Dynamic Simulation of a Lighting System Based on the Hue-Heat Hypothesis

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Abstract

It is by now accepted that light has significant effects on people well-being in terms of both visual and non-visual comfort. According to the Hue Heat Hypothesis, Correlated Colour Temperature can affect people thermal perception: a cool light would determine a cool sensation and a warm light a warmth sensation. Despite several studies investigated this issue, published results are conflicting. The paper shows outcomes of laboratory surveys that are in good agreement with the HHH. Moreover, it presents results of dynamic daylight simulations aiming at studying the way design strategies, implementing the HHH, modify indoor luminous environment and energy consumptions due to lighting.

Introduction

The Hue Heat Hypothesis (HHH) is based on the idea that light and colours of the environment can affect thermal perception and influence thermal comfort. Specifically, it states that, when spectral power distribution of light reaching an observer’s eye is characterized by long wavelengths in the visible spectrum, the space is perceived as warmer; conversely, when small wavelengths are predominant, the space is perceived as cooler.

Despite several studies tried to investigate the effects of light on thermal perception, obtained results are conflicting (Candas and Dufour, 2005).

For example, Berry (1961) carried out experiments in a test-room where 25 volunteers were exposed to five differently coloured light (amber, yellow, white, green and blue) and were asked about their thermal comfort conditions. Bennet and Rey (1972) performed similar tests, but in this case the spectrum of the light achieving volunteers’ eyes was changed thanks to the use of red, blue and clear goggles. Both studies did not reveal an interaction between the thermal perception and the colour of light. Similar conclusions were obtained by a more recent study by Baniya et al. (2018).

On the contrary, the HHH is supported by the studies of Itten (1970) and Clark (1975), underlining a relationship between indoor spaces wall colours and occupants’ thermal sensation. Moreover, Fanger et al. (1975) performed surveys on 16 subjects under an extreme red and an extreme blue light. He found that in the former case, people preferred an about 0.4 °C lower temperature. Positive results were found by recent studies as well. Winzen et al. (2014) carried out experiments in a test-room arranged to simulate an aircraft cabin alternatively equipped with two different light sources (a yellowish one and a bluish one). Huebner et al. (2016) observed the behaviour of 32 people in a climatic chamber exposed to warm and cool lights and evaluated their thermal conditions by observing the additional clothing subjects put on. Hettiarachchi and Emmanuel (2017) performed a series of experiments in Sri Lanka and observed the consequences of using red colour in indoor spaces both in cool tropical uplands and in humid coastal areas. The results of all these studies seem to confirm that light affects the thermal comfort as well and it is widely accepted that conflicting results are often related to insufficient control of lighting and thermo-hygrometric parameters in test rooms (Huebner et al., 2016).

If the HHH basics are verified, changing light characteristics could influence people’s perception. Comfort conditions could be improved increasing warmth sensation during winter and cool sensation during summer. This would determine a consequence in terms of energy consumptions as well. Taking advantage of thermal sensation alterations determined by light, it would be possible to increase or reduce indoor temperature set-points used for air-conditioning systems design and consequently to save energy.

To practically obtain these results, the following strategies can be adopted: changing electric light characteristics seasonally (e.g. varying electric lights Correlated Colour Temperatures -CCTs-); modifying daylight spectrum entering through windows (e.g. applying different filtering systems such as curtains); varying colours of indoor architectural surfaces (e.g. using movable panels covering perimeter walls).

Despite HHH implementation mainly aims at reducing energy consumptions due to air conditioning, it can affect energy consumptions due to lighting as well. Indeed, the use of curtains reduces daylight entering the space and the variation of luminaires CCT determines changes in the absorbed power (Beccali et al. 2018).

Given these premises, the goal of the paper is to analyse the effect of design strategies applying the HHH on luminous environment characteristics and on energy consumptions due to lighting. The paper is divided in two parts. In the former one results of laboratory experiments, partly presented in a previous work.
(d’Ambrosio Alfano et al., 2019), are shown. They consist in surveys performed in a test-room, where humidity and temperature are controlled and maintained constant, whereas luminaires CCT is varied. Testers are asked to answer a questionnaire about thermal comfort sensation for each considered CCT and then results are compared to verify the HHH. Given that the obtained data are in good agreement with the HHH, in the latter part of the paper, using light simulations, two design strategies, useful to put into practice HHH basics are tested: 1) installing luminaires characterized by changeable CCT; 2) shading windows by means of differently coloured curtains. At this purpose, DIVA for Rhinoceros is used to calculate daylight availability in the same laboratory used for the experiments, considering that the window is equipped alternatively with a bluish and an orangish curtain. The reduction in daylight availability due to the filtering systems use is evaluated. Then dynamic simulations are performed to model the yearly functioning of two different lighting systems: a base case study (from now on called B-C) and an experimental case study implementing the above-mentioned design strategies (from now on called HHH-C). As for the B-C, it is considered that the window is not equipped with coloured curtains and that the luminaires are characterized by a stable 4000 K CCT. On the contrary, as for the HHH-C the window is equipped with the orangish curtain from November the 15th to March the 31st and with the bluish one from June the 15th to September the 15th. When the curtain is orangish luminaires CCT is 3000 K, when it is blue, CCT is 6000 K. In the rest of the year, curtains are not used and luminaires CCT is equal to 4000 K.

**HHH verification under laboratory conditions**

**The test room**

The test room used to verify the HHH hypothesis is placed at the Photometry and Lighting Laboratory of the Department of Industrial Engineering of the University of Naples Federico II (Italy). It is characterized by an L shape (see Figure 1). A door allows the access in a sort of anteroom, connected with a wider space that is the very test-room. This space is equipped with a south-oriented balcony window 1.5 m wide and 2.6 m high. Four white and not light-transmitting curtains cover the laboratory perimeter walls, allowing completely shielding the entering daylight and separating the space from the anteroom. A desk and a chair are located in the test-room. The false-ceiling is equipped with different light sources, all managed by a DALI control unit, consisting in a touch panel installed in the anteroom, allowing to modify both the intensity of the emitted luminous flux and the CCT of the sources. During the experiment two recessed white-tuning dimmable LED luminaires were used (luminous flux according to the manufacturer’s technical sheet equal to 4820 lm). Their photometry is reported in Figure 2. Spectral radiance, illuminance and power measurements were performed to characterize the sources. The luminous light output was regulated in order to obtain at the desk an illuminance value equal to about 300 lx, corresponding to filing and copying office activities according to the EN 12464-1:2011 Standard, whereas CCT was varied according to three set points: 3000 K (warm light), 4000 K (intermediate light) and 6000 K (cool light). A Konica Minolta CS 2000 spectroradiometer was used to measure luminaires spectral power distribution, from which CRI and CCT were derived. At the same time illuminance at the desk (corresponding to the point P (see Figure 1) and the absorbed power were measured by means of a Konica Minolta T-10 A illuminance meter and of an electronic power-meter connected to the laboratory fuse-box. Measurements results are reported in Table 1.

**Figure 1: Measured plan of the test-room**
Alfano et al., 2013) consists of two sections: the assistance of a team of psychologists and doctors and a robust protocol designed consistently to the International Standard in the field (d’Ambrosio Alfano et al., 2007), involved the main physical variables affecting the thermal sensation. The questionnaire, designed with the ISO 9920:2007 Standard, was aimed at evaluating the thermal perception (how are you feeling now?), and dealing with the thermal status in terms of the thermal sensation (how are you feeling now?), by means of a special Comfort Data Logger INNOVA 1221 provided with sensors for the air temperature, the plane radiant temperatures, the air velocity, the dew point and the floor temperature all compliant with ISO 7726:1998 Standard accuracy requirements.

The microclimatic characterization of the test room, preliminary calibrated in the range of air temperature from 18 to 25 °C, was carried out by measuring all physical parameters affecting the thermal sensation by means of a special Comfort Data Logger INNOVA 1221 provided with sensors for the air temperature, the plane radiant temperatures, the air velocity, the dew point and the floor temperature all compliant with ISO 7726:1998 Standard accuracy requirements. The measurements campaign was based upon a special and robust protocol designed consistently to the International Standard in the field (d’Ambrosio Alfano et al., 2007), involving the main physical variables affecting the thermal sensation. The questionnaire, designed with the assistance of a team of psychologists and doctors (Alfano et al., 2013) consists of two sections:

- personal information (in this section subjects have to describe their clothing at the moment of the survey. This is to assess the clothing insulation according to the ISO 9920:2007 Standard);
- thermal comfort. The questions of this section have been formulated in compliance with the recommendations of the ISO 10551:1995 Standard and deal with the thermal status in terms of the thermal perception (how are you feeling now?), evaluation (do you find this?) and preference (how would you prefer to be now?) scales.

In this investigation only the answer to the thermal perception (overall thermal state) was considered. It was expressed in terms of a Thermal Sensation Vote (TSV) on the typical 7-point scale ranging from -3 (cold) to +3 (hot) and calculated as a mean value of the votes attributed to the environment.

### Laboratory experiments

66 subjects (31 females and 35 males) took part in the experiments. They were all volunteers and were selected among University students, their friends and people working at the department. For this reason they were all aged between 18 and 35. None of the subjects had a background in the lighting field.

Once arrived at the department where the laboratory is situated, subjects were hosted in a conditioned meeting room and stayed there, seated at the conference table here located. Generally, groups of 4-6 people were brought together to the department. Before starting the experiment, one of the researchers responsible of tests organization explained to the subjects how the test will be carried out, giving only the information useful to put people at ease, without mentioning the actual goal of the test, in order to not influence their judgment. Then a paper containing the authorization to use subjects’ answers for research purposes was delivered to each subject to sign. Finally, the researcher let people in the meeting room for about 15 minutes, explaining that the test-room setting needed to be accomplished. During the wait, subjects spoke one each other, read some magazines available on the table or used their smart phones. Then one subject in turn was brought to the laboratory, while the others kept waiting in the meeting room. All this procedure (lasting about 30 minutes for the first subject performing the test) was necessary not only to practically organize the experiment, but also to let people adapting to the same thermal conditions (they stayed all in the same room) and to the same activity levels (they stayed all seated at a desk listening, writing or reading). Differently, it would have been difficult to evaluate the effect of the activities performed by each subject before reaching the laboratory on the answers to the test.

Once led in the test room (settled at 20 °C in this investigation), subjects were invited to fill a short questionnaire with general information (e.g. age, height, weight, nationality, health problems if they have). Then they were asked to stay inside the test-room for a time of 10 minutes to adapt to the environmental conditions. During this short period, they were also invited to play word puzzle. This served as a distraction with respect to the surrounding environment in such a way that they would not have had memory of it in the next test. After the subjects experienced the test room conditions, a sound signal was given to prompt them to fill a questionnaire focused on the thermal perception. Immediately after completing the questionnaire, the subjects were invited to leave the test room for 10-15 minutes in order to interview another subject and then change the light scene. During the break period subjects

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**Table 1: Measured characteristics of the light sources**

<table>
<thead>
<tr>
<th></th>
<th>Warm light</th>
<th>Intermediate light</th>
<th>Cool light</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRI</td>
<td>83</td>
<td>86</td>
<td>85</td>
</tr>
<tr>
<td>CCT</td>
<td>3038 K</td>
<td>4035 K</td>
<td>6076 K</td>
</tr>
<tr>
<td>Work-plane illuminance</td>
<td>305 lx</td>
<td>301 lx</td>
<td>302 lx</td>
</tr>
<tr>
<td>Absorbed power</td>
<td>59.5 W</td>
<td>56.0 W</td>
<td>52.5 W</td>
</tr>
</tbody>
</table>

**Figure 2: LED photometry**

The measurements campaign was based upon a special and robust protocol designed consistently to the International Standard in the field (d’Ambrosio Alfano et al., 2007), involving the main physical variables affecting the thermal sensation. The questionnaire, designed with the assistance of a team of psychologists and doctors (Alfano et al., 2013) consists of two sections:

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came back to the meeting room, where they waited for the next session of the test. Then they were accompanied again in the test room, and the procedures of adaptation and administration of the questionnaire were repeated.

**Light simulations**

Static and dynamic daylight simulations were performed referring to a model with the same geometrical and optical characteristics of the laboratory used for the experiments by using DIVA, a highly optimized daylighting modelling plug-in for Rhinoceros based on Radiance engine. The used weather data file was the Naples IWEC one, downloaded from the Energy Plus web site. According to what suggested by Reinhart (2006), calculation parameters are the following: ambient bounces 7, ambient division 1500, ambient sampling 100, ambient resolution 300, ambient accuracy 0.05. The spectral reflectances of the laboratory surfaces were measured by means of a Konica Minolta CM 2600d spectrophotometer. From the obtained data, the XYZ coordinates related to the D65 illuminant were inferred (see Table 2) and then the Colour Picker for Radiance was used to obtain the reflectance value in the RGB channels, to set in DIVA (see Table 3).

### Table 2: Measured XYZ coordinates of laboratory surfaces

<table>
<thead>
<tr>
<th>Surface</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>76.39</td>
<td>80.73</td>
<td>85.28</td>
</tr>
<tr>
<td>Floor</td>
<td>53.03</td>
<td>55.31</td>
<td>46.85</td>
</tr>
<tr>
<td>Interior walls</td>
<td>77.82</td>
<td>82.03</td>
<td>83.47</td>
</tr>
<tr>
<td>Desk top</td>
<td>54.02</td>
<td>56.99</td>
<td>57.32</td>
</tr>
<tr>
<td>Window frame</td>
<td>15.80</td>
<td>13.06</td>
<td>4.20</td>
</tr>
<tr>
<td>Exterior walls</td>
<td>71.70</td>
<td>75.07</td>
<td>66.30</td>
</tr>
<tr>
<td>Exterior floor</td>
<td>53.03</td>
<td>55.31</td>
<td>46.85</td>
</tr>
</tbody>
</table>

**Table 3: R, G and B components of reflectance in DIVA**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>0.69</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>Floor</td>
<td>0.56</td>
<td>0.61</td>
<td>0.49</td>
</tr>
<tr>
<td>Interior walls</td>
<td>0.72</td>
<td>0.88</td>
<td>0.85</td>
</tr>
<tr>
<td>Desk top</td>
<td>0.49</td>
<td>0.60</td>
<td>0.57</td>
</tr>
<tr>
<td>Window frame</td>
<td>0.26</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>Exterior walls</td>
<td>0.71</td>
<td>0.80</td>
<td>0.66</td>
</tr>
<tr>
<td>Exterior floor</td>
<td>0.56</td>
<td>0.61</td>
<td>0.49</td>
</tr>
</tbody>
</table>

As for the window, a generic double pane glazing was considered (visual transmittance equal to 0.8).

Two types of simulations were performed: static and dynamic ones. As for the static simulations, they were useful to understand how DIVA accounts for the spectral characteristics of modelled surfaces, when it calculates illuminances. As it was previously mentioned, the software is based on the Radiance engine. Radiance cannot precisely simulate the light spectrum (Larson and Shakespeare, 1998), however it determines illuminance values as the sum of three different components: red light, green light and blue light, by applying the following calculation model:

\[ E = (E_{ER} \cdot 0.265 + E_{EG} \cdot 0.67 + E_{EB} \cdot 0.065) \cdot 179 \]  

Where \( E_{ER} \), \( E_{EG} \) and \( E_{EB} \) are the red, green and blue components of the irradiance; 0.265, 0.67 and 0.065 are coefficients that account for different spectral sensitivity of the human eye and 179 lm/W is the applied luminous efficacy. Using this model, it is possible to understand with a certain approximation, how the variations of the R, G and B reflectances or transmittances of the architectural surfaces affect the final illuminance values. Regarding the specific applications, it has been possible to evaluate the capability of the curtains in filtering daylight only in specific channels (the red and the blue one alternatively). To deepen this issue the winter and the summer solstices were considered and the illuminances at the eye level of a user seated at the desk and looking forward were calculated each hour from 9:00 to 18:00 considering the CIE clear sky model. For each day, the simulations were repeated twice: the former time considering that the window was not shaded and the latter one considering that it was equipped with an orangish curtain during the winter solstice and with a bluish one during the summer solstice. The curtains were modelled as a planar surface located in front of the window, to which a transparent Radiance material was applied. The RGB transmittances of the orangish curtain were 0.9, 0.4 and 0.2, whereas those of the bluish one were 0.3, 0.6 and 0.9. The R, G and B components of daylight illuminances \( (E_R, E_G, \) and \( E_B) \) were evaluated for both cases (B-C and HHH-C) and the percentage incidence of each component on the total illuminance was calculated.

Dynamic simulations were used to evaluate daylight illuminances at six different points of the desk (W1, W2, W3, W4, W5 and W6 in Figure 1) and at a point located at the ceiling, positioned like a typical photosensor used to manage the lighting system according to daylight availability (see point C in Figure 1). For the dynamic simulations a typical office scheduling was considered, i.e. it was assumed that the room was occupied from Monday to Friday, from 9:00 to 18:00. Daylight saving time ranges from April the 1st to October the 31st, daylights were measured by means of a Konica Minolta CM 2600d spectrophotometer. From the obtained data, the XYZ coordinates related to the D65 illuminant were inferred (see Table 2) and then the Colour Picker for Radiance was used to obtain the reflectance value in the RGB channels, to set in DIVA (see Table 3).

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not sufficient to prevent glare and overheating risks. To obtain the yearly illuminance trend related to the HHH-C, results of the three simulations were merged together. Specifically, it was considered that the window was equipped with the orangish curtain plus the DIVA conceptual shading from November the 15th to March the 31st, with the bluish one plus the DIVA conceptual shading from June the 15th to September the 15th and exclusively with the DIVA conceptual shading for the rest of the year.

Finally, daylight availability was evaluated in terms of Useful Daylight Illuminance according to the definition reported by Nabil and Mardaljevic (2006), considering a task illuminance equal to 300 lx for both the B-C and the HHH-C. Moreover, the annual functioning of the lighting system was simulated. It was assumed that the two luminaires of the laboratory were managed by an automated on-off switching system that turns luminaires on and off, based on indoor daylight availability. By using the calculation tool proposed by Bellia and Fragliasso (2017), the yearly absorbed power trend was calculated starting from the daylight photosensor detections, i.e. from the illuminance values calculated by means of the three dynamic simulations at the point C (see Figure 1). To simulate the lighting system, it was considered that luminaires CCT was equal to 3000 K and 6000 K, when the window was equipped with the orangish curtain and the bluish one respectively and 4000 K when it was not shaded. To obtain the HHH-C yearly absorbed power trend, results of the three simulations were put together again. According to the measured data reported in Table 1, it was considered that the absorbed power was different depending on the used CCT. Finally, starting from the hourly absorbed power trends, energy consumptions related to B-C and HHH-C were obtained and compared.

Results and discussion

Laboratory experiments

The results of the subjective investigation in terms of the thermal perception are reported in Table 4 and in Figure 3 for a set point temperature of the test room of 20 °C (winter case).

According to data in Table 4, with reference to the sample as a whole, for the light scene at 3000 K (warm light, indicated as (W)) thermal sensation by questionnaires is typical of slightly warm conditions with a percentage of persons who voted a TSV≥1 equal to 60%. To the contrary, in the presence of cool light (6000 K, indicated as (C)) the percentage of those who felt slightly warm or warm decreased to 38%. In addition, a growth of respondents under neutral conditions from 32 to 49% and an increasing of respondents who felt slightly cold (from 6 to 14%) have been observed. In addition, recorded TSV data, seem to confirm a certain gender related perception of thermal conditions resulting in a high sensitivity of women to low temperatures (Kim et al., 2013, Rupp et al., 2015) with a more pronounced effect of colour temperature on the thermal perception of females.

Table 4. Percentage of persons who voted a single option to the question on the thermal sensation ASHRAE scale (How are you feeling now?). (W) light scene at 3000 K, (C) light scene at 6000 K.

<table>
<thead>
<tr>
<th>Sensation</th>
<th>Females</th>
<th>Males</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(W)</td>
<td>(C)</td>
<td>(W)</td>
</tr>
<tr>
<td>Cold (-3)</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Cool (-2)</td>
<td>3 0 0 2</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Slightly cool (-1)</td>
<td>10 16 3 11</td>
<td>6 14 3 11</td>
<td>6 14 3 11</td>
</tr>
<tr>
<td>Neutral (0)</td>
<td>32 55 31 43</td>
<td>32 49 31 43</td>
<td>32 49 31 43</td>
</tr>
<tr>
<td>Slightly warm (+1)</td>
<td>35 26 37 37</td>
<td>36 32 37 37</td>
<td>36 32 37 37</td>
</tr>
<tr>
<td>Warm (+2)</td>
<td>19 3 29 9</td>
<td>24 6 29 9</td>
<td>24 6 29 9</td>
</tr>
<tr>
<td>Hot (+3)</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
</tbody>
</table>

Based upon data in Table 4, in case of the “warm” light scene, 54% of women (66% of men) voted warm or slightly warm with 32% of respondents under neutral conditions (43% for men), whereas, under “cool” light conditions, the percentage of women who voted TSV≥1 decreased to 29% (46% in case of men). Thus, the percentage of women who felt neither cold nor warm increased from 32 to 55% (from 31 to 43% in case of men).

Simulations

Figure 4 presents results of daily daylight simulations referred to winter and summer solstices. Graphs report illuminance values calculated at the eye level (point E in Figure 1) as a function of the time, considering that simulations were repeated with a one-hour time step. Specifically, they report the R, G and B components of the illuminance (Eₚ, Eₐ, Eₛ) and the total illuminance.
(E), sum of the three above-mentioned components, both for the simple window and for the window equipped with the curtains.

During winter the use of the orangish curtain reduces the $E_R$ in a percentage equal to about 84%-86% depending on the time of the day, bringing it to values close to 0 for most of the day. On the contrary, the trend of the red component of the illuminance remains close to the curve related to the simple window, with a percentage reduction ranging from 18% to 20%, depending on the time of the day. The percentage reduction of the green component is comprised between 67% and 69%. As a consequence, the daylight availability is globally reduced. Considering the total illuminance (black lines in Figure 4), the use of the curtain determines a percentage reduction ranging from 55% to 62%, depending on the considered hour. The variations of the percentage reduction during the day, depend on the fact that the indoor surfaces play their own role in increasing or reducing the $E_R$, $E_G$, $E_B$ components at the work-plane. Depending on the moment of the day, daylight is differently reflected by the architectural surfaces, since the luminous efficacy model, used by the software to calculate illuminances, does not change on time varying. If illuminances are outdoor calculated, the $E_R$, $E_G$, $E_B$ components have always the same weight in determining $E$. For each component, the weight is equal to the corresponding coefficient reported in the (1).

During summer, the use of the bluish curtain determines an opposite luminous scenario. As it can be inferred from Figure 5 the red component is strictly reduced compared to the winter case, and it weighs about 10% in determining the total illuminance. Conversely, the blue one has a more significant impact in defining $E$ compared to the winter case (about 9%). This is clear looking at Figure 4 as well, where it is possible to observe that the $E_b$ trends are very similar with and without curtain, whereas the $E_R$ is strictly reduced (about 76%-77%) when the window is shaded by the curtain. Overall, in this case the reductions of global illuminances are about 54%.

Based on these findings, it was possible to evaluate how the curtains use affects the yearly indoor daylight availability. Figure 6 reports results of dynamic daylight simulations in terms of UDI, referred to the 6 points of the calculation grid and calculated for both B-C and HHH-C. It can be noticed that the use of the curtains has a positive effect in reducing illuminances higher than 2000 lx, i.e. too high illuminances that can determine discomfort.

On the other hand, the annual percentage of the hours during which illuminances range from 300 lx to 2000 lx increases. These values correspond to daylight levels higher than the prescribed illuminance but not disturbing people, i.e. sufficient to perform visual task without using electric light. As a consequence, there is an increasing of the yearly percentage of hours corresponding to daylight illuminances lower than the prescribed one (comprised between 0 lx and 100 lx and between 100 lx and 300 lx), determining the need of electric light use. In the B-C the annual percentage of hours for which the electric light is needed is at most 16.59% (see point W1), whereas in the HHH-C it ranges from 16.90% to 20.61%. Obviously, this affects energy consumptions. According to simulations results, using a switching daylight-linked control system, annual energy consumptions of the B-C are equal to 32.73 kWh corresponding to 3.34 kWh/m². As for the HHH-C, annual consumptions are equal to 40.56 kWh corresponding to 4.14 kWh/m², i.e. 24% plus compared with the B-C. As it was mentioned in the introduction, the implementation of design strategies based on HHH aims at reducing energy consumptions due to air conditioning. So, the energy savings achievable thanks to the reduction of the temperature set-points to design the air conditioning systems should be compared to the
increment of energy consumptions due to lighting, in order to identify the design optimum.

Conclusions

The paper presents results of laboratory surveys aiming at verifying the effectiveness of the Hue Heat Hypothesis (HHH). Moreover, it reports outcomes of dynamic daylight simulations, evaluating the effects on lighting systems functioning of design strategies implementing the HHH: the use of coloured curtains and the variation of luminaires CCT depending on the season.

Based upon obtained results it is possible to confirm that, under winter conditions, cooler light (6000 K) induces a shift of the thermal sensation toward cold. The effect seems to be more pronounced in case of women whose percentage under neutral conditions has almost doubled by changing the CCT from 3000 K (warm light) to 6000 K (cool light). Dynamic daylight simulations demonstrate that the strategies aiming at applying the HHH affect not only the characteristics of the luminous environment but also the energy consumptions due to lighting. Specifically, the use of coloured curtains, besides the changes in the spectral characteristics of the entering daylight, globally reduces indoor daylight levels. Consequently, on one hand it has a positive effect in reducing the annual percentage of hours during which daylight levels are too high and can create discomfort; on the other hand, the reduction of the daylight levels determines an increasing of the annual amount of hours, during which daylight alone is not sufficient to guarantee the visual task performance and electric light is needed.

The CCT variation determines changes in the absorbed power: the higher the CCT, the lower the absorbed power is. However, for the specific applications, considering that the lighting system is managed by a switching daylight-linked control system, it was found that the design strategies imply an annual energy consumption increasing equal to about 1 kWh/m².

The application of the HHH is an interesting integrated approach to evaluate the indoor environmental quality. The use of dynamic simulations is a useful tool to assess the effects of the connected design strategies, in terms of both energy consumptions and alteration of indoor environmental parameters affecting people comfort conditions. To obtain an integrated evaluation it is necessary to perform integrated simulations, associating results of software specifically developed for lighting design and those provided by software for energetic simulations. In this way it is possible to globally evaluate the effectiveness of design strategies and to optimize the technical choices. Specifically, regarding lighting, it must not be forgotten that, currently, light simulations in HHH field are limited by the impossibilities to in-depth evaluate the light spectral distribution. This research is a pioneer one, but further studies should aim at validating the calculation model based on the decomposition of light in the three R, G and B components and at comparing it with a more accurate spectral analysis.

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