at the wrist only, with average durations between 200 and 420 minutes.[14–16,22,23] These differences can hardly be explained by time of year or latitude. Differences may, for example, be explained by variations in measurement methods, variations in daylight illumination of offices, occupation and local cultural circumstances that influence behaviour. In contrast to the 100 lx threshold, duration over a threshold of 1000 lx was 105 minutes, which fits well into with other investigations. In these, on an average, subjects received less than half an hour of light >1000 lx in winter and 90 minutes to 160 minutes in summer.[14–16,22–25]

Results from other, similar investigations concerning blue spectral irradiance are currently not available. As shown, most of the parameters for illuminance and blue spectral irradiance are strongly correlated. However, it is to be expected for future light applications that correlations may decrease. For chronobiological purposes, the blue spectral component may systematically be controlled in the future. Therefore, the collected data may provide a basis for the description of current light situations at work stations.

In this study, the effective light is described by means of the parameters exposure, illuminance, blue spectral irradiance, duration over thresholds, morning/evening ratios as well as the spectrum parameter vis–nonvis. In the future, however, these parameters should be

Table 6 Estimated least-squares means of sleep quality rating (and the associated standard error) for three different levels (the minimum, the median and the maximum in the sample) of exposure to light, modelled with four different exposure-related predictors. The results of the corresponding models have been reported in Table 5

Daily luminous exposure (lxh)	Day in office	Estimate (sleep quality)	SE
217	Not in office	0.43	0.38
	In office	0.53	0.34
7394	Not in office	1.03	0.26
	In office	1.13	0.20
21 815	Not in office	2.25	0.49
	In office	2.35	0.46
Vis–nonvis	**Day in office**	**Estimate (sleep quality)**	**SE**
2.18	Not in office	0.01	0.58
	In office	−0.08	0.62
2.81	Not in office	1.27	0.26
	In office	1.17	0.19
3.34	Not in office	2.32	0.57
	In office	2.23	0.48
Duration over threshold 1000 lx (in minutes)	**Day in office**	**Estimate (sleep quality)**	**SE**
1	Not in office	0.66	0.36
	In office	0.74	0.32
105	Not in office	1.06	0.27
	In office	1.15	0.20
335	Not in office	1.95	0.47
	In office	2.03	0.43
Duration over threshold 2500 lx (in minutes)	**Day in office**	**Estimate (sleep quality)**	**SE**
0	Not in office	0.56	0.34
	In office	0.84	0.25
43	Not in office	0.88	0.28
	In office	1.16	0.20
258	Not in office	2.47	0.57
	In office	2.75	0.61

complemented by a measure that includes temporal intensity gradients as well as exposure interruptions, and considers non-linearities, since it is likely that they have a considerable impact.[25,50–52] In any case, for further laboratory and field experiments, the recommendations of Remé *et al*.[53] for specifying parameters of light should also be considered in order to make it easier to compare results.

4.2 Influence of age, sex and SAD scores

This investigation confirms some of the results of earlier investigations: It can be confirmed for office workers that there is only a minor influence of age and sex on the daily exposure to light.[15,16] However, there are inconclusive findings regarding SAD scores. Similarly to Guillemette *et al*.[22], but unlike Espiritu *et al*.,[15] we found no difference between the groups. A possible explanation may be that this effect depends on the time of year. Our experiment was conducted in springtime – a season where symptoms of seasonal affected disorder are already decreasing. On the other hand, the research design may not have been powerful enough (the sample was quite small) to detect small effects. Much larger samples would be required to do so.

4.3 Daily exposure to light on workdays and days off

Our measurements taken with office workers show that the exposure to light on workdays is more or less steady, whereas it varies strongly on days off. This finding is not in line with measurements taken with daytime guards.[19] For daytime guards there is barely a difference between workdays and days off. It is to be expected that such differences will occur for subjects with different jobs.

4.4 Influence of light on sleep quality, pleasure and arousal

Light at the eye during the day appears to have a positive impact on sleep quality the subsequent night. This confirms the findings of earlier field and laboratory investigations.[17,26,27] Sleep quality is positively associated with daily luminous exposure, the spectrum parameter vis–nonvis and duration over thresholds 1000 and 2500 lx. Table 6 shows that sleep quality increases with increasing values of vis–nonvis. An increase of vis–nonvis means a decrease of blue light. This finding contradicts Francis's *et al.*[28] suggestion and Viola's *et al.*[29] finding, that blue light is positively associated with sleep quality. Landers *et al.*,[54] in contrast, showed that elderly people with blue-light-blocking lenses did not experience a change in sleep quality. For comparison, Friedman *et al.*[55] found no support for bright light treatment of older individuals with primary insomnia, but they found positive effects due to sleep hygiene. As they assume, the effect of sleep hygiene was possibly strong enough to overwhelm the effect of bright light. If this assumption may be transferred to the contradictory findings for the blue spectral component, it may be suggested that within our investigation light intensity variation might have overwhelmed the effect of the blue spectral component. Thus, the effect of amount and spectrum of light on sleep quality are not independent so a difference in spectrum may be overwhelmed by a difference in amount.

Pleasure (as an expression of contentment) and arousal (as an expression of alertness or activation) were not significantly associated with daily exposure to light. While the effect of light on mood is a subject of controversy in the literature,[31] some studies found a relationship between the amount of light and alertness.[36–39] However, the effects are relatively small and seem to show up in large samples only. It may be that the effect of light exposure on sleep quality is stronger than the effect of light exposure on pleasure or arousal, but a stronger research design would be needed to reveal such an effect. With regard to the sample size in the current study, statistical power was most probably too small for the effect to show up.

When judging the results reported here, one has to be aware of the explorative character of the study. Even if statistical models suggest causal relationships, the relevant explaining variables were not experimentally controlled, thus, the explanatory power might be reduced to some degree. Further investigations using controlled experiments or quasi-experiments will be needed to consolidate the evidence of the impact of light entering the eye of office workers on their sleep quality. For example, Aan het Rot *et al.* had a stronger temporal connection between the light exposure and the reporting of social behaviour than our daily diaries, which have reports of what one can imagine being daily averages for pleasure and arousal. Furthermore, their subjects were all mildly seasonal and therefore might be expected to be more sensitive. Such effects might have been present in this sample but masked by noise in the data.

Even if such effects were to be found it is important to remember that the extent to which healthy people could benefit from higher light exposures is the subject of debate.[3,56,57] Excessive light intensity may lead to negative effects, like headache, eyestrain and hypomania, which have been observed in connection with light treatment for seasonal affective disorder.[58,59] Furthermore, excessive intensities of the blue spectral component can easily lead to irreparable damage to the eye.[60] Thus, a head-mounted device such as the one we used may be useful for the prevention of occupational accidents or diseases. Measurements at existing work stations can detect values which are too high.

5. Conclusion

With this study, it was possible to gather detailed data for illuminance and blue spectral irradiance during time spent in the office and daily exposure to light. It was demonstrated that both the previously developed device[11] and the methodology developed for the field experiment proved useful for further investigations into non-visual biological effects of light.

The most important result of the current study is that the effects of light exposure on sleep quality were strong enough to show up in everyday life in a comparatively small sample of 23 persons. Sleep quality was positively associated with total luminous exposure, the spectrum parameter vis–nonvis and duration over thresholds of 1000 and 2500 lx.

Acknowledgements

We would like to thank our 23 subjects for their participation in the field experiment. This study was supported by VSR (Verband Schweizerischer Anbieter von Sonnen und Wetterschutz-Systemen) and SUVA (Schweizerische Unfallversicherungsanstalt).

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