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Blue-enriched office light competes with natural light as a zeitgeber

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Objectives Circadian regulation of human physiology and behavior (eg, body temperature or sleep-timing), depends on the “zeitgeber” light that synchronizes them to the 24-hour day. This study investigated the effect of changing light temperature at the workplace from 4000 Kelvin (K) to 8000 K on sleep–wake and activity–rest behavior.

Methods An experimental group (N=27) that experienced the light change was compared with a non-intervention group (N=27) that remained in the 4000 K environment throughout the 5-week study period (14 January to 17 February). Sleep logs and actimetry continuously assessed sleep–wake behavior and activity patterns.

Results Over the study period, the timing of sleep and activity on free days steadily advanced parallel to the seasonal progression of sunrise in the non-intervention group. In contrast, the temporal pattern of sleep and activity in the experimental group remained associated with the constant onset of work.

Conclusion The results suggest that artificial blue-enriched light competes with natural light as a zeitgeber. While subjects working under the warmer light (4000 K) appear to entrain (or synchronize) to natural dawn, the subjects who were exposed to blue-enriched (8000 K) light appear to entrain to office hours. The results confirm that light is the dominant zeitgeber for the human clock and that its efficacy depends on spectral composition. The results also indicate that blue-enriched artificial light is a potent zeitgeber that has to be used with diligence.

Key terms circadian clock; chronotype; field study; light environment; light power spectrum; office worker; sleep–wake cycle.

Circadian clocks regulate our daily physiology, behavior and cognition. In temporal isolation, human circadian clocks generate internal days that are usually longer than 24 hours. Periodic signals of the environment (zeitgebers) synchronize this circadian (about one day) rhythm to the 24-hour rotation of the earth (1). This synchronization is an active process called entrainment. Light is by far the most dominant zeitgeber for circadian clocks in most plants and animals (including humans, 2, 3–5).

In mammals, the clock’s central pacemaker lies in the suprachiasmatic nucleus (SCN). It receives light information via retinal photoreceptors, predominantly via the recently discovered, intrinsically photosensitive retinal ganglion cells and transmitted by melanopsin (6, 7). The action-spectrum for non-visual light responses among humans (pupillary constriction, melatonin suppression) peaks in the blue range between 420–480 nm (8–14).

The effect of light on SCN activity is phase-dependent (15–18) – exposure to bright light around subjective dawn shortens the internal day and lengthens it around subjective dusk (4, 19, 20). The degree to which the clock’s internal cycle length is shortened or lengthened by light depends on its intensity (21) and duration (22) as well as individual clock characteristics, like period (23) and internal phase (1). When the clock is entrained, it establishes a specific phase relationship with the zeitgeber cycle (phase of entrainment, for example, the time difference between the body temperature minimum and dawn).

This phase of entrainment, called chronotype, shows large inter-individual differences (24). The Munich ChronoType Questionnaire (MCTQ) allows for a reliable quantification of chronotype (24–27). It consists of simple questions about peoples’ sleep and activity habits, determined separately for work and free days.

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The mid-point between sleep onset and sleep end [mid-sleep on free days (MSF)] assessed by the MCTQ, correlates significantly with cortisol levels (28), as well as with the Morningness–Eveningness Questionnaire (26, 29). Chronotypes form an almost normal distribution in a given population with a slight skew towards late types.

Although working during similar office hours (external, social time), employees may show noticeable differences in their timing of sleep (internal, biological time), which becomes most obvious when comparing the sleep–wake behavior on workdays and work-free days. The difference between mid-sleep on workdays (MSW) and MSF reflects the degree to which an individual's circadian clock is being constrained by the social clock, and this discrepancy is called social jetlag (30). While late types typically accumulate a sleep-debt on workdays due to early office hours, early types tend to do so on weekends due to social events in the evening and their difficulty in sleeping beyond their normal (circadian) wake-up time (31). We thus correct MSF for accumulated sleep debt (MSF_{sc}) (for details on the computation, see 32).

Urban lifestyle and indoor work deprive people of natural daylight exposure and thereby weaken the strength of the zeitgeber for entrainment (1). Compared to daylight, indoor lighting typically consists of low color temperature [measured in Kelvin (K)] of 3000–4000 K; it appears warmer and less blue. Artificial, blue-enriched light of ≥ 6500 K therefore gives indoor lighting more daylight qualities.

Laboratory studies with humans living in constant conditions demonstrated that even single bright light pulses could shift the circadian phase of both physiological [as melatonin or core body temperature (20, 33, 34)] and behavioral rhythms [eg, the sleep–wake cycle (18)]. Yet not only the light's intensity but also its spectral composition determines its capacity to shift the clock's phase, with blue-enriched light being more effective than long-wavelength light (12, 35). However, two studies (36, 37) reported similar phase-advancing and phase-delaying properties of a 2-hour blue-enriched light pulse (17 000 K) when compared to a 2-hour bright light pulse (4100 K). In turn, monochromatic, short-wavelength light sources are less effective in suppressing nocturnal melatonin than polychromatic light sources, pointing to the importance of a wider light color spectrum and its potential impact on the non-image forming photic responses (38). Besides its direct effect on the circadian clock, short wavelength light has also been used to increase subjective alertness (35, 39, 40).

In field studies, the effect of blue-enriched or bright light has rarely been studied. Bright morning and evening light pulses [single 2-hour pulses of 2500 Lux (lx)] for example increase self-reported mood, alertness, energy, and productivity when applied in an office set-

ting (41). The timing of the bright light pulses turned out to be irrelevant as all participants showed a similar increase in the subjective reports. Blue-enriched light (17 000 K) was studied in two office settings: one reported improved ratings in subjective wellbeing, productivity, and sleepiness ratings, especially during the first 7 (out of 14) weeks of the light change in the group that was continuously exposed to blue-enriched light compared to the control group (42). Viola et al (43) compared the effects of the same 17 000 K lighting and 4000 K white light on self-reported mood, alertness, performance, and fatigue. After a four-week study period, participants exposed to blue-enriched light showed reduced evening fatigue, and improved performance and alertness. The few studies in real-life settings show a clear trend: at least on the subjective level, participants exposed to bright or blue-enriched light tend to feel better and perceive themselves as more alert and less tired. Taken together, the laboratory results, field study evidence, and the fact that blue-enriched light is used as therapeutic tool in treating seasonal affective disorder (44, 45–47) point to blue-enriched light as a potentially powerful agent.

In this study, we explored how changing the color temperature of office light from 4000 K to blue-enriched (8000 K) light affects sleep and activity. If the light change represented an increase in zeitgeber strength, one would expect that the timing of sleep and activity of the employees working under blue-enriched light would be advanced compared to those exposed to the warmer light source, especially since average working hours would expose the employees more in the morning than the evening. Our results, however, did not support these expectations. We found a progressive advance (in parallel with sunrise from mid-January to mid-February) both in locomotor activity and sleep–wake timing on free days in the non-intervention group rather than among those employees who experienced the transition to blue-enriched light. The experimental group showed no changes in either of these variables (sleep–wake behavior or activity), as if the clocks of these employees entrained to the fixed office hours.

Methods

Study design

The study was performed between 14 January and 17 February 2008 in the offices of the headquarters of the OSRAM Company in Munich, Germany. During the first two weeks, office lighting was identical for all participants (4000 K; OSRAM 840 LUMILUX® cool white; for the spectral power distribution, see figure S1

in the supplementary material). Over the weekend of 26–27 January 2008, three office floors were changed to 8000 K lighting (polychromatic blue-enriched 8000 K lamps, OSRAM 880 LUMILUX SKYWHITE®; see figure S2 in the supplementary material), while two office floors continued to be illuminated by the original light source. The illumination levels before and after lamp change were only slightly increased with average values rising by 6% from 715 to 760 lx measured vertically at eye level. For biological effects, vertical levels are supposed to be relevant, while horizontal data is important for good vision.

The average color temperature in the non-intervention group was around 4000 K before and after light change, while the experimental group was exposed to lighting with an average color temperature of about 6500 K after the light change (see figures S5 and S6 and table S3 in the supplementary material). The difference from measured light data at 6500 K to the nominal 8000 K of the light sources emerges due to absorption and transmission influences of furniture and other surrounding elements at the workplace. The strength of the circadian stimulus caused by the workplace lighting was estimated to increase by 80% due to the described changes in lighting. This estimation is based on the increase of the biological action factor ($a_{ms,v}$) from 0.5 with 4000 K lighting to 0.85 at 6500 K and the minor increase of illumination levels by 6%. Details on the biological action factor can be found in the documents of the German Institute for Standardization (48).

The experimental group (exposed to the light change; N=27) and the non-intervention group (no change in lighting; N=27) did not differ in terms of work rank or educational achievements. For legal reasons, participants were informed about the light changes and obviously knew their group affiliation, which prevented a study design with placebo conditions. An additional difficulty for a potential placebo lies in the fact that the participants were all lighting specialists. Although they were informed about the physical changes, participants were not well informed about the major aim of this study, namely the circadian aspects of light and sleep timing.

Participants filled out daily sleep-logs and wore actimetry devices over the entire study period. We used the MCTQ (see below) to assess the individual chronotype of all volunteers at the beginning of the study.

Participants

In total, 66 employees agreed to participate in this study, but we a priori excluded those with home office or part-time contracts, foreseeable regular commitments outside of the office building (more than once a week) and those who had planned business trips. Those who did not com-

plete sleep-logs, took extra holidays for >3 days, or had to travel on short notice were excluded post hoc. Thus, 54 participants (26 men and 26 women, 2 not indicated) between the age of 24–63 years (mean age 40.33, standard deviation 8.9) were analyzed for their sleep-wake behavior based on sleep logs. Of these, 44 participants agreed to wear an actimetry device, 17 of which had to be excluded from further analyses due to missing data that could be explained neither by the watch protocol (see below) nor the sleep log data (ie, napping). This left a total sample of 27 participants who were analyzed for their daily locomotor behavior.

Participants were informed that they could withdraw from the study at any time. The study obtained ethical approval from the Ethics Committee of the Department of Psychology of the Ludwig-Maximilians-University, Munich and was in accordance with the Helsinki Declaration.

Materials

Sleep logs. Sleep-logs assessed the following parameters: bedtime, sleep latency, time-to-wake-up, time-to-get-up (sleep inertia), use of an alarm clock, whether the day in question was a free- or workday and, in the case of the latter, exact times spent at the workplace. Participants were instructed to fill out the sleep log every morning after waking up. The main variables used to assess daily sleep timing were MSF and MSW.

Actimetry. To record locomotor activity, 27 subjects continuously wore a waterproof device around their preferred wrist (Daqtometer by Daqtix GmbH, Oetzen, Germany) and were instructed to keep a log about the times when they did not wear the device. Activity data was coded for free days or workdays on the basis of sleep log entries, so that individual differences in work presence could be accounted for (>3 days off work resulted in exclusion from the study). Previous findings indicate that locomotor activity is more sensitive than sleep-logs, for example when investigating behavioral responses to environmental changes like transitions in and out of daylight savings time (49). Activity data were consolidated in 10-minute bins and daily values of centre of gravity (ψ_{act}) on free days were calculated individually for all participants (to insure comparability workdays on weekends as well as free days during the workweek were excluded from analyses). We determined ψ_{act} with the ChronOSX program (50) by fitting a one harmonic cosine for each weekend of the study period.

Munich ChronoType Questionnaire (MCTQ). The MCTQ (25) provides a robust and reproducible measure for assessing chronotype via self-reported sleep habits, separately for standard free and workdays. Chronotype

is computed by correcting the mid-point between sleep onset and sleep offset corrected for sleep deficit accumulated during the workweek [MSF_{sc} (for details see 24, 30)]. MSF_{sc} will be referred to as chronotype.

Results

The participants in the two groups (experimental and non-intervention) were matched for age and chronotype (table 1). Weekly averages of the daily sleep-log-based MSW and MSF_{sc} were used to compare the two groups. The changes across the entire study period (5 weeks) in these two parameters as well as in locomotor activity (center of gravity or ψ_{act}) were assessed by a set of repeated-measures analyses of variance (ANOVA), separately for the non-intervention and the experimental group. No between-subject repeated measures ANOVA could be conducted, as initial computations revealed a highly significant Box's test ($P < 0.01$), suggesting inequality between the groups' covariance matrices. The sample sizes underlying the computations could differ from the above-reported sample due to missing values. Hence, the basis of calculations is indicated for each parameter separately. In case of violation of sphericity, the Greenhouse-Geisser correction values are reported.

Mid-sleep on work and free days

While the timing of MSW did not change in either of the groups across the 5-week study period, MSF_{sc} became significantly earlier, but only in the non-intervention group [$F(4,96) = 3.228$, $P = 0.016$, see table 2 and figure 1].

Activity

The dynamics of sleep-wake behavior within each group emerged in the sleep-wake behavior on free days. These results are coherent with the activity data: (center of gravity or ψ_{act} on workdays was the same in both groups and did not change over the study period ($P > 0.5$, respectively).

Chronotype was added to the ANOVA to control its influences and examine whether chronotype-specific

effects appeared. Descriptives for both groups are shown in table 3.

As in the case of the sleep-wake timing, the phase of activity (center of gravity or ψ_{act}) on free days showed significant changes over the 5-week period for the participants in the non-intervention condition, but not for those experiencing the change in their office lighting [repeated measures ANOVA with the factor "week", 1–5, and the covariate chronotype: significant effect of "week" on ψ_{act} in the non-intervention condition, $F(3.548, 39.028) = 6.339$, $P = 0.001$; Figure 2].

ψ_{act} remained stable in the experimental group, while the progressive advance of locomotor activity in the non-intervention group over the 5-week study period was influenced by chronotype: earlier chronotypes showed a more pronounced advance than late ones [significant interaction between week and chronotype, $F(3.548, 39.028) = 3.63$, $P = 0.016$; see supplementary material, figures S3 and S4]. Yet, as previously reported, the finding that ψ_{act} is significantly influenced by chronotype was reproduced in the experimental group; in general, earlier chronotypes also exhibited earlier ψ_{act} than late chronotypes [repeated measures ANOVA; main effect of MSF_{sc} in the experimental group: $F(1,12) = 26.19$, $P = 0.000$].

Discussion

Light – especially in the short wavelengths – is the most potent environmental signal (zeitgeber) synchronizing the circadian body clock to the 24-hour day. Any intervention in the light environment may therefore affect an individual's timing of bodily function, ranging from cellular biochemical reactions to complex behaviors like sleep and wakefulness. We examined the effects of blue-enriched office lighting in the OSRAM headquarters to investigate whether the lighting affects the timing of sleep-wake behavior and activity. The new lighting system was installed two months apart on different floors of the building, which allowed for a comparison between groups that were either exposed to the traditional or the blue-enriched light at the same time of year. Sleep-wake (rest-activity) behavior of the participants was monitored by both daily sleep-logs and wrist

Table 1. Descriptive participant data: age and chronotype of the groups did not differ between conditions ($P > 0.2$). [SD=standard deviation; MSF_{sc} =mid-sleep on free days corrected for accumulated sleep debt.]

	Sleep logs				Locomotor activity			
	Experimental group (N=27)		No intervention group (N=27)		Experimental group (N=14)		No intervention group (N=13)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age in years	39.92	8.72	40.37	9.18	38.21	8.45	41.08	7.14
MSF_{sc}	3.81	0.85	3.59	0.93	3.65	0.97	3.58	0.93

actimetry. Over the 5-week study period, sleep timing on free days advanced significantly in the non-intervention group but remained locked to the same local time in the experimental group (experiencing the light change). The timing of activity matched the observed changes in sleep-wake timing: on free days, the phase of locomotor activity (judged by the highly significant cosine fit of the centre of gravity) advanced significantly only in the non-intervention but not the experimental group.

Laboratory studies have shown that bright and/or blue-enriched light is more potent in phase-shifting the circadian phase than other light conditions (12–14, 18, 20, 33, 34). The response characteristic of all circadian clocks shows that single-light exposures advance the phase when presented in the subjective morning and delay the phase when presented in the subjective evening. In addition, stronger zeitgebers generally advance the phase of entrainment when presented as full photoperiods (31). It was therefore difficult to predict how the light intervention monitored here would affect phase, in addition to the fact that measurements took place in a real-life situation. Since participants were exposed to the blue-enriched light throughout the day, the advancing and delaying effects could cancel each other out, while a general strengthening of the zeitgeber

Table 2. Mid-sleep during free time (MSF) per week, separately for each group. [SD=standard deviation].

MSF-times	Experimental group (N=34)		Non-intervention group (N=25)	
	MSF	SD	MSF	SD
Week 1	4.34	1.18	4.21	1.05
Week 2	4.39	1.33	3.98	1.07
Week 3	4.29	1.08	4.17	1.14
Week 4	4.36	1.25	3.76	0.86
Week 5	4.24	0.78	3.73	0.99

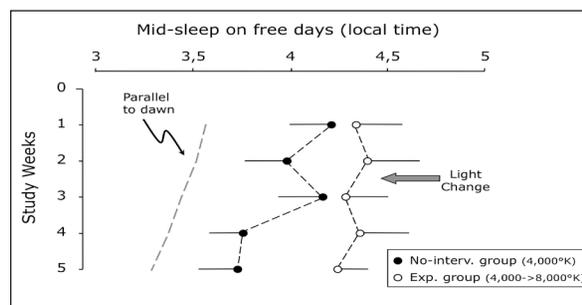


Figure 1. Average mid-sleep on free days (MSF–standard error of the mean) as a function of study-week, separately for the non-intervention group (black dots) and the experimental group (open circles). The light change occurred between week 2 and 3. While the sleep-wake behaviour in the non-intervention group advanced, it remained constant in the experimental group. Unlike in the weeks 1–3, MSF during weeks 4 and 5 is significantly earlier in the non-intervention group compared to the experimental one.

(by blue-enriched light) could lead to an earlier phase of entrainment. Our results show that the blue-enrichment led to a stabilization of the phase of entrainment, while it progressively advanced in the group remaining in the standard light environment. This advance is consistent with earlier findings showing that the timing of human sleep-wake behavior is associated with sun-time rather than with social, local time (30, 51). The timing of sleep-wake behavior in the German population progressively advances from East to West, in parallel with the longitudinal progression of dawn. In addition, it is strongly influenced by season, specifically with the changing dawn times in spring and autumn (49). During the course of our study, sunrise advanced by 42 minutes from 08:00 (beginning of week 1) to 07:18 (end of week 5) matching the observed advancement in the non-intervention group (≈ 1 hour). For an overview of the sunrise times, see supplementary material, table S1.

The remarkable stability of phase over the study period in the experimental group (in contrast to the seasonal adjustment in the non-intervention group) suggests that daily exposure to blue-enriched light during office hours may compete with the rather sparse exposure to outside light in industrial societies and thereby interferes with the seasonal adjustment of the circadian clock, even

Table 3. Average center of gravity (ψ_{act}) per study-week separately and as a function of group affiliation. [SEM=standard error of the mean].

Centre of gravity in locomotor activity	Experimental group (N=14)		No-intervention group (N=13)	
	Mean	SEM	Mean	SEM
Week 1	15.82	0.57	15.01	0.42
Week 2	15.14	0.40	14.29	0.38
Week 3	14.67	0.50	14.30	0.40
Week 4	15.13	0.37	13.90	0.42
Week 5	14.62	0.51	13.76	0.43

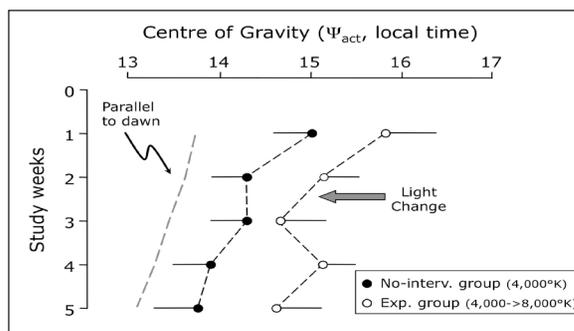


Figure 2. Changes in phase of locomotor activity (ψ_{act} , assessed by the centre of gravity method; see Methods section). The circles represent weekly averages (\pm standard error of the mean). As in the case of sleep-wake timing (figure 1), activity timing is only significantly advanced over course of the five-week study in the non-intervention condition.

on the level of different chronotypes. While our results show that the seasonal advance (in the non-intervention group) is more pronounced in early compared to late chronotypes (which could be explained by the fact that early chronotypes are more exposed to morning light), the blue-enriched light environment (in the experimental group) appears to have stabilized all participants in their respective, chronotype-specific phase. Whether synchronization of the circadian clock to office hours has advantages over its seasonal adjustments to dawn (or dusk) is still unclear. One could argue that the former would reduce the amount of social jetlag (30). In regions with strong seasonal changes however, an endogenous annual timing system can only anticipate and adjust to these changes (eg, adapting the immune system) if it has sufficient seasonal information. We still know little about the interactions between light, health and seasonal adaptation. Yet, sleep and its timing strongly influence psychological and physical health (52) and should therefore be a key variable in future research, which definitely should consider light exposure (intensity and spectral composition) as highlighted by this field study.

Our results additionally point to the importance of monitoring circadian phase with the help of actimetry; the chronotype-specific differences in the seasonal adaptation are only detectable in the activity records and not in the timing recorded by sleep-logs. This distinction has already been reported in an earlier study investigating the chronotype-specific adjustment to daylight savings time (49). The reason for actimetry being a more sensitive measure for phase of entrainment than sleep timing could lie in the fact that our sleep habits are much more influenced by social timing than our daily activity profiles. We are usually quite aware of when we go to bed and wake up in reference to social time, while we rarely consciously relate our locomotor activity profiles to social schedules – especially on free days (without obligations).

The findings presented here are based on a small sample size (especially concerning actimetry); extrapolations to the general population therefore need additional evidence from large-scale field studies. Despite these limitations, our results are consistent with earlier findings from both laboratory (12, 35) and field studies (42, 43). They suggest that blue-enriched light is a powerful signal for the circadian clock even in non-therapeutic, everyday settings. The indication that continuous, blue-enriched light exposure possibly competes with the natural zeitgeber sunlight (31, 51) advises a careful dynamic control. If, for example, lighting systems were coupled to the seasonality of the natural light environment by adding (and subtracting) the blue-enriched portion with a constant relationship to dawn and dusk, one could strengthen the weak zeitgebers in urban settings with the help of spectral changes rather than with increased light intensities. The necessity for strengthen-

ing the zeitgeber function of our light environment in modern society is huge, since insufficient entrainment of the circadian clock has been associated with many different health problems ranging from obesity (53) to psychiatric disorders (54).

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Appendix - Supplementary material

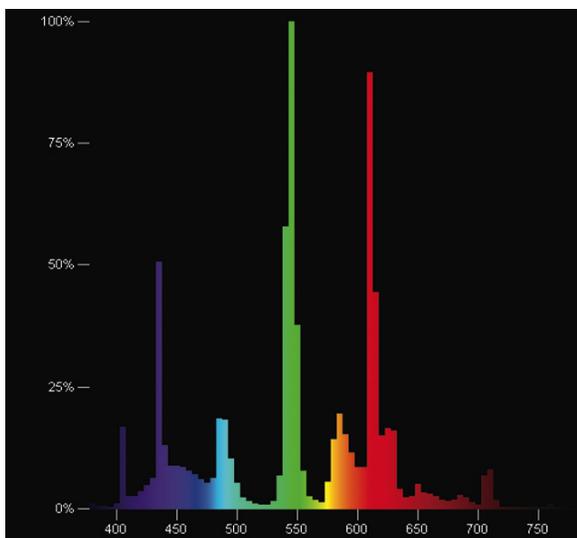


Figure S1. Relative spectral power distribution of 840 LUMILUX® cool white by OSRAM.

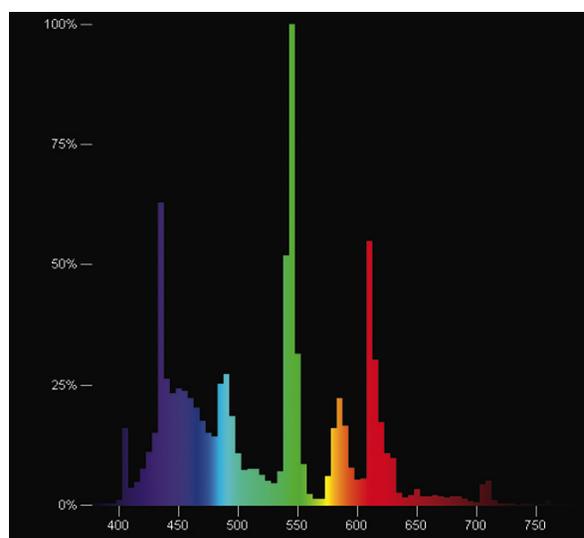


Figure S2. Relative spectral power distribution of 880 LUMILUX SKYWHITE® by OSRAM.

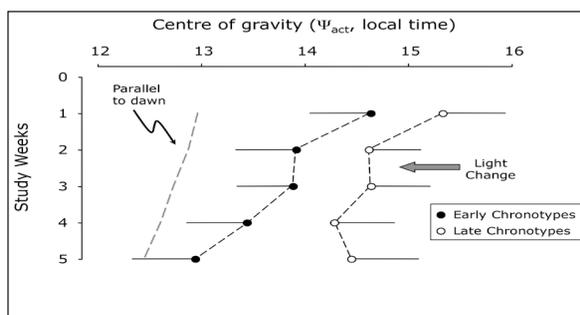


Figure S3. The progression of the centre of locomotor activity (Ψ_{actr}) over the study period in the non-intervention group as a function of chronotype [early: mid-sleep on free days corrected for accumulated sleep debt ($MSF_{sc} < 4.5$, $N=6$) and late: $MSF_{sc} > 4.5$, $N=7$].

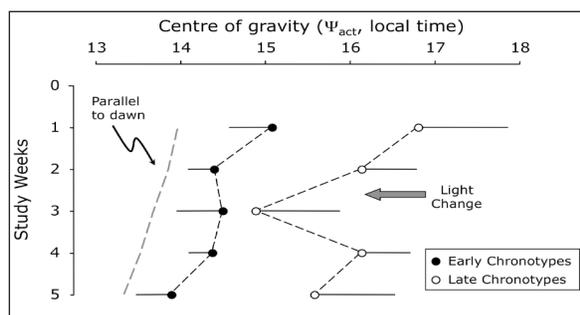


Figure S4. The change in (Ψ_{actr}) in the experimental condition for early mid-sleep on free days corrected for accumulated sleep debt ($MSF_{sc} < 4.5$, $N=8$) and late ($MSF_{sc} > 4.5$, $N=6$) chronotypes.

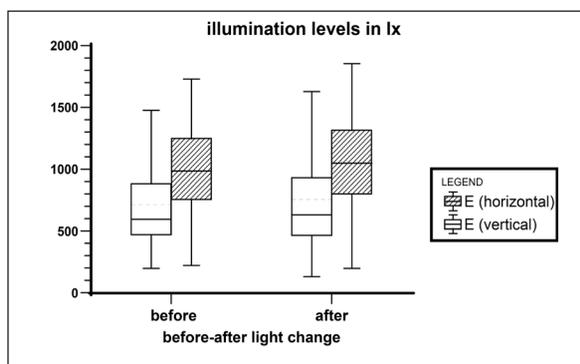


Figure S5. Boxplot of horizontal and vertical illumination levels measured before and after the light change at the subjects' workplaces. Horizontal data was measured at desk level, while vertical data was measured at eye level in sitting position (120 cm height) oriented in the subjects' main viewing direction during work. The wide spread of the data is based on the fact that measurements have been taken at the workplaces as they were during the real life setting in the field during the study. The dashed line is the statistical average, while the boxes and lines with bars correspond to the quartiles of the statistical distribution.

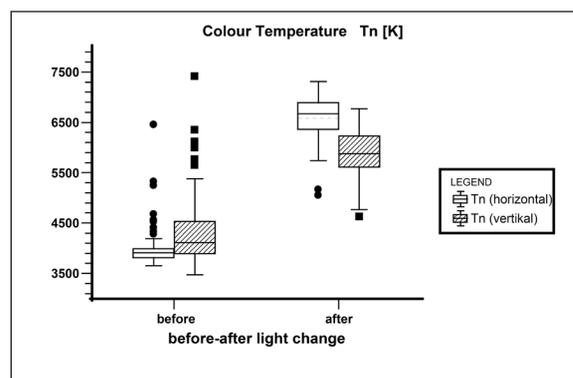


Figure S6. Boxplot of the color temperature data measured at the working places. Like described for figure S5 data has been measured horizontally and vertically. The statistical outliers in the measurement "before" shown as points are based on a stronger daylight influence at some of the workplaces. Natural daylight is shifting color temperature and illumination levels to higher values.

Table S1. This table shows time of sunrise during the study period from 14 January to 17 February 2008 for Munich, Germany, 11°34', 48°08' (from Sunrise & Sunset Calculator, <http://www.timeanddate.com/worldclock/sunrise.html>).

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Week 1 (14–20 Jan)	08:00	08:00	07:59	07:58	07:57	07:57	07:56
Week 2 (21–27 Jan)	07:55	07:54	07:53	07:52	07:51	07:50	07:49
Week 3 (28 Jan–3 Feb)	07:48	07:47	07:45	07:44	07:43	07:41	07:40
Week 4 (4–10 Feb)	07:39	07:37	07:36	07:34	07:33	07:31	07:30
Week 5 (11–17 Feb)	07:28	07:27	07:25	07:23	07:22	07:20	07:18

Table S2. Descriptive data of the light measurements. At an average color temperature of 4000 Kelvin (K) the biological action factor (a_{msv}) for light from fluorescent lamps according to DIN V 5031-100 is 0.5. At 6580 K, a_{msv} is increased to 0.85. As the vertical illumination levels are increased by 6% on average, the total increase of the circadian stimulus can be estimated to 80%. [SD=standard deviation.]

	Color temperature (Tn)				Illumination level (E)			
	Horizontal average (in K)		Vertical average (in K)		Horizontal average (in lx)		Vertical average (in lx)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Before	4308	632	3992	412	987	338	715	358
After	5884	477	6580	413	1066	350	757	416