

Testing Multisensory Stimuli to Drive Thermal Comfort and Space Perception using VR/AR: A Design Strategy to Achieve Energy Saving

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Abstract: Energy consumption of the EU has a crucial environmental impact; several efforts are nowadays thus directed into massively reducing energy consumption by envelope improvement, system efficiency and smart control. On the other hand, the indoor thermal and lighting conditions significantly influence users' wellbeing and productivity, which is especially important when dealing with educational and working facilities. Strategies to enhance system efficiency are focused on design and construction aspects. These strategies ease to promote a powerful approach which is needed when focusing on existing buildings in need of retrofit measures. When dealing with new or refurbished buildings, energy saving has a further step to achieve. In the last years, research trends moved towards an increasing inclusion of human factors in energy evaluation. This allows to account for the occupancy variability in the energy analyses, considering how to bridge the performance gap between predictive models and actual consumptions due to indoor thermal settings. In empty buildings energy consumption is huge and economic efforts are wasted, due to unconscious energy-wasting behaviors. Previous studies with Interactive Virtual Environments confirmed that indoor environments illuminated by different color lights lead to the perception of different levels of thermal comfort. The results of the present paper replicate previous evidence collected in real

conditions, suggesting that Virtual Reality is a valid and reliable tool to assess thermal comfort more quickly and cheaply. This paper provides a further perspective on this topic, including also the use of different fragrances to understand how the indoor environment could be enhanced and manipulated to increase wellbeing, thermal perception and finally energy saving.

Keywords: Energy saving, Virtual reality, Multisensory stimulation

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1 Introduction

Heating and cooling our buildings require a considerable amount of resources: in the European Union (EU), the energy consumption of houses, offices, shops and other buildings accounts for nearly 40% of the final energy consumption^[1]. For these reasons, with the aim of improving buildings energy efficiency, the EU is now discussing about the concept of Nearly Zero-Energy Buildings (NZEBS), which should be introduced by 2020^[2]. However, thermal comfort is a crucial factor influencing the occupants' wellbeing; therefore, energy conservation goals should be pursued without affecting negatively this fundamental aspect. Many

research efforts have been dedicated to the development of different strategies for energy saving, including an improvement in buildings design and the use of high-performance materials, as well as the adoption of smart control devices^[3]. However, it has been acknowledged that users' behavior also plays a decisive role in determining the consumption of energy resources, and that it is affected by several factors. Awareness is certainly one of these factors since people are often unable to see the impact of their actions on energy waste^[4]. Indeed, energy visualization is among the main research trends to support sustainable behavior: a relevant example, considering this specific context, is the use of thermal images to visualize heat escapes as proposed by Goodhew et al.^[5]. Nevertheless, one of the most popular strategies for resources visualization is the implementation of light feedbacks. For example, Arroyo et al.^[6] investigated the use of the latter to communicate water waste and temperature, while Gyllensward et al.^[7] showed how lights can be used to represent the consumption of a radiator. However, lights are not only able to raise users' attention and display energy use: they are also capable of affecting people's perceived thermal comfort. In fact, previous studies demonstrated that ambient colored lights convey a feeling of warmth or coldness according to what are defined as "conventional" color-temperature association, which lead people to link 'warm' colors (e.g. red, yellow) to 'warm' temperatures, and 'cold' colors (e.g. blue, green) to fresher ones^[8,9]. This effect could be leveraged to moderate the need for thermal regulation in buildings and, at the same time, to maintain a good perceived thermal comfort for the users^[10,11]. In a similar way to the cited studies, in our previous works^[12,13], we tested the effect of colored lights, introducing the use of Virtual Reality (VR) to perform the experiments. In fact, the use of VR to evaluate different design configurations presents many advantages, as the implementation of physical prototypes generally requires additional efforts and resources. Our results were consistent with previous studies conducted in real environments^[14], showing a correlation between colors and the perceived thermal comfort. In this work, we tested the use of additional olfactory stimuli to investigate the interaction between colored lights and smells. It is worth noting that colors are not only associated to temperatures, but also to smells, according to the objects which users link to the odor^[15]: for instance, the lemon scent is matched to the

color yellow, while peppermint is matched to green shades. Perception is in fact always the result of the integration and interaction among the inputs originating from the different sensory modalities^[29]. For this reason, smells could alter and enhance the sensation provided by colors, affecting the human-perceived comfort in synergy with the colored lights. Moreover, the thermal sensation provided by smelling is also affected by the color of the smelled object^[16]. However, the specific interaction between olfactory stimuli and thermal comfort, has not been investigated yet. In this study, we used two different scents associated with the sensations of warmth and coldness. We presented them within the Virtual Environments (VEs) validated in our previous studies^[12,13] and where different lighting conditions were presented. The results of this study confirmed that colored lights can affect perceived comfort, while the addition of the scents did not have a significant effect.

2 Related work

It is thought that the "conventional" color-temperature associations originate from our experience with natural elements: in fact, we commonly relate the color red to a hot temperature since fire is red, while we would define yellow as warm since it is the color of sunlight, blue as cold because of the oceans and green as fresh, reminding forests and vegetation^[17]. Even though we could imagine this association process as natural and intuitive, culture also plays a fundamental role: young children do not perform these association as adults^[18], while in some African countries the relationships between red-hot and blue-cold are reversed^[19]. Nevertheless, in most of the world and for most of the population these associations are strong and widespread, as we can notice by observing our products interfaces (e.g. tap knobs). This could explain why studies investigating the thermal effects of saturated colors, which have a clear correlation with temperatures, have often proved their effectiveness, while the use of less saturated colors or warm/cold whites obtained contrasting results. Considering the use of different warm/cold whites, partially positive results were found by Huebner et al.^[20], who describe an actual change of participants' behavior, consisting of wearing extra clothes when exposed to a cold light. Conversely, the findings reported by Kulve et al.^[21] and Baniya et al.^[22] were not supportive of this finding. Instead, Winzen et al.^[23] tested the use of blue and

yellow light in an aircraft cabin, finding that these colored lights affect thermal sensation. Similarly, Fanger et al.^[24] compared the use of red and blue lights: subjects preferred a lower temperature when exposed to the red one. Moreover, vivid wall colors present similar effects to the analogue colored lights, as shown by Wang et al.^[19]. However, these authors reported that users did not appreciate the vivid colors. In fact, while less saturated colors are associated with calmness, more saturated ones can generate anxiety^[25]. However, when colors are presented through lights, many other aspects should be considered, given that light affects human perception and wellbeing in several ways. First of all, visual comfort is related to the color of light, intensity, luminance distribution and amount of natural daylight experienced^[26]. Mood can also be affected by light in different ways depending on gender, with negative mood decreasing for females in warm lighting conditions, and positive mood improving for males exposed to cold lights^[27]. Moreover, the choice of a certain kind of light also depends on the context where it is presented. Time is perceived negatively (i.e. waiting time seems longer) in warm lighting conditions^[25], then it may not be suitable for areas dedicated to services. The combination of illumination and light temperature affects cognitive performances^[27]: this is relevant for working and studying spaces. Emotion, sociability and behavior are also affected by light^[28]; hence this fact should be considered when designing environments where people are supposed to meet, discuss or collaborate. All these aspects should be addressed in order to take advantage of the thermal effect of colored lights without compromising users' wellbeing. This aspect is not trivial since the concept of comfort is also influenced by individual features (e.g. age and gender) and by contextual factors (e.g. kind of building, season of the year)^[26]. However, a possible solution could be related to enhancing the thermal effects of colors by using a multisensory approach. This would allow to use more pleasant and delicate color shades and empowering them through other stimuli. In fact, our experiences with products and environments are based on the interaction between our senses, as we integrate information from different sensory modalities. For instance, our tactile exploration of a product surface is affected by what we are smelling, hearing and seeing at the same time^{[29][42]}. In particular, olfactory stimuli could potentially amplify the thermal effect of colors. Indeed, smells are associated with colors,

as they recall objects which certain color properties. Scents of food or other products having strong odors (e.g. glue, nail polish remover), are associated with the food or product color or to their common packaging color^[15]. Nevertheless, this color-odor association may be influenced by culture, as shown by De Walk et al., which compared linguistically different groups^[30]. Colors also affect the perception of odors: the intensity and pleasantness of a coherent presentation of odors and scents (e.g. strawberry-red) are evaluated higher than those of a contrasting association (e.g. strawberry-green)^[31]. Considering the thermal aspects, it has been shown that smelling red liquids gives a sensation of warm, while green solutions provide cooling sensations^[10]. Moreover, there is a correlation between the hue of the colors and the temperature associated to scents: however, the relationship between scents and temperature seems to be related to the gustatory sensations (cool, refreshing, hot, and spicy) of foods^[16]. As we discussed, the use of lighting has a great potential in affecting the perceived thermal comfort, but it requires to manage a great complexity due to the several aspects which colors and light influence. This study originates from the idea that a multisensory approach based on the integration of olfactory stimuli could then support the use of a particular lighting condition while limiting or moderating the possible side effects. Specifically, we expect that the interaction between "warm" color lights and scents increase the thermal comfort perceived as compare to the "cold" ones.

3 Methodology

The study has been organized with two levels of investigation considering a traditional survey analysis using only the visual input and a virtual reality simulation involving an immersive environment with a multisensory apparatus, able to submit visual, immersive and olfactory stimuli. The double test on the same questions (Table 1) has been used to measure the enhancement of the experience of the users considering a POE (pre occupancy evaluation). We tested the following hypotheses: could the effect of light color be appreciated starting with the visual image and one-dimension experience? How much is the increased perception of the actual situation through the IVE? Does the commonly adopted color codes suggest a cultural response and how this response is it mainly affected by the real-time experience?

3.1 Virtual reality simulation

3.1.1 Participants

Twelve volunteers (6 F; mean age: 25.5; age range: 20-44) took part in the study. All the participants reported normal or corrected-to-normal vision, and normal olfactory perception. The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki and received the approval of the University of Milano-Bicocca ethics committee. All the participants gave their informed consent before entering the test.

3.1.2 Apparatus and stimuli

Oculus Go headset was adopted for presenting the participants with the virtual scenarios, which were built in Unity 3D^[32]. These scenarios consisted of four living rooms of the same dimensional layout

and furnished with the same kind and number of items, only varying in aesthetic features. To achieve considerably standardized scenarios, the four testing rooms included basic elements such as a table, some chairs, a painting on a wall and a plant. The rooms were illuminated by different color lights (red, blue, yellow and neutral white; see Figure 1), which originated from a ceiling lamp, similar to a led panel, whose dimension, position (at the center of the ceiling) and intensity were kept constant in all the conditions. Olfactory stimuli were delivered through a scent diffuser made by Oikos Fragrances^[33], which also provided us with a wide range of scents. Two scents, named as “Amber & Wood” (including patchouli, amber and musk) and “Sea Breeze” (composed of lilac, lily of the valley and rose), were selected as respectively representative of warmth and freshness sensations, as discussed in^[10].

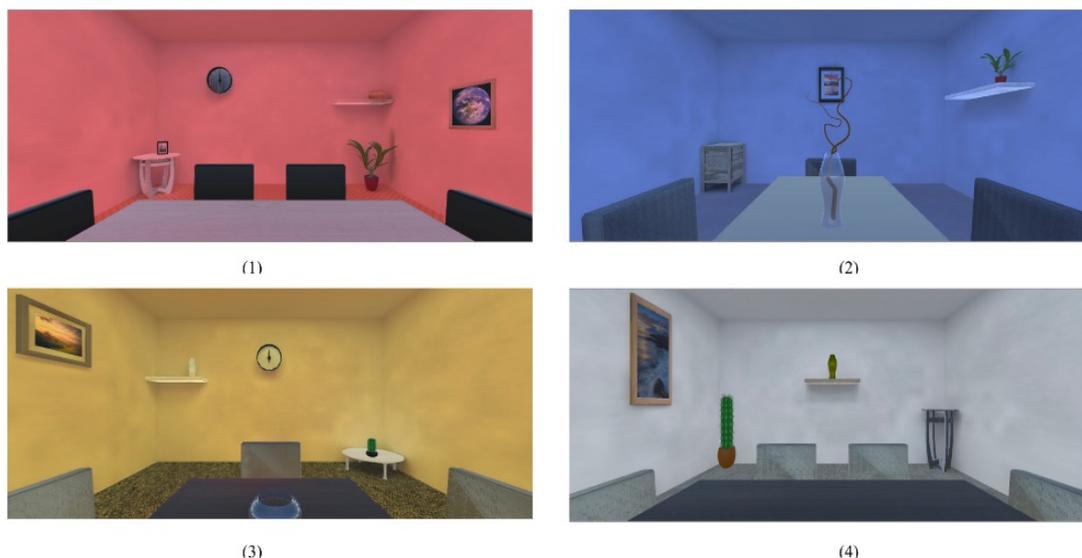


Figure 1. Front view of four testing rooms in: (1) red lights; (2) blue lights; (3) yellow lights; and (4) white lights.

3.1.3 Procedure

The study was performed in two silent and small rooms (size: 1.5 x 1.5 m) with a temperature of about 22°C. The participants explored the four virtual rooms twice: once in Room 1, where Scent 1 (“Amber & Wood”) was delivered, and once in Room 2, where the Scent 2 (“Sea Breeze”) was delivered. The entering order in Room 1 and Room 2 was counterbalanced among participants. After being presented with general information about the experimental procedure, the participants sat at a desk in one of the two rooms and wore the VR headset. For each condition, they found themselves seated at a table in a well-organized room and were invited

to look around the virtual room for as much time as they wished. In all the virtual rooms, the observer was placed in the same position, always having the same point of view on the room. After each session of virtual room exploration, the participants took off the headset and filled out a questionnaire on Qualtrics platform (Proto, UTA, USA,^[34]).

3.1.4 Survey

The survey was composed of eleven questions belonging to three categories: thermal comfort, lights and ambient atmosphere, and context of use (see Table 1 for the question list). The first category investigated how lighting can affect the perceived temperature; the

second assessed the effects of lights and scents on the general comfort, aesthetic appreciation and mood; the third explored the suitability of the lighting condition for a particular context (e.g. work or leisure activities). Each question was answered through a visual analog scale (VAS) anchored to the labels “not at all” (placed on the left extreme of the scale) and “very much” (placed on the right extreme). The evaluation was provided through a mouse and the cursor was always initially placed in the middle of the scale. When the participants explored and evaluated all the virtual rooms in Room 1, they moved to Room 2 and underwent the same procedure. Throughout the experiment, the colored lights were randomly combined with the similarly-furnished rooms. Moreover, the delivering orders of the four lighting conditions, as well as of the questions, were both randomized.

Table 1. List of questions.

Thermal comfort
Q1 This room is pleasantly warm
Q2 This room is pleasantly fresh
Q3 It is too hot in this room
Q4 It is too cold in this room
Lights, scents and ambient atmosphere
Q5 This room is cozy
Q6 This room makes me feel stressed
Q7 The light is pleasant
Q8 The scent is pleasant
Context of use
Q9 I would like to relax in this room
Q10 I would hang out with other people in this room
Q11 It is easy to focus in this room

3.1.5 Data analysis

The color lights (red vs. blue vs. yellow vs. white) and the scents (amber & wood vs. sea breeze) served as independent variables. The responses to the rating scales were used as dependent variables. These scores were obtained by measuring the position of the cursor along each scale (0-100). The participants’ scores for each question were submitted to separate repeated measures analyses of variance (rmANOVAs), using “color light” and “scent” as within-subjects factors. The significance level was set at $p < .05$ and significant effects were further analyzed by running HSD Tukey corrected post-hoc tests.

3.2 Visual simulation

3.2.1 Participants

Ten volunteers (3 F, 7 M; mean age: 26.6; age range: 24-29; 5 Countries; 2 technical backgrounds including engineers and architects) participated to the visual survey online analyzing the same space with different lighting using white, blue, red and yellow colors answering the questions in Table 1. All the participants reported normal or corrected-to-normal vision. All the participants gave their informed consent before entering the test.

3.2.2 Scenario, procedure, survey

A learning space has been adopted as reference image and the different color light (Figure 2) have been evaluated through the previous survey questions about: 1) Thermal comfort (Q1, Q2, Q3, Q4); 2) Light and ambient atmosphere (Q5, Q6, Q7); 3) Context of use (Q9, Q10, Q11).

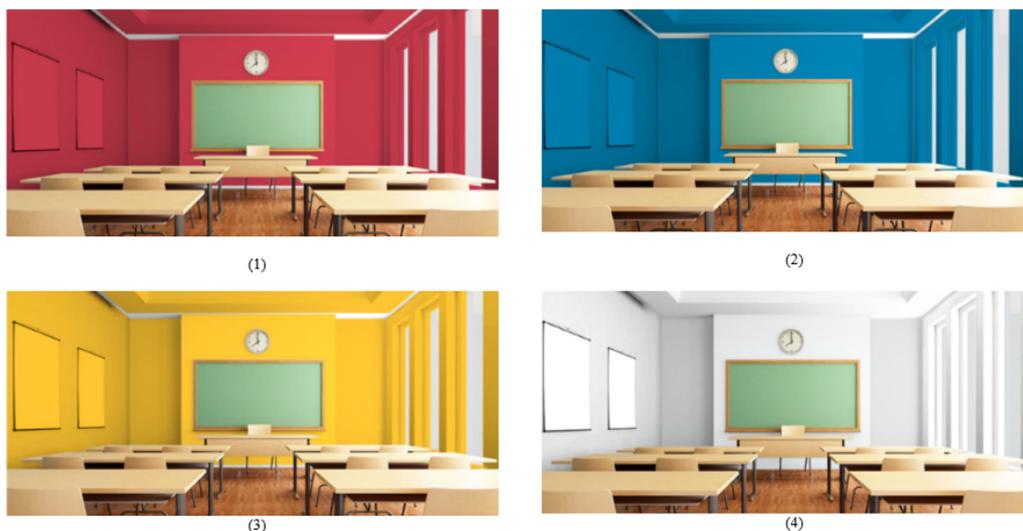


Figure 2. Front view of four testing images in: (1) red lights; (2) blue lights; (3) yellow lights and (4) white lights.

3.2.3 Data analysis

The answers have been collected as online questionnaire and the distribution of the evaluation in a scale from 0 to 5 (Not at all, Slightly, Moderately, Reasonably, Very, Very much) and evaluation have been compared for the four lighting situation to estimate the main sensation and thermal perception for the different spaces.

4 Results

4.1 Virtual reality simulation

The Mean responses to: 1) Thermal comfort questions (i.e., Q2, Q3); 2) Lights, scents and ambient atmosphere (i.e., Q6); 3) Context of use (i.e., Q9 and Q11); are reported in Figure 3 while these three sections are discussed in the following paragraphs.

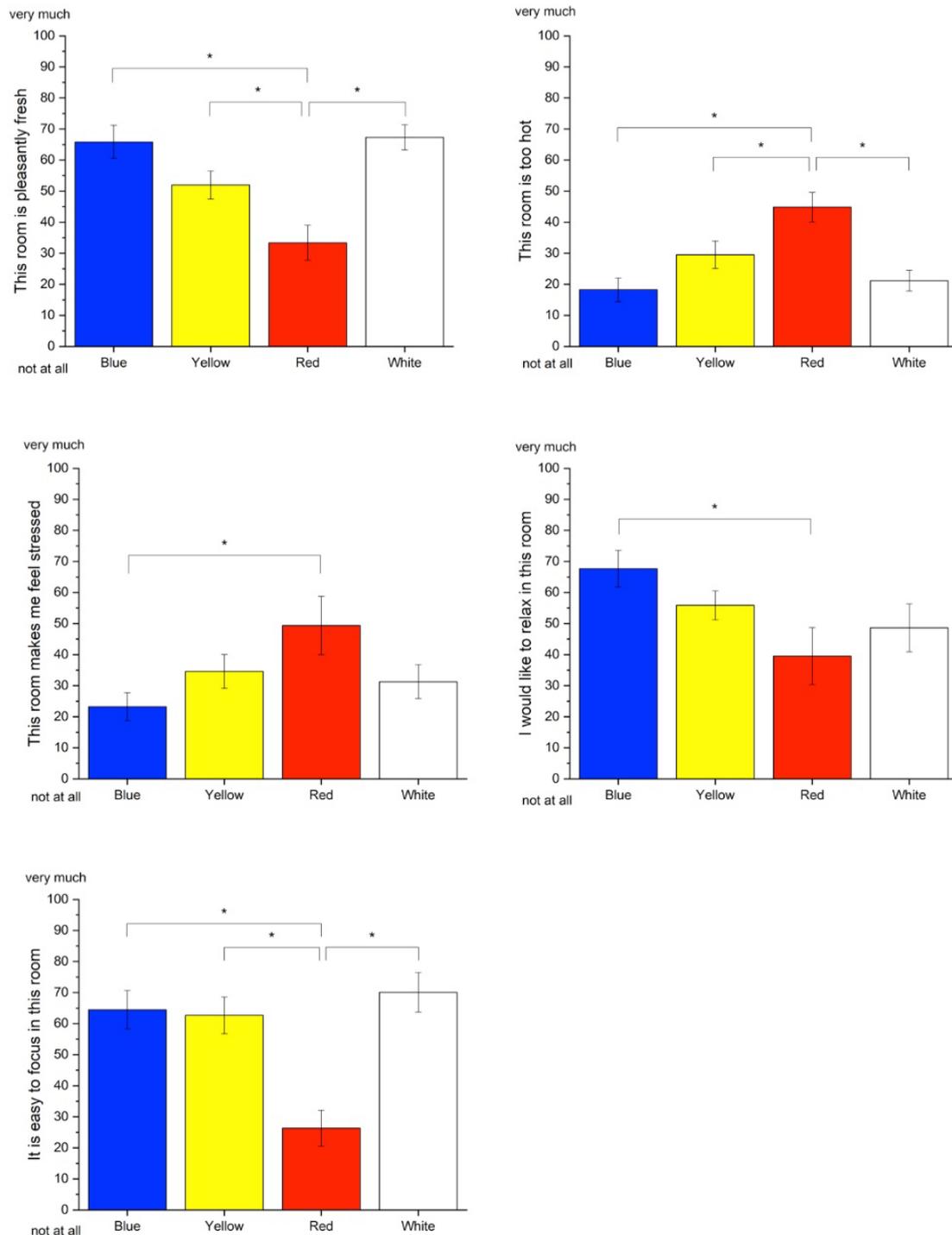


Figure 3. Mean responses to Q2, Q3, Q6, Q9 and Q11 (see also Table 1). The errors bars represent the standard error of the mean and asterisks indicate statistical significance.

4.1.1 Thermal comfort

Significant differences among the color lights were found for Q2 - pleasant freshness [$F(3, 33)=10.01$, $p<.001$] and Q3 - too much hotness [$F(3, 33)=10.16$, $p<.001$], but not for Q1 - pleasant warmth [$F(3, 33)=1.96$, $p=.13$] and Q4 - too much cold [$F(3, 33)=.80$, $p=.49$] (see Figure 2). The red light made participants rate the room as less pleasantly fresh and as hotter than blue (both $ps<.001$), yellow (respectively $p=.05$, $p=.03$) and white (both $ps<.001$) lights. The scent presentation did not affect the results. The interaction effects between color lights and scents were not significant as well.

4.1.2 Lights and ambient atmosphere

For Q6 - stress, a trend indicated the presence of significant differences among the color lights [$F(3, 33)=2.82$, $p=.053$]. The red light made the participants feel as more stressed than blue ($p=.03$). No significant differences among the effects of color lights were found for Q5 - coziness [$F(3, 33)=1.72$, $p=.18$], Q7 - lights pleasantness [$F(3, 33)=1.38$, $p=.26$] and Q8 - scent pleasantness [$F(3, 33)=.81$, $p=.49$]. Neither the scent presentation nor the interaction effects between color lights and scents, were significant.

4.1.3 Context of use

Significant differences among the color lights were found for Q11 - concentration [$F(3, 33)=10.02$, $p<.001$] and a trend indicated a difference for Q9 - relaxation [$F(3, 33)=2.29$, $p=.09$]. The red light was evaluated as less suitable for concentrating than blue, yellow and white light (all $ps<.001$), and as less suitable for relaxing than blue ($p=.07$). No significant differences among the effects of color lights were found for Q10 - leisure [$F(3, 33)=.95$, $p=.42$]. The effects of scent, and the interaction between color lights and scents, were not significant as well.

4.2 Visual simulation

4.2.1 Thermal comfort

About Q1, the white lighted room has been evaluated as pleasantly warm in the 40%. The yellow lighted room has been strongly (very much) indicated as pleasantly warm in the 40% reaching the 60% considering the score reasonable. For the red lighted room the highest scores are about 60% with 40% very and very much. About Q2 a high (very) perception of freshness has been attributed to white lighted room (50-70%), blue

lighted room (20-50%) and yellow room (30-50%). About Q3 the highest evaluations have been given to the red lighted room (40-70%) and to the yellow room (10-40%). About Q4 the highest evaluations have been given to the white (20-40%) and blue (30-60%) lighted rooms which is the only one with the maximum score (very much) in the 30% of the responses. Results are summarized in Figure 4.

4.2.2 Lights and ambient atmosphere

About Q5 the room has been evaluated as cozy when white lighted in the 30-60% of the responses with the higher scores, blue lighted only in the 10% (very much), red lighted in the 20% and the yellow lighted room in the 50% of the responses (30% very much and 20% very). About Q6 dealing with the concept of stressful environment the white lighted room gained a 20% of responses with the highest scores, the blue lighted room has 10% (very) and 10% (reasonable) while the red lighted room has 40% including the highest evaluations given by the participants. The yellow lighted room has a 20% of very much responses and 10% of reasonable. About the Q7 the light is defined as pleasant in the case of the white lighted room in the 30-70% of the responses with the highest scores, only 10% for the blue lighted room, 20% for the red lighted room (very) and 20-60% for the yellow lighted room (very much and very) (Figure 5).

4.2.3 Context of use

The Q9 states that the room is relaxing and it has been evaluated very much and very for the white lighted room in the 20-50% of the responses, 20-40% for the blue lighted room, 20-30% for the red lighted room and 20-40% for the yellow lighted room. About Q10 the white lighted room gains 30% (very), the blue lighted room 10-40%, the red lighted room 20-40% and the yellow lighted room 30-60% (very much and very scores) (Figure 6).

The results of the visual simulation gave some first but significant insights about the perception of warm and cold related to color light and possibly also about features of the indoor environments that can boost a positive influence on the users' activities. The color of light can be perceived as first through the visual input that promote the association with thermal and psychological feelings. The limit of this kind of study is the one-dimensional communication; however the establishment of complex perception is activated also starting with the visual input. The VR allows creating

an immersive experience that strengthens the effect. It should be underlined that a strongly colored light has

to be carefully evaluated considering the standard of visual comfort.

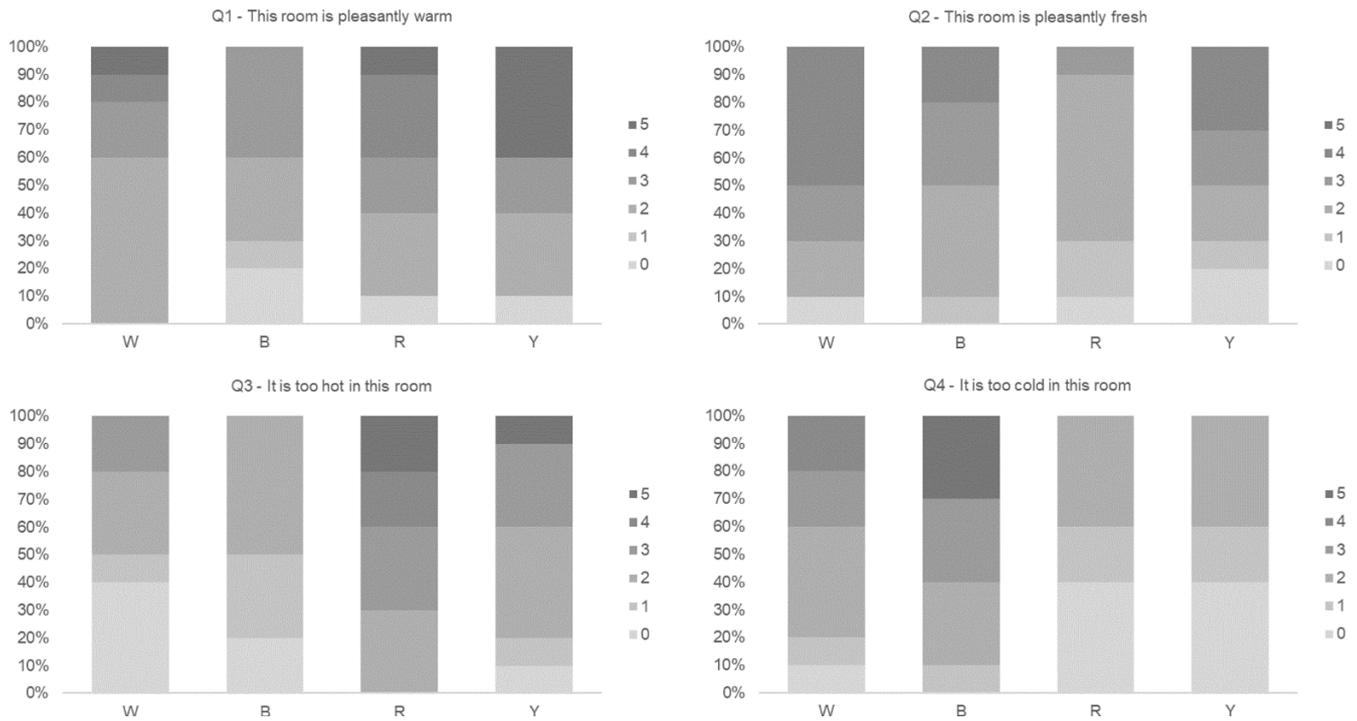


Figure 4. Responses distribution to Q1, Q2, Q3, Q4 (see also Table 1).

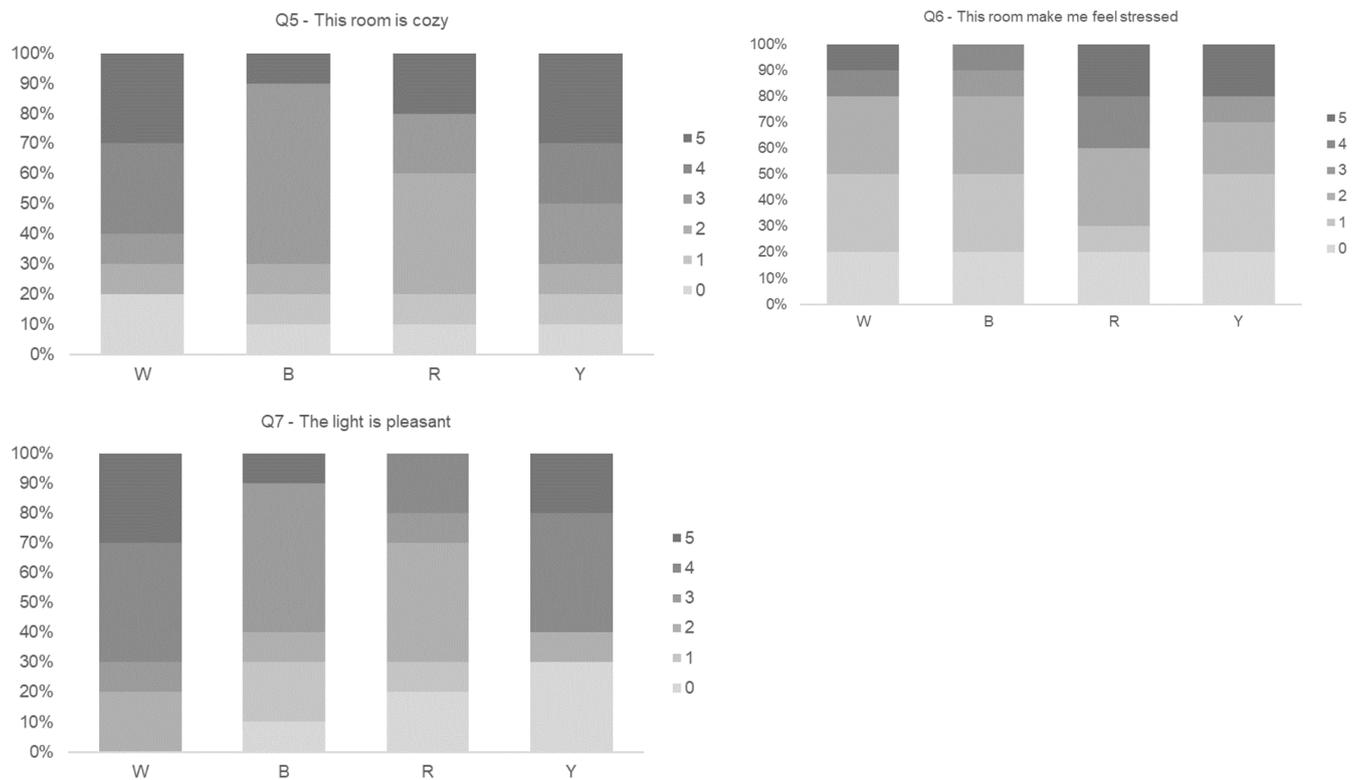


Figure 5. Responses distribution to Q5, Q6, Q7 (see also Table 1).

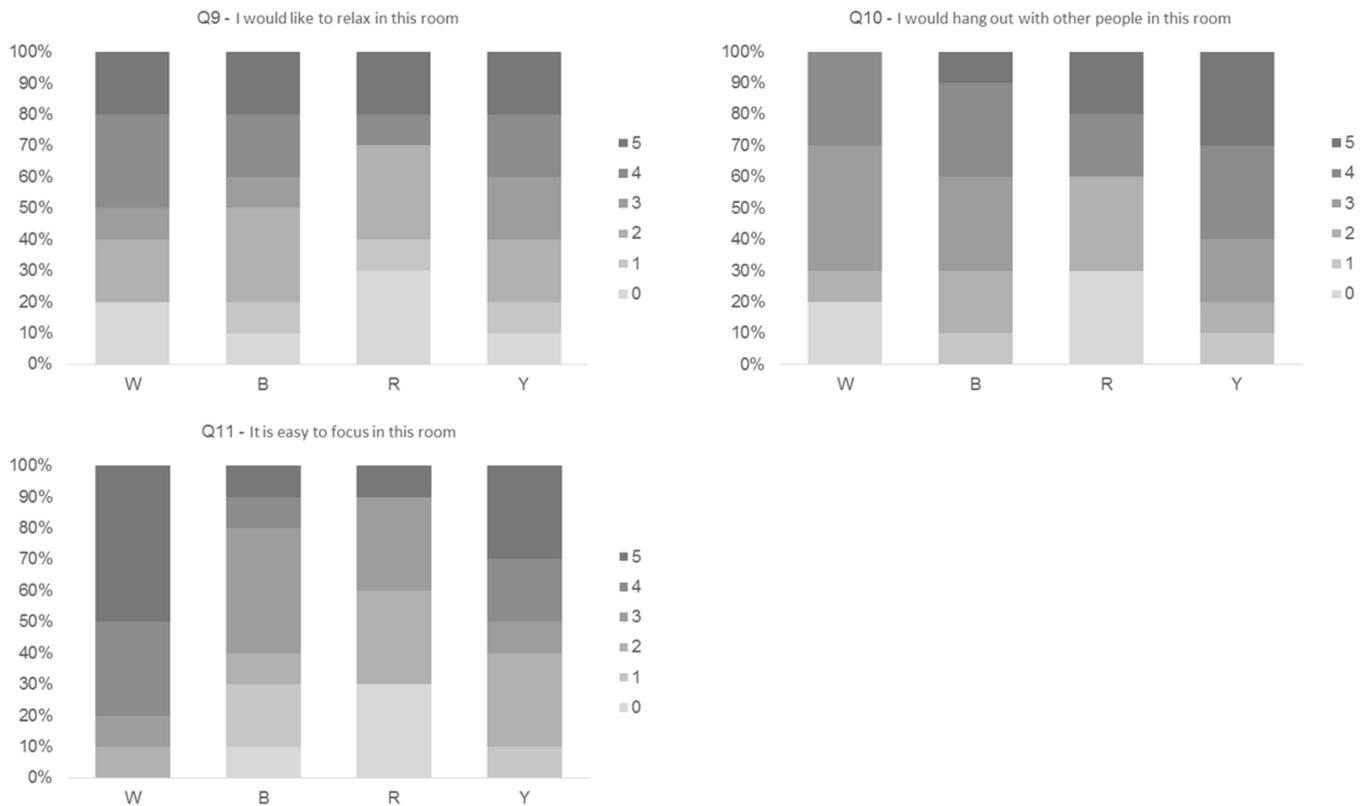


Figure 6. Responses distribution to Q9, Q10, Q11 (see also Table 1).

5 Conclusions

The present study aimed at investigating the effects of different color lights and scents on the perception of thermal comfort of indoor environments. In order to test various experimental conditions, we created VR simulations that led indeed to the modulation of the perception of thermal comfort. Even though users were exposed to the virtual rooms for a considerably short time (in most of the cases less than one minute), and despite the fact that virtual environments are less ecological than real-world ones, these results replicate previous evidence of our VR studies^[12,13]. Also, they confirm that VR is a valid and reliable tool to assess thermal comfort in a quick and economical way, since it permits to manipulate many variables, control and test them more easily, presenting a variety of environments which would not be possible in the real world. Specifically, as regards the feeling of warmth/hotness, the rooms illuminated by the red light were rated as the hottest and the least pleasantly fresh one, compared to the blue, yellow and white ones. Previous studies^[23,24] highlighted how blue and white convey a sense of low temperatures while yellow and red convey a sense of high temperature. Particularly, our

results are in line with the idea that red is likewise linked to a feeling of excessive hotness. This can be explained by the associations that people tend to create between natural colors and temperature, which lead to match red color to fire, yellow one to the sunlight, green with forests and vegetation, and blue with water and oceans^[17]. As concerns the ambient atmosphere, environments enlightened with red lights made participants feel more stressed, especially compared to blue lights. In fact, room color was found through previous studies to have specific effects on psychomotor activity and emotional states. For example, correlations were found between red room color and emotional and physical stimulation, while blue and green are associated with inhibitory effects^[36]. This study also aims at assessing whether, and if so, how different color lights and fragrances influence the activity that a person might intend to perform indoor and under an ambient atmosphere. Regarding this point, the results from color lights revealed that the red illumination led to a perception of the environment as the least suitable of all for concentration and as less suitable for relaxation than blue. Our data comply with previous studies which hypothesized that the context affects the mood and how users perceive the environment,

the lighting condition and the thermal comfort itself^[11]^{[26][37]}. On the other hand, the scent presentation in all three categories (thermal comfort; lights and ambient atmosphere; context of use) did not affect the results, as well as the interaction between color lights and scents. This lack of effect could be explained by the use of mixed fragrances (patchouli, amber and musk for the warm one; lilac, lily of the valley and rose for the fresh one). In fact, Zarzo^[38] ran an experiment to classify each single scent according to the perceived freshness, but there is still poor evidence about mixed fragrances. Further studies need to investigate the use of combined scents, to establish if different odors can strengthen or reduce the effects of single scents. Our results suggest that smell is a complex multidimensional perception difficult to measure and describe. Furthermore, sensory ratings on a scale of freshness are difficult to obtain because the fresh dimension of olfactory perception is not well understood yet. On the other hand, there is also a well-known phenomenon named olfactory fatigue (or olfactory adaptation). Sensory adaptation is the reduction of sensitivity following stimulation, and is common to all senses, although it is more striking in some senses (i.e., olfaction) than in others (e.g., hearing). Adaptation is thought to be an important functional mechanism preventing overflow by neural activity resulting from stimuli that are either too strong or of long duration. Thus, it helps the organism to remain alert for new information^[39]. Furthermore, there is another phenomenon known as cross-adaptation that happens when the exposition to a scent A is followed by an exposition to a scent B, so that the adaptation to A leads to an adaptation to B^[40]. For example, it often occurs in perfumeries when we try different perfumes. In the present study, olfactory fatigue and cross-adaptation might have led to a reduced impact of the scent on the perception of warmth or freshness. In order to avoid those issues, future researches need to involve odorant amplifiers that exploit pulse ejection, and a longer period in which there is no olfactory stimulation, as suggested by Kadowaki and colleagues^[41]. Although the present study represents only a very preliminary investigation on the possibility of using color lights and fragrances in VR simulations to modulate thermal comfort, the results suggest the need for further investigations. Therefore, this research has to be intended as a starting point for follow-up studies to evaluate the role of other environmental factors (e.g., outdoor climate and seasons, room

temperature, performed tasks, aesthetic and functional quality of the environment).

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