Effects of Coloured Ambient Light on Perceived Temperature for Energy Efficiency: A Preliminary Study in Virtual Reality

Siyuan Huang[1,2], Giulia Wally Scurati[2], Roberta Etzi[2], Francesco Ferrise[2], Serena Graziosi[2], Lavinia Chiara Tagliabue[3], Alberto Gallace[4] and Monica Bordegoni[2]

1. Department of Design, Politecnico di Milano, Italy
2. Department of Mechanical Engineering, Politecnico di Milano, Italy
3. Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy
4. Department of Psychology, University of Milan-Bicocca, Italy

ABSTRACT

The built environment has a great responsibility for energy consumption and carbon emissions worldwide. Thus, energy conservation in building plays a vital role in sustainable economic growth. Researchers from many disciplines have devoted to the field of design for energy-efficient buildings. However, human factors, as the way people interact or use the designed environment, are also fundamental. In particular, colour-temperature perceptual associations might be used to influence people's thermal experiences. In this study, we presented two national groups of participants with four rooms in Virtual Reality (VR) to test the effect of coloured ambient light on the perceived thermal comfort, context of use and ambient atmosphere. The results showed that room-lighting could affect the thermal comfort perceived and its advantage for energy conservation. Detailed analyses and future developments are also discussed.

Key Words: Coloured ambient lighting; Thermal comfort; Virtual reality;

1. INTRODUCTION

The central theme of the Sustainable Development Goal 7 of United Nations is ensuring access to affordable, reliable, sustainable and modern energy for all, with the ambition of reaching the energy targets for 2030 (Economic and Social Council, 2018). It is reported that buildings and construction are responsible for 36% of global energy consumption and 39% of energy-related greenhouse gas emissions (International Energy Agency, 2017). Also, the Joint Research Centre of European Commission announced the economic growth has a positive relationship with the efficient use of energy, especially in the residential sector (Bertoldi P, Diluiso F, & Castellazzi L, 2000), due to the increasing demand of thermal comfort and the trend towards efficient buildings, as well as the use of advanced appliances and systems (Pérez-Lombard, Ortiz, & Pout, 2008). In fact, space heating takes up the highest proportion of building energy consumption (The World Bank, 2018).

With a spacious room for improvement, smart and energy-efficient buildings (L. Wang, Wang, & Yang, 2012), as well as sustainable architecture and green design (Amirhosein GhaffarianHoseini et al., 2013) have becoming a tendency in the built environments industry. Specifically, implementations include optimised adaptive control systems (Yang, Yan, & Lam, 2013), innovative energy-efficient appliances (Chua, Chou, Yang, & Yan, 2013) and embodied energy construction materials (Cabeza et al., 2013). Nevertheless, human factors such as the ways occupants make use of the designed environment should be likewise addressed. The built environment can affect human comfort and wellbeing. On the other hand, people’s choices and behaviours also influence indoor energy use, building operations and performance (International Energy Agency, 2017). Therefore, more design and implementations in the human-building interaction aspect are needed for energy efficiency without sacrificing the human thermal comfort, health and wellbeing.

In this work, we attempted to use Virtual Reality (VR) for investigating the effects of coloured ambient light on people’s perception of thermal comfort, ambient atmosphere, and space function for energy efficiency. Simulation technologies such as VR have already been employed as a valuable tool for design and research purposes because of their time and cost efficiency (Thrash, Dalton, & Hölscher, 2015). Besides, this work follows the results of our previous study (Scurati, G.W., Etzi, R., Huang, S., Graziosi, S., Tagliabue, L.C., Gallace, A., Ferrise, F.,& Bordegoni, 2019) with a further validation on the comparison between two different cultural groups (fifteen Chinese and fifteen Italian subjects).

2. EFFECTS OF COLOURED AMBIENT LIGHT ON HUMAN PERCEPTION AND BEHAVIOR

People all over the world make colour-temperature matchings. These associations are influenced by environmental and natural phenomena, human experience, cultural and geographic origin (Wierzbicka, 1990; Wright & Rainwater, 1962). At the same time, colour perception affects human physiological reactions, cognition and behaviour (Madden, Hewett, & Roth, 2000), despite this kind of influence varies individually (e.g., age, gender, personality) and situationally (Priluck Grossman & Wisenblit, 1999). In the research field of space and interior design, plenty of studies showed that there is a significant correlation between the occupants’ visual comfort and lighting conditions (Hwang & Jeong, 2011). In fact, among different indoor lighting systems, the coloured lights are leveraged as an active element in creating environment atmosphere, influencing occupants’ mood, visual-related thermal comfort, and cognitive performances (Huebner et al., 2016). Moreover, coloured ambient light has been widely used in indoor environments like workplaces (Juslen & Tenner, 2005), residential buildings (Frontczak, 2012), health and clinical locations (Dalke et al., 2006).

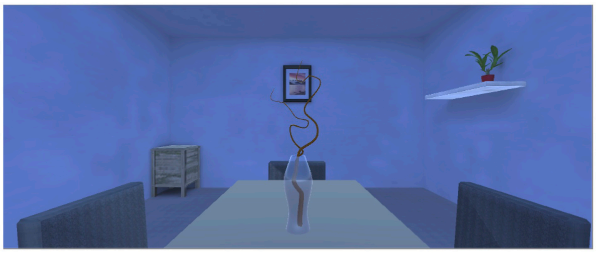
Indoor lighting can affect people’s perception of thermal comfort that may result in energy-efficient behaviours (Huebner et al., 2016; Juslen & Tenner, 2005). One vital aspect is the hue-heat hypothesis, which postulates red links to warm and blue to cold temperature (Bennett, 1972). As a laboratory study indicated that visually comfortable light could improve the satisfaction towards indoor environments like thermal comfort, which may serve the benefits of energy-saving and healthy building design (te Kulve, Schlangen, & van Marken Lichtenbelt, 2018). A study conducted inside of an aircraft cabin showed that participants report a higher temperature when exposed to yellow ambient light than the condition of blue hues (Woldemedhin, Raabe, & Hassel, 2013). Another experiment carried out in a climate chamber supported the hue-heat hypothesis based on a subjective assessment with collected heart rate data (H. Wang, Liu, Hu, & Liu, 2018).

3. CURRENT STUDY

3.1. Participants and experimental conditions

Thirty subjects voluntarily participated in our study. They are all students and belonged to two nationalities: fifteen Chinese (seven females; mean age= 26.6) and fifteen Italian (seven females; mean age= 25.13). Before entering the experiment, subjects read and signed a consent form. All of them reported normal or corrected-to-normal colour vision, as well as normal colour perception. The study received the approval of the University of Milano-Bicocca ethics committee and respected the ethics guidelines by the Declaration of Helsinki. Three simulated rooms are in red, blue and yellow lights respectively. An additional colour (e.g., white) served as a neutral condition (see Figure 1). The virtual scenarios were designed in Unity 3D (https://unity3d.com) and were presented with the Oculus Go headset (https://www.oculus.com) together with the questions about the scenarios. The participants used a controller to answer.


(1)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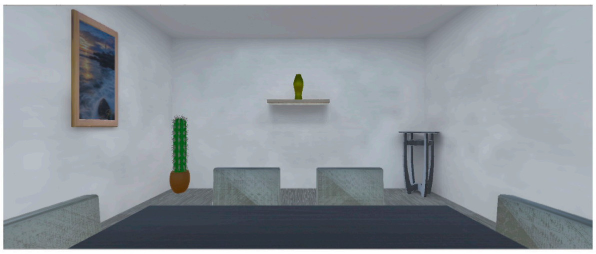

(4)

[Figure 1] *Four simulated virtual rooms in red(1); blue(2); yellow(3) and white(4) ambient light conditions*

3.3. Procedure and measurement

The experiment took around 15 minutes per person and was performed in a room with a constant temperature of about 22 °C. The participants sat at a table and for each condition were instructed to observe the ambient indoor room. When they reported being satisfied with and having acquired sufficient information about the environment, a series of questions were shown up within each virtual scenario. The order of presentation of the rooms associated with the lights, as well as the order of the questions, were randomised among participants. The evaluations mainly covered three aspects: (1) Thermal comfort; (2) Lights and ambient atmosphere; (3) Perceived context of room usage (Table 1).

[Table 1] *Sub-descriptive statements in experiencing simulated virtual rooms*

Category	Sub-descriptive statements			
Thermal comfort	Q1 This room is pleasantly warm.	Q2This room is pleasantly fresh.	Q3 It is too hot in this room.	Q4 It is too cold in this room.
Lights and ambient atmosphere	Q5 This room is cosy.	Q6 This room makes me feel stressed.	Q7 This light is pleasant.	
Context of use	Q 8 I would play with friends in this room.	Q 9 I would like to relax in this room.	Q 10 It is easy to focus in this room.	

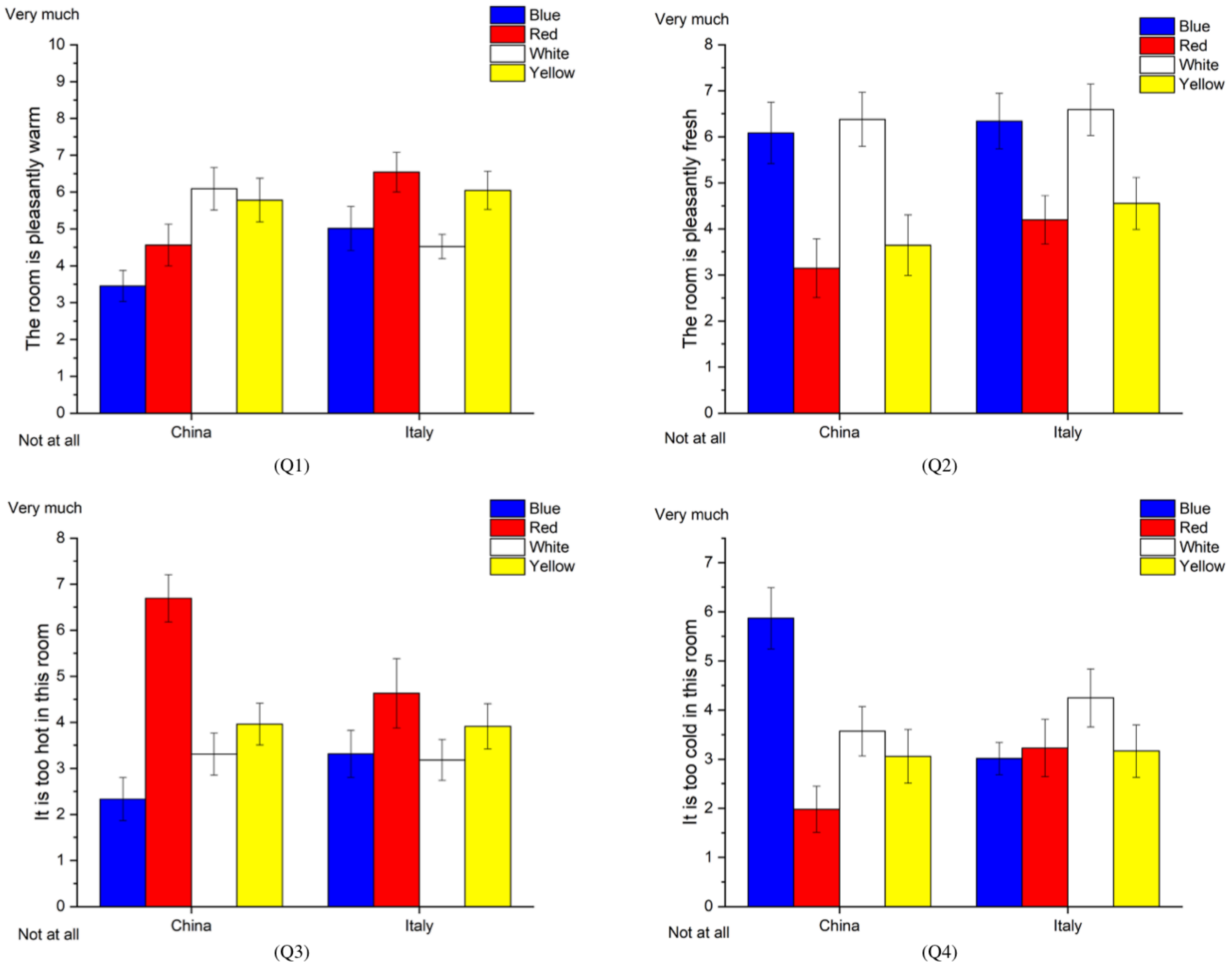
For each evaluation, the participants were asked how much they agreed with an affirmation on a visual analogue scale (VAS). This scale was anchored to the labels "not at all" and "very much", respectively placed on the left and right extremes. The cursor on the line was moved through the Oculus Go controller and subjects could interactively select the position of a slider which always appeared in the middle of the rating scale. For the data analysis, the colour lights (four levels: red, blue, yellow, white) and the nationality (two levels: Chinese and Italian) served as independent variables. The responses to the rating scales were used as dependent variables. Scores were obtained by measuring the cursor position along each scale. The subjects' scores for each question were submitted to separate mixed analyses of variance (ANOVAs), using "colour light" as within-subjects factor and "nationality" as between-subjects factor. The statistical significance level was set a $p<.05$ and significant effects were further analyzed by running HSD Tukey corrected posthoc tests.

4. RESULTS AND DISCUSSION

As shown in Figure 2, for Q1 – pleasant warmness, the significant main effect of *colour* [F(3, 84)=4.19, p=.008] indicated that the red (p=.05), white (p=.03) and yellow (p=.01) rooms were rated as pleasantly warmer than the blue-illuminated room. This result confirms the findings by previous experiments conducted in the real world (Hardin, 2000). For instance, a study conducted inside of an aircraft cabin showed that participants reported a higher temperature when exposed to yellow ambient light as compared to blue (Woldemedhin et al., 2013). The interaction effect of *colour*nationality* [F(3, 84)=3.06, p=.03] was significant as well and indicated that the difference between blue and white (with lower ratings for blue) was present for Chinese (p=.01) but not for Italians (p=.99). This result is similar to a comparative study on the colour-associations: 71% of Chinese subjects linked white with "cold," while 96% of American respondents linked to blue (Courtney, 1986). The main effect of *nationality* was not significant [F(1, 28)=1.33, p=.25]. Q2 – pleasant freshness: The main effect of *colour* was significant [F(3, 84)=9.08, p<.001]. The blue and white rooms were rated as pleasantly fresher than the red (both ps<.001) and yellow (respectively, p=.03 and p=.01). Similar findings are also found in package design, where blue and white are always selected for indicating the semiotic sense of freshness as in the case of yoghurt label due to a natural representation of sky (Ares et al., 2011). The effect of *nationality* [F(1, 28)=1.80, p=.19] and *colour* nationality* [F(3, 84)=0.44, p=.71] were not significant.

Q3 – too much hotness: The significant main effect of *colour* [F(3, 84)=13.12, p<.001] indicated that the red room was rated as more "too much hot" than the other coloured rooms (all ps<.001). The significant interaction *colour* nationality* [F(3, 84)=03.06, p=.03] revealed that this effect was present for Chinese (all ps<.001) but not for Italians (p>.05). The main effect of *nationality* was not significant [F(1, 28)=0.09, p=.75]. Q4 – too much cold: The main effect *colour* was significant [F(3, 84)=5.81, p=.001]: participants rated the room with blue light as colder than the red (p=.001) and yellow (p=.01) lights. Findings from Q3 and Q4 comply with the previously discussed hue-heat hypothesis. Likewise, a study on the cold-hot association showed that yellow and orange are prone to the scale of warmness, while red has the highest linkage to hotness. Also, blue is more associated with coldness and coolness (Lewinski, 1938). Another research on colour-concept matchings showed that red is associated with hotness and fire, also revealed red lights can refer to a very high-temperature sensation, even sometimes to the signal of danger, as compared to the comforting sense induced by yellow lights (Pravossoudovitch, Cury, Young, & Elliot, 2014). The effect of *nationality* [F(1, 28)=0.21, p=.64] and *colour* nationality* [F(3, 84)=2.25, p=.08] were not significant.

Q5 – cosiness: The main effects of *colour* [F(3, 84)=2.08, p=.10] and of *nationality* [F(1, 28)=3.28, p=.08], as well as the interaction effect of *colour* nationality* [F(3, 84)=1.34, p=.26] were not significant. While in Q6- stress, the main effect of *nationality* was significant [F(1, 28)=3.92, p=.05] and the Chinese sub-sample gave higher ratings than Italians. The main effects of *colour* [F(3, 84)=1.83, p=.14] and the interaction effect of *colour* nationality* [F(3, 84)=1.57, p=.20] were not significant. Q7 - light pleasantness, the significant main effect of *nationality* [F(1, 28)=7.52, p=.01] indicated that Italians gave higher ratings than Chinese. One interesting point worth mentioning is the impact of *colour* showed a trend toward significance [F(3, 84)=2.38, p=.07], which indicates that the white room received higher ratings than the blue (p=.07). The reason of this trend may be that white has a general reference to pleasant and positive traits (Clarke & Costall, 2008). The interaction effect of *colour* nationality* [F(3, 84)=1.98, p=.12] was not significant. Q8 – leisure: The main effects of *colour* [F(3, 84)=1.49, p=.22] and of *nationality* [F(1, 28)=0.24, p=.62], as well as the interaction effect *colour* nationality* [F(3, 84)=2.21, p=.09] were not significant. Q9 – relaxation: The main effects of *colour* [F(3, 84)=0.84, p=.47], of *nationality* [F(1, 28)=1.34, p=.25], and the interaction effect *colour* nationality* [F(3, 84)=1.50, p=.21] were not significant. Q10 – concentration: The main effect of *nationality* [F(1, 28)=6.67, p=.01] indicated that Italians gave higher ratings than Chinese. The main effect of *colour* [F(3, 84)=4.05, p=.009] indicated that the white room was evaluated as more suitable for focusing as compared to the red-illuminated room (p=.004). The result towards the attention is in agreed with a study of using white light is more appropriate for office settings than red and green colours (Kwallek & Lewis, 1990).



[Figure 2] *Mean responses to Q1, Q2, Q3 and Q4 (the error bars represent the standard error of the mean)*

4. CONCLUSION

The current study proved that indoor ambient light affects the human perception of indoor climate according to the colour-temperature association, together with its advantage for energy conservation. Besides, the effectiveness of different hues on perceived temperature, the preferred activities under different lighting conditions among two cultural groups are in demand of advanced investigation and explanation due to the limitation of this ongoing project (e.g., sample size, light exposure time, level of immersiveness in VR, manipulation of other environmental factors, and etc.). However, the adoption of VR as a research tool for study human-environment interaction is validated since the finding is following previous studies that were conducted in a real-world setting. Future development of the study could be the integration of different hues, control of photometric parameters, the collection of physiological data, and more sophisticated analyses.

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