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The Effect of Colored Light in the Vehicle Interior on the Thermal Comfort and Thermal Responses of Vehicle Occupants

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ABSTRACT

Light and color may have an effect on the thermal comfort in vehicles to improve the driving comfort. This can be an important factor by developing the e-mobility by saving battery power. This work aims to investigate the subjective thermal perception and physiological responses of vehicle occupants through the influence of thermal and visual stimuli in the vehicle interior. The results show that colored light affects thermal perception under different temperature conditions.

Keywords: Thermal comfort, Colored light, Energy saving

INTRODUCTION

In the last few years, there has been a strong change in the interior design of vehicles. This change will continue in the future, especially in case of autonomous driving. For an interior design, the satisfaction, well-being and acceptance of the user is extremely important and can be characterized by the factors visual comfort, thermal comfort, air quality and acoustics (World Health Organization 1990). To address the visual sensation light and color in the interior getting more and more important. From a technical point of view, there is the possibility of using a variety of different ambient lights and colors for individualization and personalization to satisfy customer needs and increase sales. In the market, there is an increasing number of cars in the middle and upper class that already have ambient lighting installed (Caberletti et al. 2010). But not only new cars from the OEM's have ambient lights, there are a lot of retrofit options on the market. Ambient lights with different lights and colors can support the car driver's emotion. The last years publication "Enhanced driver's experience through emotion sensitive lighting interaction" at the AHFE 2022 showed, that light and color have an impact on the mood of car drivers by their emotional change. The result is, light and color can change the driver's emotions to the positive and also negative (Braun et al. 2022). By using this effect, it could be possible to change the driver's thermal sensation by using light and color. Especially in case of the e-mobility, warming light and color can support the heating system to get thermal comfort to the driver and save energy. The usage of light and color can help to support the heating system in the car by giving the driver a good thermal comfort. In this case, the energy use of the system is reduced and that can increase the electric range (Flieger 2014). In addition, thermal comfort is a very important factor for driving comfort and can contribute to (mass) personalization and individualization (Frisch et al. 2013).

This work aims to investigate the subjective thermal perception and physiological responses of vehicle occupants through the influence of thermal and visual stimuli in the vehicle interior. While the thermal and visual perception are recorded in a proband study with the help of a questionnaire, the physiological reactions are continuously measured using skin temperature and heart rate.

In general, there is existing an approach, which describes the correlation to reduce thermal discomfort with colored light. The principal of this approach is based on the Hue-Heat-Hypothesis (HHH). This hypothesis states, that colored light can change people's thermal perception. For that, a colored environment at the red end of the visible spectrum is perceived as warm and a colored environment at the blue end of the visible spectrum as cold (Bennett and Rey 1972). With this hypothesis, an application to the automotive sectors is possible by using colored light at the interior to manage the user's thermal sensation. This work should verify the hypothesis for the automotive sector because it is less researched. The conducted literature review shows that color and light have effects on the human thermal sensation and comfort (Huebner et al. 2016; Winzen et al. 2014; Chinazzo et al. 2021). However, the application, especially of visualizations, in vehicles for drivers has not been extensively researched.

The objective of this work and the literature review raise several research questions. The main question is:

Does colored light in the vehicle interior influence the thermal sensation of vehicle occupants in terms of the Hue-Heat-Hypothesis?

Beside this main research question, there are more central questions to be answered, such as whether …

- *colored light in vehicle interior influences the physiology of the passengers, in case of heart rate and skin temperature,*
- *the influence of colored light in the vehicle interior changes the subjective thermal sensation at different levels of temperature,*
- *the influence of colored light in the vehicle interior changes the thermal comfort by dynamic lighting.*

To answer this research questions, a technical Early-Prototype[1] was build and an experimental subject study was carried out. The methodological approach for that is shown in the following chapter.

[1] An Early-Prototype is defined as an easy- and fast-to-build but incomplete type of a prototype as it focusses on those aspects that are necessary for a defined test. Unlike a commonly known prototype, an Early-Prototype only includes properties which are necessary to realize a prototype at an explicit moment for the development of new technologies and to reach the defined testing goals (Braun et al. 2022).

METHOD

To achieve the described goal and answer the research questions, a methodological approach was developed for this work. The first step was to define the research questions. Then, the state of the art in the fields of thermal comfort, psychological effects of light and color, lighting in vehicle interiors and the influence of colored light on thermal sensation was researched. This research defines the experimental setup of the subject study, which is done via a 2x4 factorial study design with the factors temperature and light color. This is followed by user testing, data analysis, and evaluation. Figure 1 shows the methodological approach of this work.

The research questions and the summary of the research work have already been mentioned in the previous chapter. Due to space limitations, it cannot be discussed in detail here. The focus of this paper is on the experimental setup, user testing and results. For the experimental setup, lighting scenarios have to be defined and for the investigation of the thermal comfort, the temperature needs to be controlled to a planned value and a consistent test environment.

Light Scenarios: The defined light scenarios have three different colors for the static scenarios and two dynamic light scenarios. The colors as well as the illuminance of the colors for the static scenarios are orange (RGB: 255/177/0, 200lx), white (255/255/255, 280lx) and blue (0/179/255, 150lx), which are based on the Hue-Heat-Hypothesis. The dynamic scenarios are candlelight (139/85/38, 114lx) and winter landscape (124/134/143, 104lx). To get the RGB-value for the dynamic scenarios, the average color value of the whole dynamic sequence was measured. By using these colors, the aim is to investigate, if people have a colder thermal sensation by blue light and whether people have a warmer thermal sensation by using orange light, compared with white light, which is used as the reference color.

Temperature Levels: The light scenarios are combined with two temperature levels 24.5 °C and 26 °C (297.65 K and 299.15 K). The lower temperature level is within the comfortable temperature range for the vehicle interior and the higher level is outside the comfortable temperature range (Thomas Kroher 17.11.2020). Two temperature levels are important to get a variety of test sections with different temperatures to prevent wrong subjective thermal feelings. The light scenarios and the temperature level are the independent variables of this study.

Experimental Setup: For that an experimental setup was developed and build. The vehicle which is used for the user tests is a light electric vehicle (Renault Twizy). This vehicle has the advantage, that the driver, who is sitting in the middle of the vehicle, can be surrounded by visualizations and

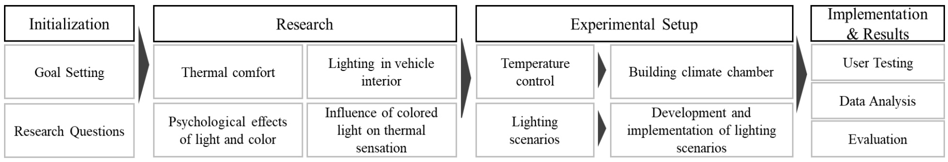

Figure 1: Methodical approach.

displays with the same distances. The Twizy's Interior is nearly symmetrical, which helps to create a perfect light and color effect for the test persons. For the implementation of light and color output, and in addition showing dynamic visualizations, three curved displays are installed. One on each side at the door and one in the headlining. The displays are curved for a better fitting into the interior of the vehicle. To support the visual effects on the displays, five ambient lights are installed, which are connected to the display signal. To regulate the temperature inside the vehicle (for the test temperatures and to eliminate the waste heat from technical devices) three temperature sensors are built in. These sensors are connected with a several build climate chamber to analyze and adjust the interior temperature. The climate chamber has a heating fan to raise the temperature, a cooling system to lower the temperature and several fans to transport the air into the climate chamber and vehicle. In front of the vehicle, a big display and inside of the vehicle a sound system completing the experimental setup to present a driving scenario. The laboratory for conducting the study is an empty room with darkened windows, low light, and a monitoring station. Figure 2 shows the experimental setup of the vehicle and the climate chamber.

To get results about the thermal sensation of the test persons, in this study the psychological and physiological variables are measured with qualitative and quantitative methods. The qualitative method is a questionnaire to get the subjective perception of the test persons regarding their vehicle environment. The questionnaire contains questions about the thermal and visual sensation at the vehicle environment, which are inspired by EN ISO 10551 and Chinazzo et al. (2021). The questions and the response scales with answer options are the following:

Thermal Perception

(1) How do you feel exactly in this moment? (Thermal sensation) [From *Cold*: -3 to *Hot* +3]
(2) How do you feel about the thermal environment? (Thermal comfort) [From *Comfortable*: 1 to *Extremely uncomfortable*: 5]
(3) How would you rather feel now? (Thermal preference) [From *Much cooler:* -3 to *Much warmer*: +3]

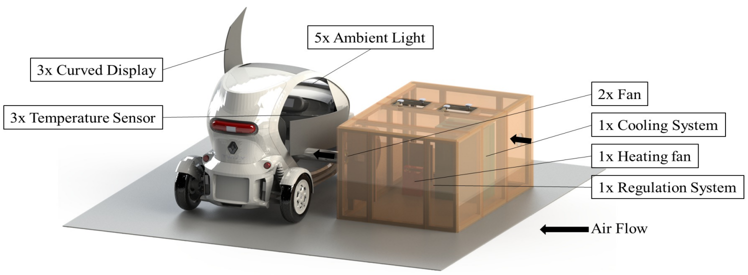

Figure 2: Experimental setup for visualization and temperature control in the test vehicle.

Visual Perception

(4) The actual lightening is … (Brightness sensation) [From *Extremely dark*: 1 to *Extremely bright*: 7]
(5) How pleasant do you find the brightness of the vehicle lighting? (Visual comfort) [From *Pleasant*: 1 to *Extremely unpleasant*: 5]
(6) How do you perceive the lighting in the room? (Cold-Warm Association of Light) [From *Cold*: 1 to *Warm*: 5]
(7) How do you perceive the light color in the vehicle interior? (Color acceptance) [From *Pleasant*: 1 to *Extremely Unpleasant*: 5]

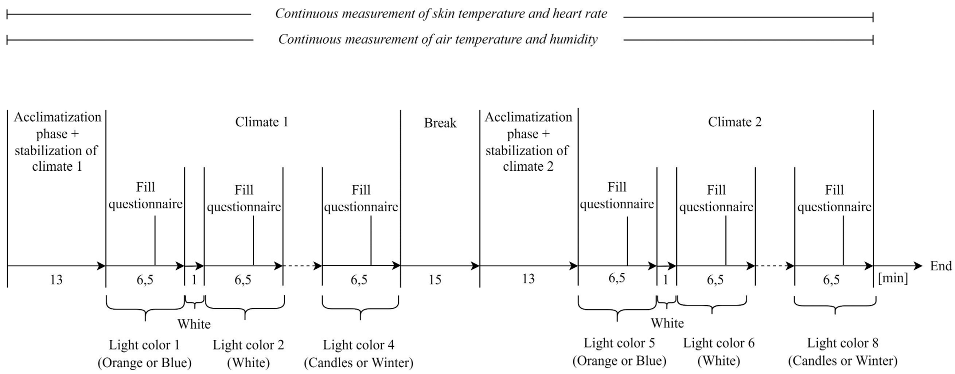

Figure 3: Procedure of the study (inspired by Chinazzo et al. (2021)).

The quantitative method is used to record changes in the body of the subjects in relation to the respective environment. Therefore, skin temperature and heart rate are measured with an Empatica E4 wristband, which the subjects must wear during the user test. These physiological variables are measured because they are suspected to be influenced by colored light, as shown in the literature review (te Kulve et al. 2016). With the technical experimental setup and questionnaire described above, the mentioned light scenarios can be executed. A study procedure is developed to have a structured, standardized and comparable process. The procedure is a mix of acclimatization, test sections, questionnaire and short breaks. The overall time for the study is about 99 minutes. More details of the procedure are shown in Figure 3.

Participants

A total of 15 adults (9 males and 6 females) with normal color vision participated in the study. Due to technical problems in stabilizing the temperature inside the vehicle, the data of 3 participants were excluded from the analysis. This resulted in the final sample size of 12 participants (6 males and 6 females). Table 1 describes the characteristics of the participants.

Participants were required to wear a specific dress code during the study to ensure a similar level of clothing insulation. This consisted of a shirt, thin long pants, underwear, thin socks and closed shoes. In combination with the vehicle seat, this resulted in a thermal insulation of about 0.75 clo (EN ISO 9920). Participation in the study was not compensated. All participants went

Table 1. Participants' characteristics (n = 12).

	Mean ± Standard Deviation (*SD*)
Age [years]	26.33 ± 7.43
Weight [kg]	70.33 ± 15.50
Height [m]	1.74 ± 0.09
BMI [kg/m^2]	23.01 ± 3.83

through all light scenarios and both temperature levels and answered questions about thermal and visual comfort of the vehicle interior environment at the end of each combined scenario.

Statistical Analysis: To analyze the subjective ratings and physiological responses, statistical tests were performed using IBM SPSS Statistics 26. Initially, the data were tested for normality using the Shapiro-Wilk test, and parametric or nonparametric analysis was performed depending on the test result (Field 2017).

In the case of a parametric analysis, the effects of the lighting scenarios on the dependent variables were examined using a two-way ANOVA with repeated measures. An exception is made for the dynamic lighting scenarios, as they were only studied at one temperature level, so t-tests are performed for dependent samples. The effect of vehicle temperature on the dependent variable was also tested with a t-test for dependent samples due to their two manifestations. In the presence of a significant effect, a post-hoc test in the form of a pairwise comparison was also performed and the effect size $\eta^2{}_{part}$ was determined.

In the case of nonparametric analysis, Wilcoxon tests and Friedman tests were performed. In the case of a statistically significant difference, post-hoc tests were also performed, and the effect size r was determined. Potential covariates were also included in the statistical analysis. These are the personal factors age, BMI, and gender of the probands as well as the temperature variation $\Delta T_{Vehicle}$, which represents the difference between the target temperature and the measured temperature. The significance level α is set to $\alpha = 5\%$ for all analyses.

RESULTS

The subchapter first describes the climatic conditions measured in the vehicle. Then, the results from the analysis of the subjective and physiological data are described. The results from the subjective data are divided into two areas: Thermal perception and visual perception. Finally, the covariates that may have an influence on the dependent variables are shown.

Thermal Vehicle Environment: The statistics for the mean, operative air temperature inside the vehicle for each combination of temperature level and lighting scenario are shown in Table 2. The measurements show that the mean room temperatures differ only slightly between the color exposures and that the variations are slightly higher at the lower temperature level

Table 2. Mean values ± *SD* of the measured air temperature depending on the light scenario and temperature level (values in °C).

Target air temperature	Blue	White	Orange	Candlelight or winter landscape
24.5 °C	24.59 ± 0.29	24.51 ± 0.28	24.55 ± 0.28	24.61 ± 0.33
26 °C	25.98 ± 0.29	25.98 ± 0.16	26.02 ± 0.13	26.04 ± 0.21

(24.5 °C) than at the higher temperature level (26 °C). As listed in the previous, these temperature variations are accounted for as a covariate $\Delta T_{Vehicle}$. The relative humidity (RH) was between 20 % - 35 % RH. The air velocity was below the threshold value of 0.1 m/s.

Thermal Perception: The subjective responses to the evaluation of the vehicle thermal environment are shown in Figure 4 and Figure 5. The left side of the figures shows the results of the means and *SD*s of the dependent variables for 24.5 °C, and the right side shows the results at 26 °C. Significant effects are marked with "*" $p < 0.05$, "**" $p < 0.01$, "***" $p < 0.001$. It can be seen in the figures that under the same temperature, the thermal perception varied with the colors.

The effect of light colors on thermal sensation ratings can be seen in Figure 4. The statistical analyses show that significant differences exist between the colored lights in the evaluation ($F(2, 22) = 13.23$, $p = < 0.001$). Pairwise comparisons lead to the conclusion that thermal sensation was rated significantly higher under the orange condition than under the blue condition and than under the white condition, regardless of temperature level. In addition, the vehicle environment was perceived to be significantly cooler in the winter condition than in the orange condition ($t = 3.03, p = 0.012, r = 0.67$).

The colored light also influences thermal comfort, although only at the temperature level of 26 °C. The light color white was perceived as more uncomfortable than all other light colors ($\chi^2(3) = 12.84$, $p = 0.005$).

Preference to change temperature was significantly different between light exposures only at the higher temperature level ($\chi^2(3) = 8.78, p = 0.032$). The post-hoc analyses show significant differences between the blue and orange colors ($z = -2.07$, $p = 0.038$, $r = 0.42$) and between the orange and winter

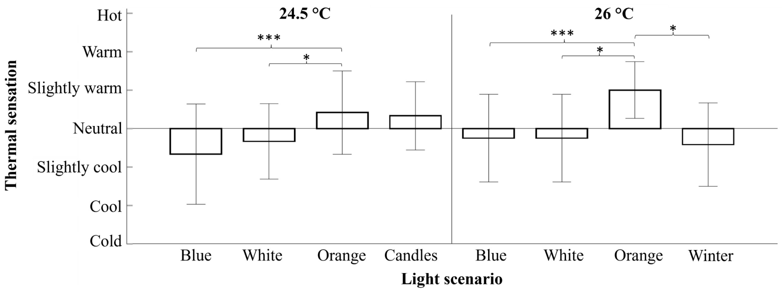

Figure 4: Mean value and standard deviation of the thermal sensation rating for each temperature level and light scenario.

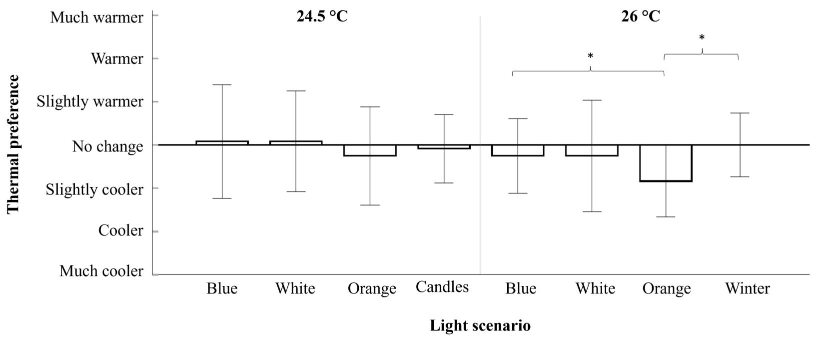

Figure 5: Mean value and standard deviation of the thermal preference rating for each temperature level and light scenario.

light scenarios ($z = -2.43$, $p = 0.015$, $r = 0.5$). As can be seen in Figure 5, participants at the higher temperature level preferred a cooler environment for the orange exposure than for the "cool" light exposures. Statistical analyses of the effect of temperature on thermal perception show, contrary to expectation, that our temperature difference has no effect, except on thermal preference ratings. In this, the study participants preferred a significantly cooler environment at 26 °C ($z = -2.56$, $p = 0.01$, $r = 0.31$).

Examining the covariates $\Delta T_{Vehicle}$, age and BMI on thermal perception, the results show that these had a significant influence. While $\Delta T_{Vehicle}$ significantly influenced thermal sensation (at a temperature level of 24.5 °C), probands' age and BMI influenced thermal comfort and thermal preference scores. Younger probands found the thermal environment at 24.5 °C less uncomfortable than older probands and probands with a higher BMI (> 24) preferred a cooler environment than probands with a lower BMI. Gender had no effect on thermal perception.

Visual Perception: The analysis of the effect of temperature and light scenario on visual perception is performed using non-parametric tests. The statistical analyses show that the temperature has no significant influence on the visual evaluation, but the lighting situation does. Here, the results show that the light color has an influence on the cold-warm association ($\chi^2(3) = 19.53$, $p < 0.001$ at 24.5 °C and $\chi^2(3) = 16.16$, $p = 0.001$ at 26 °C). The post-hoc analyses show that the light scenario orange was perceived as warmer than blue, confirming the cold-warm association of the colors. In addition, the candlelight scenario was perceived as a warmer light scenario than the blue and white scenario.

In addition, the white light scenario was perceived as significantly brighter than the other light scenarios ($\chi^2(3) = 10.03$, $p = 0.018$). This is also evident in the illuminance of the light colors. The high illuminance may have caused the white light color ($M = 2.5$, $SD = 0.9$) to be perceived as significantly more unpleasant than the winter scenario ($M = 1.5$, $SD = 0.7$) and than the blue light scenario ($M = 1.6$, $SD = 0.7$). For lighting comfort, light color did not prove to be a significant factor.

Physiological Measurements: In the analysis of the physiological data, the heart rate and skin temperature data are evaluated. For heart rate, it is shown that it is neither influenced by the light scenarios ($F(2, 20) = 0.83, p = 0.45$) nor by the air temperature ($F(1, 10) = 1.46, p = 0.26$). Furthermore, no effect of the light scenarios on skin temperature was detected.

DISCUSSION

In the following, the influence of light scenarios and temperatures on thermal perception as well as on physiological responses is presented. The limitations of the study and the need for further research are then highlighted.

Effect of Colored Light and Temperature on Thermal Perception: It was observed from the results that the "warm" light scenarios (orange and candles) were perceived as warmer than the "cold" blue light scenario. These results confirm the HHH. In addition to the perception of a warmer environment under an orange light influence, the probands also desired a much cooler environment at the temperature level of 26 °C than under the blue light influence and the winter scenario. The results agree with further literature in which thermal perception was investigated after being influenced by artificial, colored light (Huebner et al. 2016; Lu et al. 2015; Winzen et al. 2014). Another finding from the results of this study is that the temperature difference of 1.5 °C did not lead to any significant change in thermal sensation. It is therefore more interesting that the light scenarios were able to achieve this effect.

Effect of Colored Light and Temperature on Physiological Responses: No effect of light color and temperature on physiological responses was found. The lack of effect of light color on skin temperature and on heart rate agrees with other research findings by Fanger (1972), Lu et al. (2015) and Chinazzo et al. (2021). Since physiological values did not change between light scenarios, the authors assume that the influence of light color on thermal perception is only psychological.

Study Limitations and Further Research: The study was conducted in a self-developed experimental environment where one difficulty was to accurately control the air temperature in the interior of the small vehicle. In addition, the subjects in the experiment were exposed to a relatively narrow and high temperature level. Since the results show that the temperature change did not lead to any influence on the dependent variables in most evaluations, future studies should be conducted with larger temperature differences and lower temperature levels. Another limitation of the study was that the illuminance of the light colors was not exactly the same. Furthermore, the sample was quite small. In addition, with 75 % mainly younger people (under 30 years) participated in the study. Therefore, the results are not transferable to persons of other ages. Considering this, other age groups should be considered in future research.

The study took place in summer. As thermal and visual perception may also depend on the season, further studies should be conducted at different times of the year. It should also be mentioned that the vehicle occupants in this study did not have to perform any driving tasks. It is possible that the effect of the change in thermal perception caused by colored light is less strong when people take over the driving task. In addition, it must then be investigated whether the driving performance remains the same due to the color effect and what energy savings can be achieved.

CONCLUSION

The main goal of this study was to investigate whether colored light (static: blue, white, orange; dynamic: candlelight and winter landscape) in the vehicle interior at two different temperatures (24.5 °C and 26 °C) can influence the thermal perception of vehicle occupants. The results show that colored light affects thermal perception under different temperature conditions. The indoor environment under the orange light was perceived as warmer than under the blue light. In addition, participants found the blue light more comfortable than the orange light in warm environments and they preferred a lower temperature with orange light compared to the blue light or the dynamic video of a winter landscape in warm environments.

To sum up, results provide initial evidence that colored light in the vehicle interior can influence the thermal perception of the vehicle occupants. However, whether colored light can actually be used as a tool to reduce energy consumption for heating and cooling the vehicle interior needs to be investigated in further studies during ongoing driving operations.

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