On the Impact of Integration of Non-Image Forming (NIF) Effect of Light on Electrical Lighting Control in Non-Residential Buildings

Ali Motamed[1,*], Marta Benedetti[2], Jean-Louis Scartezzini[1]

[1]Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
[2]Faculty of Science and Technology, Libera Università di Bolzano, 39100 Bozen-Bolzano, Italy

[*]*Corresponding email: ali.motamed@epfl.ch*

ABSTRACT

Lighting has an impact on the visual as well as cognitive performance of people in non-residential buildings. Light is the most powerful time cue for resetting the circadian pacemaker and ensuring correct synchronization of the internal clock with the environment: these effects are called "Non-Image Forming" (NIF) functions. The expected neuroendocrine and neurobehavioral responses of subjects to light exposure can be summarized in four principal categories: alertness, sleep quality, mood and performance. The properties of light such as intensity, timing, pattern and light history influences neurobehavioral responses. These significant effects of light are currently not considered in building automation mainly due to the unknown and complicated nature of NIF effects as well as lack of proper technology. This leads likely to a considerable loss of productive time and momentum for the office occupants.

This paper explores the existing knowledge of NIF effects of light on human beings and consequently proposes a novel dynamic lighting pattern, which is used as a set point for an integrated daylighting and electric lighting system. In other words, the existing scientific knowledge of NIF effect of light is introduced into the lighting engineering and automation domain. This user-centric approach allows for a system level study of the suggested variable lighting set points. A novel High Dynamic Range (HDR) vision sensor installed next to the office user allows for an 'on-the-fly' evaluation of the light flux received by the human eyes during daytime: it also offers a personalized, refined control of an integrated electric lighting and sun shading system.

KEYWORDS

Dynamic Lighting Pattern, NIF effect of light, HDR Vision Sensor, Circadian Rhythm, Daylighting and Electric Lighting Control

INTRODUCTION

It is known that for a good entrainment of the biological clock, it is important for humans to their eyes receive a sufficient light flux during daytime. In case of insufficient lighting levels (e.g. low pupilar illuminance), drawbacks can occur such as reduced concentration, well-being or performance, and it is more likely to undergo tiredness and fatigue (Aries 2005). Several light features, such as illuminance, timing, spectrum, duration/pattern and history are known to play important roles.

Currently, no specific criterion exists for the required vertical illuminance: recommendations for office lighting are usually based on visual criteria and use the horizontal workplane illuminance as the main lighting design parameter (those standards are based on traditional offices where paperwork was the most common activity). For instance, the standard EN

12464-1 (Light and lighting; Lighting of work places) recommends a 300 – 500 lx horizontal illuminance for normal office work (Begemann, van den Beld, and Tenner 1997). Regarding non-visual effects, the same standard declares that « light can entrain circadian rhythms and influence physiology and that variability of light is important for health and well-being ». The standard EN 15193 (Energy performance of buildings Energy requirements for lighting) introduces the concept of "Algorithmic lighting", i.e. lighting systems suitable for non-visual biological effects of light. Recommendations in this respect involve lighting conditions varying over time (illuminance and color temperature, spatial distribution). In order to optimize the biological effects of light, "higher lighting levels than required for pure visual effects are necessary for part of the day (especially in the morning and early afternoon)". All in all, current standard regulations are rather general and qualitative; they do not include any specific indication about dynamic office lighting for non-visual effects of light.

The objective of this study is to investigate the possibility of establishing a novel lighting pattern to enhance productivity and well-being of an office worker according to his neurobiological needs. Among all the important factors, the pupilar (vertical) illuminance as well its daily pattern, were first considered in this paper. In a next step, the suggested illuminance variable set point was implemented in an experimental building by the way of a building automation system based on a novel High Dynamic Range (HDR) vision sensor.

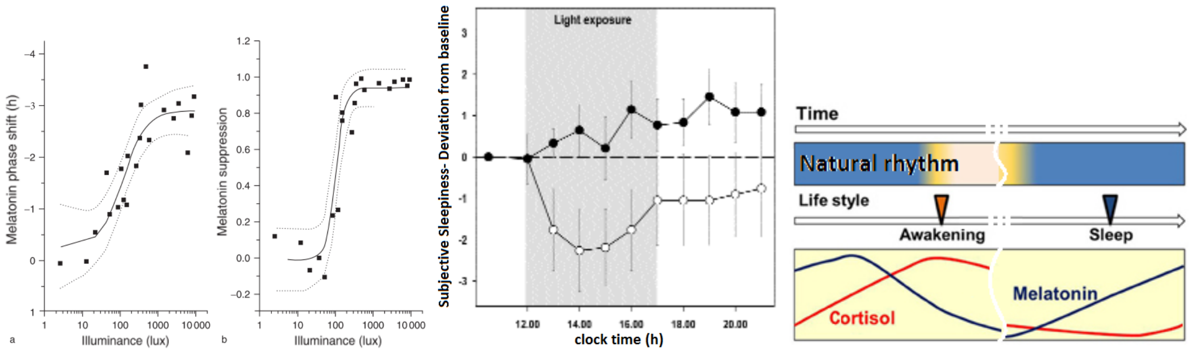
METHODS

Two important hormones (e.g. melatonin and cortisol), whose concentrations are believed to have a considerable impact on the performance, alertness and mood of human beings, have been identified. Using the results of human studies conducted in different time of the day or the night with different light intensities would allow establishing an optimal quantitative dynamic lighting pattern. Moreover, the phase-response curve, a chronological diagram depicting the circadian phase shift as a result of exposing the subject to light, could also be taken into consideration to optimize the lighting pattern.

Night-time light-induced melatonin suppression

It is well known that exposure to light for healthy humans during night causes alerting effects (non-visual responses), which are strongly correlated with the degree of "melatonin suppression". Melatonin is released during the biological night and provides the body's internal biological signal of darkness. Exposure to light both resets the circadian rhythm of melatonin and acutely inhibits melatonin synthesis. In other words, if a person is exposed to light when melatonin concentration in his/her body is high (during the night), melatonin concentration decreases, its suppression being accompanied by an increase of alertness.

Light-induced melatonin suppression depends on illuminance at the eye level (e.g. pupilar illuminance). Several studies have been carried out in order to establish the relationship between pupilar illuminance and non-visual/circadian responses (such as melatonin suppression and phase shift, objective and subjective assessments of alertness, etc.). In particular, (Zeitzer 2000)(Cajochen et al. 2000) and (McIntyre and Norman 1989) demonstrated that there is a non-linear relationship between pupilar illuminance and the relative fraction of melatonin suppression (Figure 1a). These studies showed that the alerting response elicited by light exposure is strongly associated with melatonin suppression.



a) b) c)

Figure 1: a) Studies by (Cajochen et al. 2000) and (Zeitzer 2000); illuminance-response curves for circadian phase resetting and melatonin suppression, b) Study by (Phipps-Nelson et al. 2003a) for, among others, subjective sleepiness, bright light leads to less sleepiness, c) Melatonin and cortisol rhythms in humans.

It is important to note that the mentioned studies are based on exposing subjects to light during nighttime (i.e. when melatonin concentration is high).

(Amundadottir et al. 2013) suggested as well a linear-nonlinear-linear mathematical model that incorporates variables of light to predict the non-visual effects of light on humans based on some of the mentioned publications. This model is supposed to provide a framework that can inform designers about how lighting improves human health.

Effects of daytime light exposure on melatonin concentration

Since the non-visual response in terms of alertness elicited by light exposure at night is often associated with melatonin suppression, further studies were carried out in order to examine the effects of light exposure during daytime, when the melatonin level is normally low.

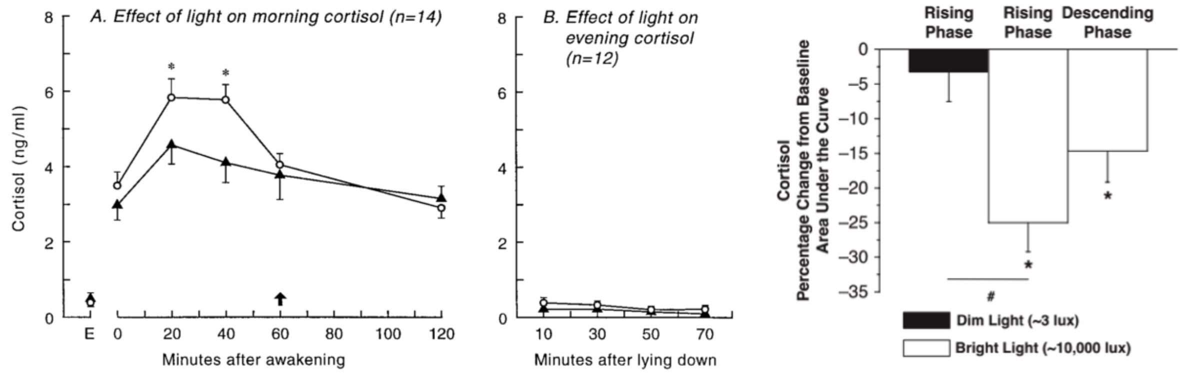
(Phipps-Nelson et al. 2003b) showed that daytime bright light exposure (~1000 lux eye illuminance from 12h00 to 17h00), compared to dim light, reduces sleepiness and improves performance (Figure 1b), and these effects are independent on melatonin suppression. In fact, melatonin concentration levels (not shown here) are very low during daytime and are not subject to variations due to light exposure. Moreover, a similar study by (Rüger and Gordijn 2005) proved that a bright light stimulus (~5000 lux at eye level) from 12h00 to 16h00 reduces subjective sleepiness but does not cause any change in melatonin concentration; instead, the same stimulus given in the night time contributes to suppress melatonin. The presented findings suggest that the alerting effects of light exposure during daytime are not only associated with variations in melatonin concentration.

The influence of light on cortisol

Since the impact of daytime light exposure on the non-visual system is not thoroughly consistent with melatonin suppression, we decided to examine the influence of light on secretion of cortisol, the "stress hormone" whose pattern is nearly opposite to melatonin, as shown in Figure 1c). Cortisol secretion has a peak around wake-up time and decreases during the day, reaching the lowest level around the usual bedtime.

Optimal cortisol concentrations are required for health reasons. In fact this hormone, amongst other things, increases blood sugar to improve the human metabolism and stregnthen the immune system. However, when cortisol levels are too high over a too-long period, the body becomes exhausted and inefficient (van Bommel 2006).

Although cortisol levels are always higher around wake-up time, morning light exposure can have an effect on cortisol concentration in the human body. Nevertheless, studies in this regard provided unfortunately with different conclusions. (Scheer and Buijs 1999) showed that one hour exposure to 800 lux of pupilar illuminance in the morning after wake-up time can further increase cortisol levels, whereas exposure to the same light flux in the evening does not have any effect on cortisol (Figure 2a). This suggests the existence of a phase-dependent effect of light on cortisol secretion, e.g. light has an observable effect in the morning when cortisol level is high.



a) b)

Figure 2: a) (Scheer and Buijs 1999). Effect of exposure to 800 lux for 1 hour in the morning (left) and evening (right) on salivary cortisol concentration (mean ±SEM), b) Percentage change from baseline for area under the curve cortisol levels during the light exposure session for the rising and descending phases of the cortisol rhythm. * denote significant decreases in cortisol levels between baseline (Jung et al. 2010).

Differently, a more recent study by (Jung et al. 2010) showed that a prolonged bright light exposure on the rising and on the descending fraction of the cortisol curve (i.e., when cortisol levels are high) *reduced* cortisol levels compared to dim light exposure (Figure 2b). The results were obtained by exposing subjects to ~10000 lux for 6.7 hours in the night time before wake-up (rising fraction of the curve) and immediately after wake-up time (descending fraction).

A recommended illuminance value based on the existing norms for workplane lighting sufficiency as well as for avoiding discomfort glare is also needed. Regarding the lighting sufficiency, the standard EN 12464-1 recommends a horizontal illuminance of 500 lux on the workplane. The Handbook of Industrial Engineering (Salvendy 2001) declares that for offices illuminated by overhead luminaires (as in our case) the ratio between vertical and horizontal illuminance must be in the range of 0.3 to 0.5. Thus a minimum vertical illuminance equal to 250 lux (500*0.5) can be assumed. In addition to illuminance, discomfort glare is also taken into account by defining boundaries for simplified Daylight Glare Probability (DGPs) (Wienold and Christoffersen 2006). This index indicates the probability for the user to experience glare sensations; in order to avoid perceptible discomfort glare, the DGP must be lower than 35%.

In order to verify the impact of the proposed dynamic lighting strategy, setpoint variable illuminance values were used for an integrated lighting control system implemented in our experimental building. This system comprises a novel HDR vision sensor (Motamed, Deschamps, and Scartezzini 2015) connected to a movable sun shading and dimmable LED electric lighting system. This vision sensor, upon installation next to the eye of a seated office worker, provides with the vertical eye illuminance (lux) as well as a discomfort glare index (i.e. DGPs). These variables, alongside time of the day, are used by a Fuzzy Logic based controller to drive the sun shading and electric lighting system in an optimal way. The performance of the controller, with dynamic lighting setpoint has been evaluated in comparison with a 'best-practice' controller of the market.

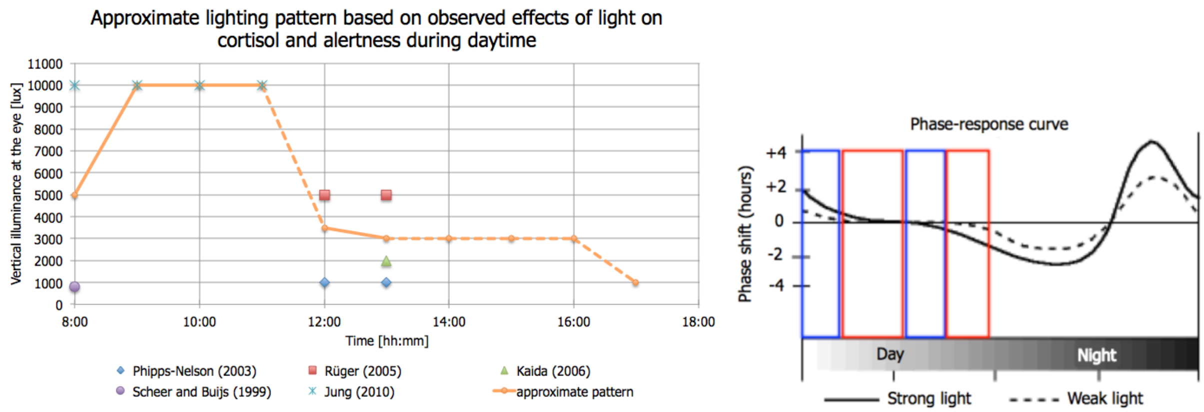
RESULTS

Results of the studies concerning the impact of light exposure on the non-visual system during daytime were considered for the choice of a dynamic lighting pattern. Figure 3a illustrates the illuminance levels reported in the previous studies, associated with their respective timing of light exposure and the approximate effect in terms of cortisol concentration an/or alertness variation.

Based on the considerations by (Aries 2005) and (de Kort and Smolders 2010) as well as on the results of the reviewed studies (Figure 3a), a dynamic lighting pattern was created (Figure 3b). The latter one reflects the presented experimental findings: when more than one illuminance value is suggested at the same time by different authors, an average value is applied.

Practical considerations in dynamic lighting pattern

In practice, reaching illuminance levels, such as those shown in Figure 3, would probably be unfeasible, especially in the early morning, due to several reasons (e.g. insufficient daylight or limited artificial lighting power). Moreover, at such levels, users are likely to experience visual discomfort: the lighting pattern was accordingly adapted for practical reasons. What is certain is that a higher illuminance level needs to be provided in the early morning and for a short time after lunch break, when the user is more likely to undergo daytime sleepiness according to the temporal profiles of human sleep propensity (Lavie and Zvuluni 1992).



a) b)

Figure 3: a) Approximate dynamic lighting pattern based on experimental data of the reviewed studies, b) Phase-response curve (phase shift plotted against time). The working day is divided in 4 time spans. Blue boxes indicate the time spans of the day in which circadian criteria are applied (higher lighting levels) and red box correspond to visual criteria (lower lighting levels). Adapted from ("Science Blogs, Http://scienceblogs.com" n.d.)

With the double objective of optimizing the non-visual effects of light on users and limiting the energy consumption, the Phase-Response Curve (PRC) for the timing of light exposure (Figure 3b) was also taken into consideration. According to this curve and the literature review, the working day was divided in four time spans. Figure 3b (blue and red boxes) indicates the approximate timing in which *circadian criteria* and *visual criteria*, respectively, are applied in the decision process regarding the targeted lighting pattern. Circadian criteria involve high illuminance levels and are applied in those time spans of the day during which higher light fluxes are needed (i.e., in the early morning and in the early afternoon). As shown in Figure 3b, exposure to brighter light in the early morning advances the circadian phase, in other words it contributes to increase alertness. The phase delay in the early afternoon when circadian criteria are also applied is supposed not to have a significant impact on the circadian clock; it can actually compensate the phase advance of the morning.

For the rest of the day (late morning and late afternoon) lower illuminance levels can be chosen based on visual criteria, following the standard regulations. In the late morning (starting approximately a couple of hours after the beginning of day), phase shift is negligible, and so are supposed to be non-visual effects. For this reason, it would not make sense to have high illuminance in that time span. A lower illuminance level would actually help relaxation around lunchtime, as well as in the late afternoon and evening hours. Visual criteria are thus applied in the last time span, also to avoid inducing an important phase delay (with consequent negative effects on the circadian clock) that would be caused by bright light exposure at the end of the day.
Finally and of equally importance, using a dynamic lighting pattern that involves lower illuminance levels in some time spans of the day would also allow energy savings with respect to steady-state electric lighting conditions.

Figure 4 represents the dynamic lighting pattern adapted for practical reasons and based on both visual and non-visual (circadian) criteria in function of the time of day. A tolerance is set on the illuminance levels as indicated by error bars derived from the following considerations: The maximum DGP value is set at 35% for visual criteria sections and 40% for circadian criteria parts of the day, thus reflecting the different priorities of the two types of criteria: visual comfort and glare protection, and NIF effects and circadian entrainment, respectively. The illuminance ranges corresponding to these limits for the DGP are represented in Figure 4 through error bars. For visual criteria, the largest tolerated value of vertical illuminance is equal to 2670 lux.

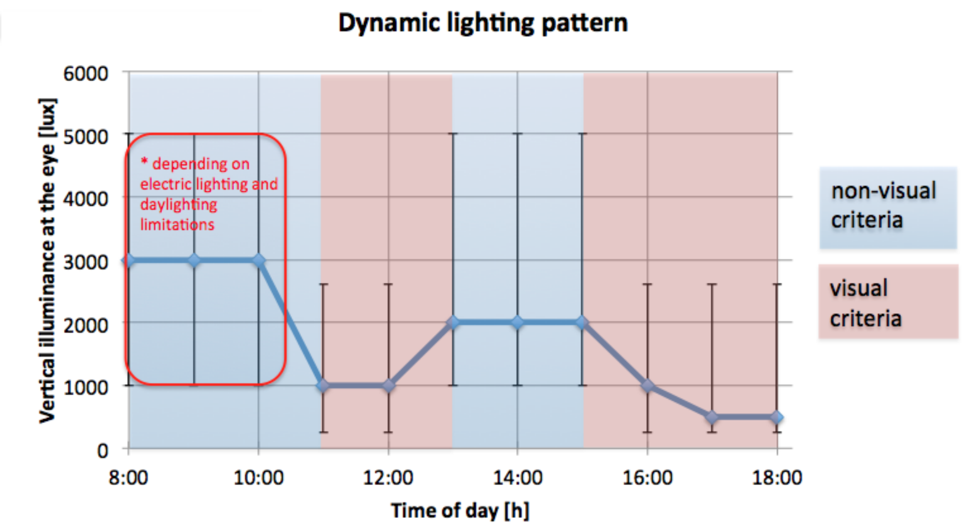


Figure 4: Final dynamic lighting pattern adapted for practical reasons for a whole day. 4 zones are defined during which visual or circadian lighting criterion are applied.

DISCUSSIONS

For the visual part of the suggested lighting pattern, the user's visual comfort and light sufficiency for proper paper-based task according to existing norms are prioritized. On the other hand for circadian criteria, the limits are based on the considerations mentioned in Figure 3a, issued from a literature review. However, these boundaries are most probably not met due to the electric lighting limitations and daylight availability: in some cases, especially in the morning and for overcast skies, those limitations would not allow to reach such levels. Knowing the importance of bright light in the early morning and early afternoon, an attempt has been made to obtain the largest illuminance (mostly through daylight) in those time spans, always complying with the visual requirements.

This dynamic lighting pattern is integrated in the building control system and its performance in terms of energy savings and users visual performance being compared with those of a reference controller. Presenting the results of this next study is unfortunately beyond the scope of this article and will be the subject of future publications.

CONCLUSION

Health and visual performance of building users are considerably vulnerable to the indoor lighting conditions. In spite of the proven importance of the lighting environment, scientific findings regarding Non-Image Forming (NIF) effects of light were only recently brought to lighting designers and practitioner: they may contribute to improve lighting design and control. In this paper, a dynamic illuminance pattern for daylighting and electric lighting systems in an office environment is suggested based on the state-of-the-art in of photobiology and neuroscience. This lighting pattern is believed to have positive impact on the health and well-being of office occupants and would lead to higher visual performance. It is shown that a day can be divided in four zones during which different visual and circadian criterions are taken into account. Moreover, the dynamic lighting pattern is expanded further in order to include practical aspects and limitation of the lighting system. Further research will be undertaken in a short future in order to compare the performance of an advanced controller based on this dynamic pattern with those of a reference controller issued from the 'best-practice' in building control technology.

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