Energy and Buildings 78 (2014) 105–112

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Yellow is green: An opportunity for energy savings through colour in architectural spaces

J. López-Besora*, A. Isalgué[1], H. Coch[1], I. Crespo[1], C. Alonso[1]

Architecture & Energy, School of Architecture of Barcelona, UPC, Av. Diagonal, 649, 7th floor, 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 30 January 2014
Received in revised form 3 April 2014
Accepted 7 April 2014
Available online 18 April 2014

Keywords:
Spatial brightness
Luminosity
Visual perception
Colour
Luminance
Architectural spaces
Lighting quality
Energy savings

ABSTRACT

Today, the building sector is one of the greatest energy consumers of the world. Therefore, it is important that designers think about strategies to save energy at the different stages of the building process, including during its life. Considering that a great deal of energy will be spent in artificial lighting, an improvement in the performance in front of light of the architecture itself could lead to a better vision of the spaces, which depends on the quantity and quality of light available and on the architectural characteristics as well. One of the most influential aspects is the colour of the space. Here, a case study is presented in which three coloured spaces were assessed by observers under different lighting conditions. Luminance and illuminance measurements were taken to compare these values with the votes given. The results query the correlation between measured values and luminosity of three-dimensional spaces. As a consequence, the choice of a particular colour may increase the sensation of light in a space and, therefore, a reduction of energy use in artificial lighting is possible. In addition, architectural design can take advantage of colour to improve the visual quality of indoor spaces.

1. Introduction

Today, a large part of the energy consumed in the world is related to the building activity. In most countries, it is the main source of the greenhouse emissions to the atmosphere. It is associated to the large amount of energy spent during the periods of construction and life of the building. During its life, a high percentage of energy will be consumed for lighting, heating, cooling, ventilation, appliances and others. In that sense, energy savings can be achieved through a range of measures including smart design, improved insulation, low-energy appliances, high efficiency ventilation and heating/cooling systems, and conservation behaviour of building users [1]. According to that, "green building" designers may take several strategies to make feasible these energy savings.

Here, we focus on lighting and architecture, and its potential to reduce energy consumption during the life of the building. As it is widely known that the integration of daylighting in architecture is the best option to optimize the use of artificial lighting, this integration must be accurate in order to obtain the quantity and quality of light required and to avoid an undesired excess of light. According to that, many aspects like windows, glazing, interior finishes, skylight, light shelves, light wells and light pipes, as well as the harmonization of the daylighting and lighting interaction must be taken into account so as to get an optimal result [2]. Although the attention is usually focused on the characteristics of windows and glazing, in order to predict the amount of light available in the interior, other aspects like a smart design of the interior finishes are also important. In that sense, one important characteristic is the colour used on surfaces shaping a space.

As a physical phenomenon, colour is a consequence of the interaction between the reflecting properties of materials and the nature of incidental light. But colour can also be explained from a perception standpoint, connected to psychological factors such as culture, age or education, and to physiological factors as well. The last ones are influenced by the human visual system which shows a different degree of sensitivity based on light wavelength. According to the photopic $V(\lambda)$ and scotopic $V'(\lambda)$ human response curve [3], the peak visual response corresponds to 555 and 505 nm, respectively. In photopic vision, it corresponds to a greenish yellow.

Our environment is made up of coloured surfaces and objects with different luminance which are perceived as different degrees of brightness. The perceptual response is based on a different sensitivity for different light colour. Many studies have been made in

* Corresponding author. Tel.: +34 93 4010868.
E-mail address: juditlb@yahoo.es (J. López-Besora).
[1] Tel.: +34 93 4010868.

http://dx.doi.org/10.1016/j.enbuild.2014.04.011

the field of brightness and colour, some of them referring to lamp properties and perceived brightness with a variety of experimental techniques [4]. When referring to illuminated surfaces most of them compare samples of colour in terms of brightness and in contrast with a lighter or darker background and by means of double-booth experiments [see Ref. [5] and references therein]. Other experiments have been reported with fixed, reduced scenes (covering less than 0.1 sr solid angle from the point of view) with scale-models of exterior spaces at relatively low levels of lighting [6]. In some cases, the results referring to comparison with different light sources were given [7]. Nevertheless, from the point of view of architectural spaces, which corresponds to a three-dimensional experience, there is little research. Some of them have analyzed the consequences of brightness and surface colour in spaces in terms of light perception at the levels found in architectural spaces as offices and homes from a theoretical standpoint [8], focused on the surrounding illuminated surfaces appearance, with the conclusion that in some cases, even at lower levels, great visual satisfaction can be achieved. Other studies [9] show that surface lightness seems to influence the perception of room height, especially when applied to walls and ceiling.

Furthermore, the perceptual response to colour in spaces has been studied by authors such as in Ref. [10] or [11], in terms of the psychological and physiological response to coloured environments. Mahnke [11] reports an experiment carried out by him with the purpose of determining the reaction of participants in front of coloured light. The results show the stimulating effect of red and orange, while blue and green produce calming feelings. Next, the author [11] explains other experiments with coloured rooms instead of coloured light. Most of them are clinic experiments, and show the psychophysical reaction and the assessment of observers in front of red, yellow, blue and green spaces. In general terms, these works conclude that yellow and red spaces are stimulating, while blue and green spaces are calming.

From the results of different studies shown above, it is clear that surface colour affects the perception of spaces in terms of dimension and lightness, and it has even an influence on the mood of the users.

Even though brightness and psycho physiological judgement are important when comparing different coloured surfaces under the light, other factors related to the individuals take part in the perception process. For example, the users' attitude in front of light, which may have no connection with the physical parameters given, as it happens with the perception of glare related to the type of window view [12] and the interaction of users with lights and blinds irrespective of lighting conditions [13,14].

On the other hand, although the integration of daylighting in buildings contributes to reduce the amount of energy destined for lighting, it may lead to an increase of heat load due to an excessive solar radiation contribution [15]. Some traditional systems like the Mediterranean blind [16] or lattice windows [17] provide an efficient distribution of light indoors without overheating the space. Also, other more sophisticated systems control glazing's transmittance depending on solar wavelength in a climate-based approach [18,19]. Therefore, if a high entrance of radiation in a space is not desired, the performance of some colours in front of light can make easier to attain a better vision at lower levels.

Just like light perception in a space is affected by factors such as colour surfaces, the use of colour offers a chance to reduce the use of energy in lighting. With a higher sensation of light under the same lighting conditions, a better vision with fewer fixtures would be possible, resulting in an energy saving obtained only by design. This is an important consequence which could especially be applied in spaces where a good vision is needed, for example, transition spaces from one lighted space to a differently lighted one. Other situations, such as when passing from natural to artificial lighting or from a corridor to a working space, might profit from this study. In these cases, the effects of dark or light adaptation could be minimized.

2. Methods

With this purpose in mind, three spaces were built in a controlled set. The set was appropriate because there was room enough to move in front of the spaces as well as because lighting conditions could be adjusted. The spaces, called A–C, were of the same dimensions, 2 m wide, 1.5 m deep and 3 m high, and no ceiling, as seen in Figs. 1–4.

The U-shaped spaces were assembled with self-supporting wood panels (Fig. 3) and each space was painted in a different colour: yellow (NCS S 1070-Y10R) for Space A, blue (NCS S 1030-B) for Space B, and grey (NCS S 1500-N) for Space C. The choice started with a bright yellow because it is often associated with a sensation of light, and at the same time its wavelength is close to the point of highest sensitivity of the eye, according to the human response curve [3].

In fact, the association of yellow with luminosity can be seen in another experiment that took part in the International Association of Color Consultants seminars in the United States and Europe [11]. A group of people was asked to associate some terms such as love, hatred, peace, and others with colours. When asked about the luminous term, the vast majority associated it with yellow, both in the United States and in Europe.

In our case, the purpose was to compare a yellow with a grey with the same reflection index and with a similar blue, in terms of brightness, when lighted by the same lamps. From the measurements of luminance and illuminance taken later on the experiment, the effective reflection index of each colour was calculated. The following equation was used based on the assumption that all the surfaces were Lambertian:

$$E \cdot r = \pi \cdot L$$

As a result, the reflection indexes for each painted surface are: 0.64 for A (yellow), 0.50 for B (blue) and 0.66 for C (grey), with the used lamps.

Theoretically, under the same lighting conditions, yellow and grey surfaces would have very nearly the same luminance value, higher than the blue one. Starting from these values, the objective was to check what was perceived by a sample of observers in this situation as well as when modifying the lighting conditions. In consequence, three lighting arrangements were performed taking into consideration the availability of material and the purpose of the work.

First of all, the same lighting fixtures were used in all spaces, a 2000 W quartz halogen light in zenithal position filtered with a 50% diffuser frame so as to provide a diffuse and even light. The colour temperature of all the lamps was 3200 K. A white board was set in the upper part of the front side of each space to diffuse light and hide the lamps from the observers (Figs. 2 and 5). The colour temperature, the lamps and the power given to the lamps remained the same during the experiment, even though the light reaching the spaces was modified in three lighting arrangements, as explained below. Thermal sources were used in order to have a smooth, continuous spectral distribution of light and avoid singularities. The used "white" light had then low content of short wave ("blue") radiation.

Next, as the aim was to compare the amount of light perceived in the spaces under different lighting conditions, two light levels were set and combined: a starting level and a modified one which was half of the previous. To these ends, the lighting fixtures (lamp height and lateral baffles of the lamp) were set in order to provide a starting