Review on visual comfort in office buildings and influence of daylight in productivity

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SUMMARY

The use of artificial light is debated due to the contribution to energy reduction in buildings consumption, comfort and productivity. The importance of daylight in buildings is therefore nowadays of particular interest, in terms of visual comfort and well-being. People live most of their time indoor, so it is necessary to create a comfortable environment to prevent disease, lack of motivation and sometimes even sickness. Many studies have demonstrated that if daylight is the primary source of lighting, there is a great improvement in productivity, performance and well-being in general.

This article would like to be a sort of review on the factors which contribute to enhance visual comfort, especially in office buildings, where vision occurs to be the most important of all the five senses.

KEYWORDS

Daylight, Visual comfort, Productivity

INTRODUCTION

Humans, from the origins, have always lived in daylight conditions, since the Sun was the only known lighting source. For that reason, some researchers have stated that all physiological processes can develop in the right way only under daylight (Wurtman, 1975).

For fifty years, people have been affected by the so-called three screens syndrome: cinema, television and computer. In all these three situations, people are forced to stay in indoor environments and this new condition leads to a considerable adaptation. The research is therefore addressed to recreate the original human environment, since light impacts human health and well-being, by controlling the body's circadian system, by affecting mood and perception and by facilitating the direct absorption for critical chemical reactions within the body.

The aim of this work is to demonstrate, by means of a literature study about the state of knowledge and test experiments, that there is a strict link between lighting quality and people productivity and well-being. The goal is to awaken public opinion to the importance to reach a high lighting quality, especially in office buildings, to improve performance and satisfaction at work. This review could also provide an input to revise current lighting standards and to guide future research.

Daylight

Daylight is the preferred lighting source: it is energy-efficient, flicker-free, dynamic and it has a spectrum that ensures excellent colour rendering. However, a good combination of daylight and artificial light has to be reached, since daylight cannot be the only source, because of its continuous variability, according to weather, the time of day and year and because its intensity decreases as the distance from windows increases. Natural light has positive effects on human beings and these effects can be distinguished in two types: direct and indirect. The direct effects are caused by chemical change in tissues due to the energy of the absorbed light, while the indirect ones are the regulation of the basic biological functions and the production of hormones, connected to light exposure. The regulation of circadian rhythms, seasonal cycles and neuroendocrine responses in many species, including humans, is due to light stimuli (Klein et al., 1991; Wehr, 1991). Circadian rhythms are changing patterns that run over a period of approximately 24 hours, trying to establish an internal replication of external night and day: these rhythms are associated with body temperature, alertness and the secretion of hormones, such as melatonin and cortisol (Fig. 1).

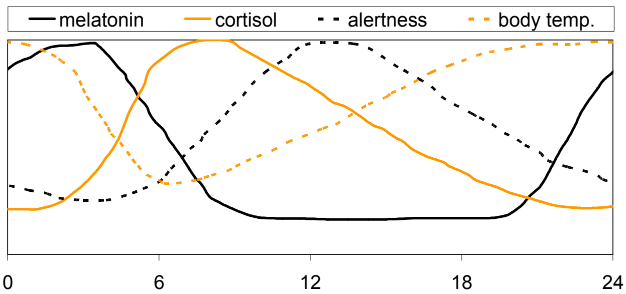

Figure 1. Typical daily rhythms.

Melatonin is known as the “sleep hormone”: it drops in the morning, reducing sleepiness and it rises when it becomes dark. Cortisol is the “stress hormone”: its level increases in the morning, falling to a minimum at midnight.

Shift work may cause a shift of the biological clock that may result in extreme sleepiness, in lack of concentration, increasing the risk of accidents. Manipulation of the circadian system, by means of different lighting conditions, can make people work at times when one would normally be sleeping; this statement is at the basis of the concept of the dynamic lighting. Some researchers have argued that all the physiological processes should work optimally when exposed to daylight, since daylight has been the sole source of illumination for most of the period of humans’ evolution (Thorington et al., 1971). According to this hypothesis, electric lighting should be as similar as possible to daylight.

John Ott (1973; 1982) was the pioneer of full spectrum light: initial interest in Full Spectrum Fluorescent Lamps (FSFLs) began with observations of plants’ growing under different lamp types. FSFLs emit light that is supposed to be similar to daylight over the visible range and some in the ultraviolet-A region of short-wavelength, high energy radiation. However, FSFLs cannot be like daylight, because of the colour temperature (daylight varies in colour temperature from 5000 K to 10000 K, according to sky conditions, season and time of the day), of the illuminance that they provide and of the polarisation of daylight.

Light and work

Lighting quality can be measured in terms of how much an installation meets the objectives and the constraints set by the client and the designer (Boyce, 2003).This is not a technical definition and there is no mention to numbers as it could be expected: the reason is that the perception of lighting quality is influenced by many physical and psychological processes.

Especially in an office space, it is necessary to establish a hierarchy of luminances, in which it is suggested that the working area has the highest luminance, to avoid distraction and fatigue. Boyce (1979) has found that the most preferred form is to provide a uniform illuminance in a surrounding area of about 1 m^2 and lower illuminances outside that area, since having high illuminances immediately outside the working area resulted in distraction and irritation. Another problem concerns the desk surface reflectance, relative to the reflectance of the task materials. Many studies analysed this aspect: Touw (1951) found that the preferred luminance ratio (desk/paper) was 0.4. Wibon and Carlsson (1987) studied the effects due to a repeated movement from a low luminance surface to a higher one, as it happens when watching a computer monitor and a piece of paper. The results showed a marked increasing in eye discomfort for a luminance ratio greater than about 15:1.

The availability of daylight is one of the main important requirements, especially for office buildings. In fact, one of the main sources of dissatisfaction in offices is the lack of the physical connection with the outside: the contact with the natural environment is important because it brings dynamism to the indoor and a sense of relax for people. Artificial light is static, while natural one changes all over the day and year, providing many different scenarios which can enhance productivity and attention. For this reason, the concept of dynamic light has been recently introduced, in order to model, as far as possible, the variable lighting conditions that occur outdoor. The question is if daylight is requested for natural illumination or for view out. Many studies have been developed in windowless spaces, aiming to define how important is the view out. Heerwagen and Orians (1986) observed that in small windowless offices there are more natural illustrations on the walls than in offices with windows. It would be argued that the view out is more important than natural light, but many times it happens that, when the blinds are pulled down to avoid glare, people leave the blinds down for days, months or even years (Rea, 1984).

For a conventional office building, about the 95% of all costs is represented by the salaries, therefore any action devoted to increase individual comfort is a greater cost that can be sooner recovered, thanks to the reduction of sickness and absenteeism. Vision is the most important of all the five senses, especially at work, hence a good lighting quality is strictly connected to people's comfort and consequently to performance, even if it is impossible to find an objective law to describe the relationship between light and productivity, as many other factors are involved (Fig. 2).

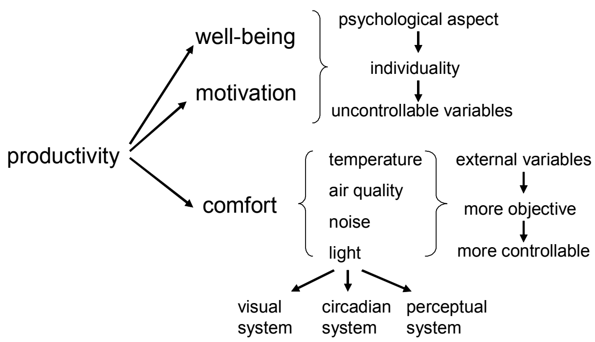

Figure 2. Productivity related to people and indoor environment.

The use of daylight as a primary source in buildings can reduce energy demand, in terms of electricity consumption, but construction and maintenance costs of glazing surfaces are higher than opaque walls. Moreover, a large use of glazing surfaces can cause glare and overheating, if shading device is not sufficient. The benefits of daylight in terms of human performance, workplace productivity, human health and, eventually, the financial return on investment of daylight in buildings has been analysed (Boyce, 2003).

The disruption of the biological clock, due to a poor exposition to sunlight, can cause many problems, both physiologic and psychologic. Especially at high latitudes, during the dark season (from November to February), a large part of the population is affected by excessive fatigue or even depression, due to the decrease in the number of daylight hours. These symptoms can lead to a serious disorder, the so-called Seasonal Affective Disorder (SAD). This disorder can be alleviated by means of exposure to bright light or, in the most serious cases, by light therapy (Küller, 2002).

Since the fertility is low and people retire late, the working force is growing old and visual performance is affected by age. In fact, the need for light increases as a function of age, due to the deterioration of the transmittance of the eyes lenses with age (Edwards et al., 2002). Lighting for older people should be designed more carefully than ordinary office lighting, due to the particular requirements especially in visual acuity and in glare (Boyce, 2003).

METHODS

This work has been carried out in order to look for the results of tests and experiments about the interaction between people and light. The research started with literature, concerning daylight, productivity, visual comfort and lighting quality in offices. The book "Human factors in lighting" written by Boyce has been very useful, since it is a sort of collection of the main results and reflections over several years of studying about these items. This book also provides an exhaustive bibliography, which has been very helpful to enlarge the research.

RESULTS

Many tests and experiments have been carried out, with the purpose to create comfortable environments for workers, preventing disease, sickness, dissatisfaction, accidents and to understand in which way light can influence productivity and well-being in general.

Begemann et al. (1994) studied a long-term behaviour/response of people working in cell-offices, equipped with different experimental lighting systems. They found that most people prefer a variable lighting level which follows the daylight cycle instead of a static one. The results also show that indoor lighting standards levels are lower than preferred ones, which correspond to levels where biological stimulation can occur: therefore a poor lighting quality can cause sleep problems, lack of performance or even depression.

Fluorescent light is the typical lighting installed in office buildings. One of the main problems that may occur with such installation is flicker. Küller and Laike (1998) studied the impact of the non-visible flicker from fluorescent tubes on subjective well-being, performance and physiological arousal. The experiment has been carried out inside a laboratory office, comparing the effects of fluorescent light powered by the conventional and high-frequency ballasts on 37 healthy males and females. The affective state of the participants was tested twice, in terms of activation (awake/sleepy), orientation (interested/bored), evaluation (happy/sad), control (confident/hesitating) and other subjective ratings. Performance was tested by a numerical proof-reading test and it was measured in terms of speed and accuracy. Küller and Laike's results show that people with high critical flicker fusion frequency (the frequency at which even for 100% contrast the subject sees no fluctuation) responded with an increase in speed and a decrease in accuracy. In general, light powered by conventional ballasts resulted less pleasant than light powered by high-frequency ballasts, but no relevant effects were found in terms of visual comfort, headache, stress and fatigue. The lack of effects on headache and eye-strain in this experiment can probably be justified by the insufficient exposure time of only three hours.

Nogouchi and Sakaguchi (1999) tried to verify Kruithof's research (Kruithof, 1941), investigating how illuminance and colour temperature in illumination affects the autonomic nervous system and central nervous system, in terms of lowering physiological activity. Kruithof studied the interactive effects of colour temperature and illuminance to establish which combination defines a comfortable and pleasant lighting condition.

The experiment has been performed on 8 healthy male subjects in four different conditions obtained by the combination of two levels of colour temperature (3000 K and 5000 K) and two levels of illuminance (30 lux and 150 lux). The index of autonomic nervous system has been the heart rate variability (HRV) and the index of the central nervous system has been the alpha attenuation coefficient (AAC) and the mean frequency of the electroencephalogram (EEG). The AAC is defined as the ratio of mean total alpha power (frequency range of 8-12 Hz) recorded with eyes closed and open. An increase in AAC indicates a higher alertness level. Nogouchi and Sakaguchi found that low colour temperature light determines a lowering of central nervous activity.

S.L. McColl and J.A. Veicht (2001) analysed critically the direct effects of FSFL through skin absorption and indirect effects on hormonal and neural processes. Whillock (1988) stated that people, under interior conventional fluorescent lighting condition, receive only about 5% of the UVR dose received from daylight exposure over the year at 50°-60°latitude. The question is whether FSFL are more efficacious than other lamps for supplying this need. One of the most important effects due to light exposition is the metabolism of vitamin D, essential to calcium metabolism and to the maintenance of bones and teeth. Hathaway et al. (1992) analysed the effects of FSFL in schools, measuring them in terms of likelihood of developing dental caries.

All the experiments aiming to support the superiority of FSFL over other lighting sources have not shown evident dramatic effects on behaviour, visibility, academic performance, fatigue in office workers, hyperactivity in children and in health in general. For example, Hathaway's experiments are influenced by many uncontrolled external variables, such as nutrition, tooth-brushing, fluoride treatments, etc., that make the outcome unreliable.

Tanabe and Nishihara (2004) developed some new methods to evaluate the factors affecting productivity, involving fatigue and not only task performance. They state that in experiments, generally carried out for a short time period, people are highly motivated and this fact leads to conflicting and not significant results. To evaluate the feeling of fatigue, subjects had to evaluate their symptoms, belonging to three different categories (this evaluation method is used in the fields of science and of labour and ergonomics in Japan): drowsiness and dullness (I), difficulty in concentration (II) and projection of physical disintegration (III). Yoshitake (1973) suggested three types of fatigue, depending on the rate of complaints among the three categories above-mentioned: general pattern of fatigue (if I> III > II), typical pattern of fatigue for mental work and overnight duty (if I> II > III) and typical pattern for physical work (if III> I > II). Sixteen college-age males have been involved to perform two different tasks, an addition of three-digit numbers on paper and reading aloud, under two different lighting conditions, 800 lux and 3 lux. Physical fatigue and the degree of mental effort required to perform the task were measured by voice analysis (Shiomi, 1999) and cerebral blood oxygenation changes, the last one by means of near infrared spectroscopy (NIRS). The results in terms of evaluation of fatigue by human voices show an increasing fatigue after performing tasks at 3 lux. This result has been validated even with the evaluation by near infrared spectroscopy which has shown an increasing in haemoglobin concentration in the brain under 3 lux, despite the one under 800 lux. Moreover, the performance of addition task did not show significant differences under the two lighting conditions, but, after performing the task, the rate of complaints increased. The condition of 800 lux caused a general pattern of fatigue, while the 3 lux one a typical pattern of fatigue for mental work and overnight duty. The conclusion is that, even if it seems that performance is not affected by illuminance level, a low lighting level increases mental fatigue and therefore performance.

Ariës (2005) analysed the lighting conditions in ten office buildings in the Netherlands, by means of questionnaires and of lighting measurements at workstations. The purpose of this study was to characterize these offices with regards to current lighting standards and non-visual effects and to find solutions for a so-called "healthy lighting", which satisfied both visual and non-visual demands. Many parameters that could be related to the vertical illuminance level have been taken into account: these parameters are reported in Table 1, which shows some recommendations, based on literature and on Ariës results from the short-term measurements in real offices and the long-term measurements in laboratory offices. The amount of light falling on the retina has been measured in "Troland" units with a tailor-made measuring instrument called RED (Retinal Exposure Detector). Troland values are related to illuminance at the retina (Nilsson, 1983). In 90% of the cases, visual lighting criteria are satisfied, but not non-visual criteria. According to literature and standards, 1000-1500 lux are the required vertical illuminance for biological stimulation: Ariës measured these values only in 20% of the examined buildings.

Table 1. Ariës' recommendations for a "healthy lighting".

Building orientation	It has no influence on the amount of vertical illuminance. Diffuse daylight through a vertical window determines a higher vertical illuminance than direct daylight. More openings do not always mean higher vertical illuminances. East, South and West orientations require shading devices.
Obstructions	Surrounding buildings are permanent obstructions that reduce daylight penetration substantially. Vegetation (if not evergreen) can be considered as a shading device only in summer.
Daylight opening	A window in the upper part of the façade increases the penetration of daylight in the deeper part of a room and it contributes to enhance vertical illuminances.
Office type	It has no significant effect on the vertical illuminance, but people prefer a window position.
Interior	Lighting measurement should be done in furnished rooms, since surface reflections contribute to enhance or reduce the illuminance. Specular reflections can cause glare. Using different colours is more preferable for users and it can increase interest.
Position of the work station	A window-facing position is more effective for a high daylight illuminance at the eye, even in the deeper part of a room
Daylight control devices	They should be effective, adjustable and user-friendly. In multi-occupied offices, individual control is often disliked, since it can bring into conflict with other occupants. People are dissatisfied with permanently closed blind, but they often leave the blinds down: an automatic system which opens the blinds in the evening would be useful.
Electric lighting	The highest vertical illuminance values can be obtained with a perpendicular view and with a little distance (0.5 m) from an upper luminaire.
Fatigue	It decreases with high levels of vertical illuminance, determining more alertness.
Sleep quality	Higher levels of vertical illuminance increase the level of sleep quality.
Physical health	Its correlation with the vertical illuminance is not significant.
Other human parameters	Gender, age, eye correction, season sensitivity, chronotype and light sensitivity have no significant influence in the relationship between vertical illuminance and the parameters fatigue and sleep quality.

Boyce et al. (2006) tried different lighting conditions, in order to evaluate the effects on office worker performance, health and well-being. They experienced direct and indirect lighting and the possibility to have an individual lighting control and they found that a direct/indirect system is more comfortable than a fully direct one and that an individual control increases motivation and vigilance over the day.

DISCUSSION

All the experiments are related to a specific group of people, therefore maybe an analysis on different groups of people could reach different results. An acceptable lighting condition can change from one person to another and the same lighting condition can be suitable depending on the context (i.e. flicker light in an office or in a dance club). In laboratory experiments, people are usually highly motivated and they probably would ignore any discomfort. Analysing human factors in lighting, Boyce states that there is no doubt that motivation can affect task performance, but motivation is not only related to lighting conditions, but to many other factors. Moreover, even if lighting requirements are reached, visual comfort is linked to people's expectations and these expectations can change over time.

The reference standard for lighting requirements in indoor workplaces is the EN 12464-1. This standard gives some recommendations, for many different tasks, based only on visual criteria (minimum illuminance level, UGR value and colour rendering index), omitting to mention also the vertical illuminance, which should be evaluated, in order to know the amount of light entering the eye. Moreover, there is no reference to the possibility to increase lighting quality and productivity by means for example of personalised lighting control, dynamic light and indirect light and there is a poor investigation on colour appearance, colour rendering and daylight. It would be necessary to underline the importance of a high lighting quality, to persuade the employers to invest in new technology and in the optimization of daylight, demonstrating them that the over cost will be justified by the amount of productivity and the reduction of absenteeism and dissatisfaction.

CONCLUSIONS

It would be interesting to develop the concept of the interaction between people and light, especially by means of test and experiments, trying to find an objective law, which is rather impossible, due to the fact that vision is a subjective feature, connected to many psychological and physiological aspects. It would be easier to define which lighting conditions allow disease, annoyance, irritation, etc. As this literature study shows, once visual discomfort is avoided, the creation of a stimulating environment must be perceived, especially in office buildings, where workers, living in a pleasant condition, would feel and perform better (Baron, 1994). For this reason, field tests will be carried out in offices and classes in order to evaluate the effective visual conditions in workplaces.

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