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Evaluating thermal perception of different wall colors in workplaces using virtual reality

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Abstract: People spend most of their time in their homes, workspaces, health care facilities, educational spaces, or even recreational ones. The research problem focuses on how their thermal comfort and sensation of colors will be affected contributing to a higher demand for heating and cooling which consume a massive amount of energy. Since walls are considered the largest area that people are exposed to in interior spaces, this study aims to investigate the effect of wall colors on users' thermal perception and sensation. The methodology involves a comparative analysis of different scenarios of wall color conditions, accepting or rejecting the hue heat hypothesis. This was performed by testing the influence of two walls colors (red, blue), representing warm and cool colors respectively, with two indoor air temperatures (23–33 C) on participants' thermal sensation and comfort in a virtual environment of a shared office room. The use of virtual environments allows them to perform the experiments easily and economically in controlled environments with less effort than applying them in real environments. The results showed that wall color could affect the thermal comfort perceived in different room temperatures, red color was more comfortable for subjects in cold environments while blue one was more comfortable in warm environments. Future work shall investigate a wider range of colors and temperatures to address design guidelines helping to optimize occupants' thermal perception against their actual thermal conditions to minimize energy use.

Keywords: Wall colors; Thermal comfort; Virtual reality; Workplaces.

1. Introduction

According to the Organization for Economic Co-Operation and Development in developed countries, the average annual working hours of a full-time employee is about 1734 hours, which means around 36.8 hours weekly [1]. Since most workdays are spent indoors, it's critical to design productive, efficient, and comfortable workspaces. It improves employees' wellbeing and productivity, maintaining an aesthetically pleasing, comfortable and healthy environments which is considered as a way to mitigate climate change by reducing energy consumption.

It is widely documented and known that indoor environmental quality has an impact on employees' well-being and productivity [2]. According to Al Horr et al., there are eight environmental factors that mostly affect occupants' comfort: ventilation and indoor air quality, lighting and daylighting, thermal comfort, noise and acoustics, layout of the workplace "office", biophilia and views, look and feel, location and amenities [3].

Additionally, while focusing on thermal comfort, it's found that air movement, relative humidity, occupant clothes, dry-bulb temperature, mean radiant temperature, and physical activity (metabolic rate) are the six main elements influencing thermal comfort, according to thermal comfort theory [4,5]. Ambient temperature for example affects humans' thermal sensation, there are physiological explanations regarding this. The body will need additional cooling when the temperature rises in a normal environment. Blood flow is directed closer to the skin's surface in higher temperatures to allow blood to cool down. Because of this, in environments that have higher temperatures, the human heart beats faster to encourage blood circulation and regulate body temperature [6].

As stated in ASHRAE Standard, "thermal comfort is a condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". This condition of mind could be influenced by other sensory stimuli, individual preference, and psychology in addition to the six elements discussed [7]. Our knowledge of the process behind thermal comfort is being improved thanks to the continuous research on the topic, promoting relevant theories and models, and offering energy-efficient solutions for establishing the appropriate temperature perceived under various circumstances.

1.1 Research Problem

What is more interesting is the investigation of color effect on temperature perception in interior spaces and occupants' thermal comfort in return. Colors are related with psychological meanings, which evoke various emotional feelings such as excitement, energy, and calmness. Thanks to the "hue-heat hypothesis," which has been around for over a century [6], it has also been established that an object's color affects their perceived temperature. The hue-heat hypothesis indicates that there is a psychological difference between "warm" and "cool" colors. It takes into consideration how an object's color affects one's subjective perception of temperature. On fact, this theory states that colors on the red and blue ends of the visual spectrum are viewed as warm and cool, respectively. Researchers have recently shown an increased interest in this topic, seeking to determine whether and to what extent the use of warm and cool colors in interior spaces, whether through furnishings, walls, or lighting, can improve users' perception of their actual temperature and eventually result in energy savings. Nevertheless, the research in this field is still in its early stages and the findings are conflicting and inconsistent [6,8]. Some studies already validated the hue heat hypothesis, providing significant results concerning comfort optimization such as the research of Fanger et al study which supported that color has a slight impact on human comfort [6]. Additionally, D'Ambrosio Alfano et al. conducted experiments in a test room with various Correlated Color Temperature (CCT) of luminaires with results supporting the hue-heat hypothesis [9]. However, others did not find any consistent impact of colors on the perceived room temperature or thermal comfort [6].

1.2 Research Objectives

As a result, this research aims to study the relationship between thermal perception and colored walls which is still ambiguous according to recent research. The approaches, methodologies, and color manipulation techniques used in earlier research make it more difficult to compare studies and establish conclusions [6]. But as stated by Albers et al and Hettiarachchi et al, Color has very little effect on temperature and comfort level, but when used frequently it may have a quantitative effect on energy savings [6,10]. Nowadays, the 0.4 °C difference found in Fanger's study may also result in measurable energy saving towards a comfortable building thermal environment.

And since it's hard to test different colors physically, virtual reality "VR" is a valid tool to simulate different alternatives, designs, and configurations of a real space in a virtual scenario going beyond the limitations of the physical model [11]. There are key benefits and differences of the technologies and techniques that have been utilized so far to assess the comfort-oriented designs as they are: inexpensive, repeatable, quickly, and easily accomplished. Over the past two decades, there has been a growing recognition of the potential of Immersive Virtual Environments (IVEs), such as ones based on head-mounted displays that offer a realistic experience, to aid in the designing, building construction, and the management of the built environment [11]. Multiple studies have demonstrated that IVE may offer an appropriate technique for investigating human behavior by examining how people interact, perceive their surrounding environment, and their habits whether in constructed, unbuilt, or maintained contexts [12,13].

This research performs an experiment suing VR to test the influence of wall colors on thermal perception and it's null hypothesis "H0" is that wall color can affect Body Temperature "BT", Heart Rate "HR", Thermal Sensation Votes "TSV", Thermal Comfort Votes "TCV" & Color Satisfactory Votes "CSV" under different room temperatures with direct positive relationship. So, the alternative hypothesis "H1" will be that wall color has no influence on them. Then the second part of the study is about the methods and techniques used for such experiments with a detailed description of experiment location, phases, surveys, and environmental conditions followed by the third part of research which is about the research results and findings while the discussion is shown in the later section followed by the study conclusion and recommendations for future research.

2. RESEARCH METHODOLOGY

Thus, being motivated by the increased potential for color to influence thermal sensation, this study conducted experiments testing the impact of cool "blue" and warm "red" wall colors on occupants' thermal perception and comfort in a shared office room.

From past research, it was hard to test various wall colors influence on thermal perception of the same place as changing the colors physically need much effort to be implemented but nowadays, it can be solved using virtual models that are similar to ones in the real scenarios with the colors and environmental conditions needed for the test.

2.1 Test room and tools

In this experiment, a closed shared office room "7m long x 6m wide x 3.5m high" at Ain shams university, faculty of engineering, used to test different wall colors and their influence on the users in two different room temperatures presenting cool and warm climates. Fig. (1) shows the real wall color of the room is white "neutral color with RGB 255,255,255" while the other two colors are shown in Fig. (2,3); blue for cool with RGB 0,0,255 and red for warm with RGB 255,0,0. Blue and red were selected to represent cool and warm colors. Colors were tested through virtual 3d geometric model using Autocad and Sketchup softwares for modelling, then Simlab VR studio and Simlab VR Viewer were used to generate the realistic virtual immersive 3D representation for the model then it was connected to Oculus Quest 2.

FIGURE 1. White wall color as a neutral one in the real space.

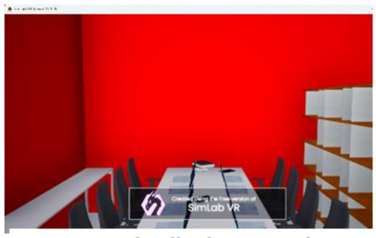

FIGURE 2. Red wall color in virtual scenario

FIGURE 3. Blue wall color in virtual scenario

As there is no natural daylight is considered through the experiment, windows had been closed and daylighting was blocked by dark curtains with the same color used in each case “white, red and blue”. And for ensuring good quality of lighting in the space, artificial LED lights with color temperature 4000 K were used in the ceiling. The illumination was kept unchanged during the experiment.

To access the quantitative aspect of thermal perception; a realme smart watch S100 is used to measure heart rate, body and skin temperatures which are used as an indicator for the body’s thermal state. But for the qualitative aspect of users’ thermal perception, sensation and comfort; a survey was conducted asking for the TCV “thermal comfort vote”, TSV “thermal sensation vote” and CSV “color satisfactory vote”. Participants were required to perform this survey after each experiment “experiment flowchart is shown below”.

2.2 Participants

30 volunteers (20 Females, 10 Males) from Ain shams university, faculty of engineering, participated in this experiment. They were selected from 3rd and 4th year students, Masters and PhD candidates and researchers with age ranging from 20’s to 30’s to simulate the age of users which will be working in a shared office room in their daily work.

At least 12 hours before the start of each experimental session, the subjects were required to avoid smoking, alcohol, and any intensive exercises. Also, they were coming from nearby spaces, it took from them 3 to 5 minutes walking to the test room. Additionally, studies by Goto et al. show that after walking for 15 minutes with a variable speed, a person's heart rate returns to normal after 5 minutes (metabolic rate around 137 W/m 2 and 210 W/m 2) [6]. The subjects in their experiments were university students, which is similar to this study. That’s why the effect of walking on participants was thought to be diminished within 10 – 15 minutes of sitting in the resting zone, in which white color was used, before performing their experiment.

2.3 Experimental procedure

Each subject participated in the experiment was asked to wear the smart watch shown before and lasting for 40 minutes and repeating this process for 2 times “total of 80 minutes”. Fig. (4) and Table (1) shows the experimental procedure for each time. Experiments were performed in the mornings “9 – 11 am” and noon “12 – 15 pm” on weekdays at December 2023. And the air conditioner was used to control the room temperature to be 20 °C for the first experiment and 30 °C in the other case presenting cool and warm temperatures in hot arid climate for Egypt.

FIGURE 4. Experimental Procedure

TABLE 1. Experimental Procedure

Phase 1: Preparing tests	Phase 2: Collecting data and Changing wall color	Phase 3: Collecting data
- It takes place in the resting zone to ensure that subjects have a balanced metabolic rate. -Explaining the experiment procedure to the subjects. -Subjects wear the VR and realme smart watch S100. -Testing initial BT and HR. -Subjects are required to fill in the 1st part of the survey which contains their general information and their thermal sensation of the physical space with its white wall colors. -The researcher controls the room temperature through the air conditioner.	-Starts after testing the 1st color which is Red. -It takes 5 minutes. -Taking the new readings of ST, BT and HR from the smart watch. -Subjects are asked to perform the 2nd part of the survey which is asking about their sensation, comfort and satisfaction of this color “Red”. -The researcher changes the wall color of the model to be Blue for the 3rd phase of the test.	-Starts after testing the 2nd color which is Blue. -It takes 5 minutes. -Taking the new readings of ST, BT and HR from the smart watch. -Subjects are asked to perform the 3rd part of the survey which is asking about their sensation, comfort, and satisfaction of this color “Blue”. -The researcher ended the experiment after this phase and asked the participants for a suitable time to perform it again with different room temperature.
After applying this 40-minute experiment for the 1st time, participants are required to perform it again for the 2nd time with the same procedure but different room temperature in another day.		

Most of the research on color response used a 10-minute exposure period for each color condition [15,21], which indicated that the color-emotion impact stabilize in 10 minutes. That's why participants were assigned to spend 10 minutes in each single-colored environment then they were required to complete questionnaires.

Each phase of color testing, the participants wore the smart watch at their left wrist and the VR glasses on their eyes in a suitable resting position. They were asked to perform a small productivity test to make sure that they are concentrating on something else, not only on the wall color on the space, and also to simulate their concentration if they are working in such place as the experiment aims to test an office worker.

2.4 Questionnaire

Participants are asked to fill in a questionnaire for each experiment, so each one performed 4 surveys for the two colors with two different room temperatures. The survey includes 4 sections:

- 1st section is for general information about their gender, age, health status, initial HR and BT measurements and asks about their thermal sensation of the white color used in the real space.
- 2nd section is for evaluating the design of the shared office room and users thermal comfort within it physically so it was asking for the new BT and HR after staying in this virtual space for 10 minutes and psychologically through their TSV "Thermal sensation vote" and TCV "Thermal comfort vote".
- Based on the ASHRAE/ISO seven-point thermal sensation scale, thermal sensation votes (TSV) are collected. ASHRAE/ISO defines this seven point scale by numbers from +3 to -3; +3 for hot, +2 for warm, +1 for slightly warm, 0 for neutral, -1 for slightly cool, -2 for cool, -3 for cold.
- Thermal comfort votes (TCV) are collected based on the ISO Standard 10551, which used a 5 points scale to address thermal comfort; from 0 = comfortable to +4 = extremely uncomfortable.
- 3rd section is for the level of psychological satisfaction with the tested color and the users expected thermal sensation and energy consumption if using this space for 8 hours per day for their daily work. It tested the possibility to choose the optimum solution for optimizing energy consumption so it was asking for the CSV "Color satisfactory vote" and their expectations about the need for air conditioning if being in such place for about 8 hours daily.
- Like TCV, Color satisfactory votes (CSV) are collected using a 5 points scale; from 0 = very satisfied to +4 = very unsatisfied.
- - 4th section is the last one and it was only for recommendations, it was asking for the most and least thermally comfortable color scheme in their opinion and their recommendations for any other colors that can be more satisfying. That's why this section was filled at the end of the experiment "participants were asked to fill it after performing the 4 experiments of the two colors in two room temperatures".

3. RESULTS

To analyze the experimental data, SPSS statistical analysis software was used to perform GAMA and ETA tests to analyze the correlation between different wall colors in different room temperatures on the thermal perception of users through accepting or rejecting the null hypothesis based on the P-value "significance". GAMA test was used when both variables were ordinal while ETA test was used when one variable was nominal while the other was a scale one. If $P < 0.05$, so "H0" will be accepted and if $P > 0.05$, so "H0" will be rejected and accept "H1" instead.

3.1 Heart Rate "HR" & Body Temperature "BT" measurements

As shown from the results of HR and BT measurements after the experiment, the P-value from GAMA test is higher than 0.05 so "H0" is accepted and there's a correlation between wall color and HR in different room temperatures. And as shown in tables below, same analysis is gained for BT as its P-value is higher than 0.05 too.

Table (2) and table (3) showed that in warm temperature room case, red color caused an increase in the HR for around 65% of participants. On the other hand, blue color caused an increase for HR too but for only 50% of participants while the rest of them showed a reduction in HR measurements or been the same as before experiment. Results showed that even within the cool temperature room case, red color caused an increase in the HR and BT measurements while blue one kept them lower or same as before the experiment in most cases.

TABLE 2. Heart Rate votes in warm and cool room temperature cases

		Higher	Lower	The same		Higher	Lower	The same
Red	Warm Temperature	19	7	4	Cool Temperature	16	8	6
Blue		15	12	3		10	13	7
Total		34	19	7		26	21	13

TABLE 3. GAMA test for HR votes in warm and cool room temperature cases

		Value	Asymptotic Standard Errora	Approximate Tb	Approximate Significance
Gamma Test	Warm	.179	.227	.781	**.435**
No of Valid Cases = 60	Cool	.266	.203	1.278	**.201**

According to tables (4) and (5), Results showed that red color made users' body temperature higher than before the experiment for more than 50% of participants but blue color helped to keep it the same and sometimes lower.

3.2 Thermal Sensation Votes "TSV"

As shown from the results, TSV votes were increasing with temperature increase. Under same temperature conditions; TSV for red color was higher than TSV for blue one. Statistical analysis of both colors in both different room temperature on TSV is shown on Table (6), since P value is lower than 0.05 in both cases warm and cool room temperatures, so H0 will be rejected which means that there is no direct relation between wall colors and thermal sensation votes, but it could be seen that the effect of temperature on TSV is significant.

3.3 Thermal Comfort Votes "TCV"

Results showed that TCV votes for dissatisfaction were increasing with temperature increases. Under same temperature conditions; TCV for dissatisfaction of red color was higher than of blue one. Statistical analysis of both colors in both different room

temperature on TCV is shown on Table (7), And since P value is higher than 0.05 in both cases warm and cool room temperatures, so H0 will be accepted which means that there is a positive direct relation between wall colors and thermal comfort votes.

3.4 Color Satisfactory Votes "CSV"

CSV votes were decreasing towards satisfaction with red color once temperature increases while it became more satisfying with decreasing temperature and same for

the blue color; CSV were increasing with decreasing temperature. Statistical analysis of both colors in both different room temperature on TSV is shown on Table (8), since P-value is higher than 0.05 in both cases, so H0 will be accepted which means that there is a negative direct relationship between room temperature and color satisfactory votes which means that increasing temperature reducing CSV for red color and vice versa.

TABLE 4. Body Temperature votes in warm room temperature case

		Higher	Lower	The same		Higher	Lower	The same
Red	Warm Temperature	16	4	10	Cool Temperature	13	8	9
Blue		9	7	14		5	12	13
Total		25	11	24		13	8	9

TABLE 5. GAMA test for BT votes in warm and cool room temperature cases

		Value	Asymptotic Standard Errora	Approximate Tb	Approximate Significance
Gamma Test	Warm	.333	.197	1.613	**.107**
No of Valid Cases = 60	Cool	.379	.185	1.934	**.053**

TABLE 6. GAMA test for TSV in warm and cool room temperature case

		Value	Asymptotic Standard Errora	Approximate Tb	Approximate Significance
Gamma Test	Warm	-.734	.105	-5.741	**.000**
No of Valid Cases = 60	Cool	-.942	.036	-14.959	**.000**

TABLE 7. ETA test for TCV in warm and cool room temperature cases

		Value			Value
Eta Test	Wall Color Dependent	.512	Eta Test	Wall Color Dependent	.307
Warm Temperature	TCV Dependent	**.474**	Cool Temperature	TCV Dependent	**.119**

TABLE 8. ETA test for CSV in warm and cool room temperature cases

		Value			Value
Eta Test	Wall Color Dependent	.591	Eta Test	Wall Color Dependent	.430
Warm Temperature	TCV Dependent	**.563**	Cool Temperature	TCV Dependent	**.274**

4. DISCUSSION

Results showed that changing colors from blue to red has a direct influence on subjects' thermal sensation and comfort. Red color causes higher HR and BT measurements which causes thermal discomfort for occupants especially in warm temperatures while blue color reduces the HR and BT measurements in relation to red color.

According to the physiological explanations regarding the way ambient temperature affects heart rate, increasing in thermal sensation which means feeling warmer causes an increase in the body demand for cooling too. And since H0 was accepted for both TCV and CSV, it proves the hue heat hypothesis, which indicates that warm colors help feeling warmer while cool colors help feeling colder, proving that colors have a direct influence on thermal comfort and satisfaction.

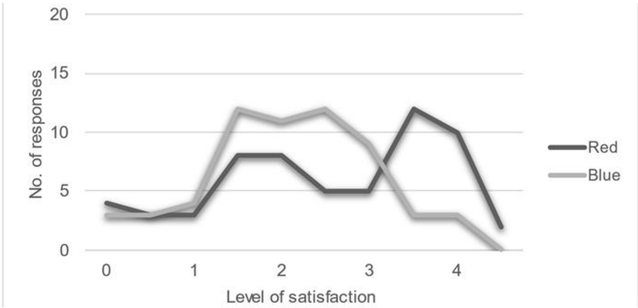

FIGURE 5. TCV vs CSV in cool room temperature case

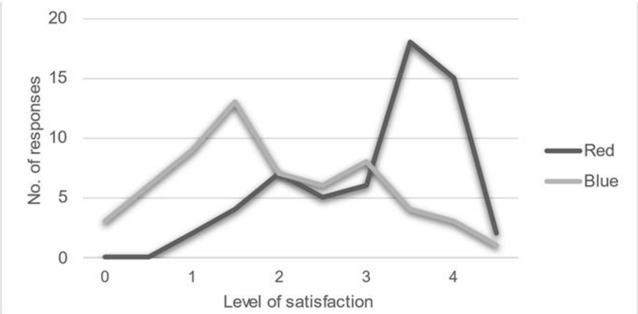

FIGURE 6. TCV vs CSV in warm room temperature case

Combined the analysis of TCV and CSV as shown in Fig. 5 and Fig. 6 below, it was clear that cool colors make people feel cooler and is more satisfying for them in office spaces while the red one is the least comfortable color for them. And since P-value of CSV is the highest value reached and it's approximately very close to the one for TCV, it indicates that subject's satisfaction with colors has a strong direct relationship with their thermal comfort which will affect their energy demand in return.

5. CONCLUSION

This study investigated the influence of wall color in interior shared office on thermal sensation and comfort of users under different ambient temperature cases through VR. Two colors were tested representing cool and warm colors in two different room temperatures representing summer and winter, and experiments were conducted to evaluate the subjective thermal sensation "TSV" and comfort "TCV" and the psychological responses of "HR" and "BT" in both scenarios. Several results were obtained from the experiment and statistical analysis performed.

Subjects felt warmer when being surrounded by the red color, which represented warm colors, but while room temperature increases, it became more dissatisfying, and increased heart rate and body temperature, increasing the need to cool down their bodies which causes an increase for energy demand and consumption for air conditioning. Blue color, which represents cool colors, kept their heart rate and body temperature at most times same as before the experiment and it sometimes helps lowering them, proving the hypothesis of the study, and it also had been more satisfying for them. In general, warm colors are more satisfying in cool temperatures and vice versa. Integrating warm or cool colors in warm or cool interior spaces can psychologically promote an optimized thermal perception against the actual thermal condition that occupants feel, which has direct relation with energy saving.

6. RECOMMENDATIONS FOR FUTURE WORK

As a result of this research, wall colors can affect users' thermal comfort and energy demand in return so it would be preferred to optimize the colors to reach the optimum thermal comfort during different seasons. And since it's hard to change wall colors every time temperature changes in real scenarios; future work can investigate the applicability of changing users' thermal perception of color while it's kept as it is without any change, it may be reached through lighting, changing fabrics or other solutions. Also testing its' influence on energy consumption shall be tested to get the actual percentage can be reduced.

Also, there are some limitations in this study. First one, it didn't work on the relation between gender and color perception and thermal sensation in return. Some evidences showed that thermal perception might vary according to differences in thermoregulation between females and males mainly as a result of the anthropometric differences in body fatness and the ratio of body surface area to size [6]. So considering this, future work can investigate the relation between gender and thermal perception of colors.

Second limitation is about exposure time as each participant was asked to be exposed to each color for only 10 minutes to avoid any disturbance, fatigue or discomfort for them can be caused due to the longtime of experiment of different colors using VR glasses [17]. Some studies proved that occupants' response to color varied by different exposure times, so we can study each color separately in different temperatures but with more exposure times in the future.

The third one was about the colors tested in this study. It focused mainly on red and blue as a reference for warm and cool colors but to get a framework that can help in designing the interior spaces with colors helps for energy optimization, more colors need to be tested with different saturations.

The study focused exclusively on participants from the engineering sector. To obtain more comprehensive and accurate results in future research, it would be beneficial to expand the sample to include individuals from diverse backgrounds and professions. This was the last limitation which would allow for a more thorough examination of the thermal influence on a broader population.

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