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Investigating the validity of the hue-heat effect on thermal sensitivity

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In this study, we aimed to investigate the validity of the hue-heat effect on the body thermal sensitivity. Previous research on thermal comfort has proposed associations between red and warmth, and blue with cold. However, inconsistencies in confirming this effect have arisen, with studies often relying on subjective scales for thermal comfort assessment, introducing potential confounding variables. To overcome these limitations, we conducted a study focusing on the hue-heat effect within the domain of thermal sensitivity, providing a more objective measurement of thermal perception. Participants ($n = 26$) were required to compare the perceived temperatures inside different climate chambers lighted by either red or blue lights following two different paradigms. In the congruent paradigm, the warmest chamber was lighted by red lights, while the coldest chamber had blue lights. On the contrary, the incongruent condition featured the warmest chamber with blue lights and the coldest chamber with red lights, thereby violating the hue-heat effect. We found comparable performance in both conditions, challenging the hypothesis that congruence between colour and temperature enhances thermal perception. Notably, some participants aligned with our hypothesis, while others exhibited opposing behaviour, highlighting the potentially subjective nature of the hue-heat effect. Furthermore, we compared the present results with our previous data without the added stimuli of the lights. Surprisingly, the sensitivity observed in this experiment was even lower than the one measured in our previous study (p -value < 0.0001), suggesting that the colour of the lights might have increased participants' cognitive load, leading to a decline in their performance.

Keywords Thermal perception, Colour-temperature association, Multisensory perception, Thermal comfort

When discussing thermal comfort, the term refers to a thermal state that elicits satisfaction among individuals¹. Specifically, the ANSI/ASHRAE Standard 55 (2017) defines thermal comfort as a subjective state of mind, emphasising the subjective nature of this perception. The role of the body's thermal sensitivity in contributing to thermal comfort is a topic of ongoing debate, with a belief that thermal sensations, particularly, from the face (specifically the forehead and cheeks) hold significant importance². However, temperature information coming from the periphery of the body (e.g., the hands and arms) emerges as the primary driver of thermoregulation behaviours³, despite being heavily influenced by vasodilation and vasoconstriction, making accurate assessment of the environmental temperature challenging¹.

Furthermore, the perception of thermal comfort is shaped by both physical and psychological factors. Factors such as the prevailing microclimate and weather conditions are as crucial as individuals' enduring preferences and momentary thermal perceptions⁴. These results illustrate the intricate nature of thermal comfort, prompting numerous researchers to explore the elements influencing it. A common approach involves investigating thermal comfort alongside other sensory modalities to assess their impact on judgments of thermal comfort. Recent studies have shown that the sounds of water and birdsong can enhance thermal comfort during summer days⁵, just as the scent of peppermint can elicit a perception of cooler temperatures⁶.

Nonetheless, in the investigation of factors influencing thermal comfort, cues belonging to the visual sensory modality were the ones that received the most attention, with a particular focus on exploring the potential impact of colours on thermal perception. In 1926, Mogensen and English⁷ proposed a hypothesis suggesting that colours inherently evoke temperature sensations, proposing that warm colours, such as yellow and red, give rise to a perception of heat, while cool colours, like green and blue, elicit a sensation of cold. Expanding upon this hypothesis, commonly known as the hue-heat effect, numerous researchers have endeavoured to establish a

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correlation between colours and temperature. For instance, Ho and colleagues⁸ conducted an Implicit Association Test involving two colour patches (red and blue) and two words (warm and cold). Their findings indicated shorter reaction times when the colour-word pairings were congruent (e.g., red with warm and blue with cold), providing supporting evidence for the existence of this automatic association.

The hue-heat effect has collected significant attention, primarily due to its potential to manipulate individuals' thermal comfort without actually altering the environmental temperature⁹. Pioneering this exploration, Fanger and colleagues¹⁰ were among the first to explore whether the presence of blue or red lights could influence the preferred environmental temperature. They conducted an experiment where a room was illuminated with either red or blue light, initially set at 25 °C, and participants were subsequently asked to adjust the temperature to match their preference. The results revealed a tendency for participants to select a slightly cooler temperature when the room was illuminated in red, confirming that red conveys a sense of warmth while blue conveys a sense of cold. Following their work, other researchers have obtained similar findings using cold white (6000 Kelvin Correlated Colour Temperature) or warm (3000 K CCT) white lights (e.g.,¹¹) and in more ecologically valid settings where participants' responses were inferred from their clothing preferences (i.e., addition or removal of pieces of clothes)¹².

The majority of studies examining this relationship have relied on subjective measures, such as thermal comfort scales ranging from -3 (indicating discomfort) to +3 (indicating comfort), where participants are prompted to express their preferences regarding the conditions they experience. However, these measures pose a potential limitation due to interindividual variability, wherein distinct response styles may exist: some participants may exhibit more conservative tendencies and confine their responses within the neutral part of the scale (ranging from -1 to +1), while others might incline toward expressing more definitive preferences, encompassing the extremes¹³. This potential limitation remains challenging to eliminate and might contribute to the divergence within the literature concerning the hue-heat hypothesis.

Brambilla and colleagues¹⁴ recently observed that the apparent hue-heat effect manifested solely under one of the tested temperature conditions. Specifically, they investigated the impact of different white lights (warm, neutral, and cold) across three different environments (21 °C, 24 °C, and 26 °C), discovering a significant enhancement in thermal comfort only with cold white lights at 26 °C. The absence of evidence for the hue-heat effect in the other two conditions remains uncertain. Similarly, Chinazzo and colleagues¹⁵ reported analogous equivocal findings, noting that an orange light increased the perception of warmth solely at 24 °C, but not at 29 °C. Additionally, te Kulve and colleagues¹⁶ found that white cold lights induce a sensation of coldness, while warm white lights exhibited no discernible impact on thermal comfort.

Taking together, these results underline the ambiguity of this line of research, with some studies confirming the hue-heat effect while others introduce challenges in drawing definitive conclusions. To address this issue, a possible strategy could involve shifting the research focus from thermal comfort, a subjective dimension of thermal perception, to thermal sensitivity, a more objective measure of it. Exploring whether the hue-heat effect extends its impact beyond comfort judgments to affect our more objective perception of the temperature could enhance our understanding of the phenomenon. In our previous study¹⁷, we introduced an innovative experimental paradigm utilising four climate chambers to assess human sensitivity to environmental temperature. The results obtained revealed that individuals exposed to a temperature of 24 °C ± 1 °C consistently discriminated temperature differences of ± 0.92 °C, with an average Just Noticeable Difference (JND) of 0.38 °C. Our current research question focuses on whether the colour of lights can influence such sensitivity.

In the present study, participants move between two climate chambers and indicate whether the second one is warmer or colder than the previous one. We investigated two different paradigms: a congruent one, where the warmest between the two chambers is illuminated by red lights and the coldest one by blue lights (the hue-heat hypothesis is respected); and an incongruent one, where the warmest chamber has blue lights and the coldest red ones (not adhering to the hue-heat hypothesis).

We hypothesise that participants in the congruent condition will exhibit higher sensitivity, as the presence of colour in the lights will enhance their thermal judgments. In particular, we anticipate that participants will accurately identify a slightly warmer target chamber due to the presence of red lights, thereby enhancing their perception of warmth. Similarly, a slightly colder target chamber illuminated with blue lights will be correctly perceived as cooler. On the contrary, we anticipate lower performance in the incongruent condition, as the colour of the lights is likely to lead participants to inaccurately perceive temperature differences. For instance, a warmer target chamber with blue lights may feel less warm than it actually is, introducing challenges in participants' decision-making. Moreover, we expect the advantage conferred by the congruent condition and the challenge posed by the incongruent condition to manifest also with respect to a condition where no different colours of the lights were introduced (i.e., our previous study). Specifically, our main research questions are: i) is there a discernible difference between the congruent and incongruent conditions? ii) are there disparities between the current results and our previous ones¹⁷?

Results

Congruent condition vs. incongruent condition

The model comparison reported in Table 1. underlies a lack of the effect of the condition on participants' answers. Both the information criteria are in favour of model 1 (AIC = 63%, BIC = 58.9%), indicating that our data are better explained by the differences in temperature alone than when the variable condition is added.

Looking at model 1 more in detail, the effect of the temperature differences on participants' answers is extremely significant (p -value < 0.0001) and we can observe that increasing the delta increases the probability of saying "warmer" of $pnorm(DT*1.26)$, where 1.26 is the Estimate of the temperature differences effect. This means that if the temperature differences are of 1 °C, participants have a probability of 89.62% of saying warmer;

Model	AIC	BIC
glm0: Answer ~ DT + (1 Participants)	3109.6 (0.1%)	3127.8 (39.9%)
glm1: Answer ~ DT + (DT Participants)	3096.8 (63%)	3127.0 (58.9%)
glm2: Answer ~ DT + Condition + (DT Participants)	3098.5 (27%)	3134.7 (1.2%)
glm3: Answer ~ DT + Condition + (DT + Condition Participants)	3104.0 (1.8%)	3158.3 (<0.1%)
glm4: Answer ~ DT * Condition + (DT + Condition Participants)	3101.1 (7.4%)	3161.5 (<0.1%)
glm5: Answer ~ DT * Condition + (DT * Condition Participants)	3105.5 (0.8%)	3190.1 (<0.1%)

Table 1. Results of the model comparison for the first experimental question. In parentheses, information criteria weights are reported.

if the temperature differences are of 2 °C, this probability is 99.41%. Such a result shows the substantial impact of temperature alone on participants' answers, making the effect of light insignificant. Moreover, this model demonstrates a strong capability to explain the data, as indicated by the R-squared, signifying the goodness of fit of the model (R^2 marginal = 47%; R^2 conditional = 51%).

Previous experiment¹⁷ vs. congruent condition and incongruent condition

Table 2 reports the results of the comparison between the Generalised linear mixed models computed to analyse the difference between our previous experiment and the current one. Such a comparison shows a discrepancy between the AIC criterion, favouring model 4 (92.6%), and the BIC criterion, favouring model 1 (98.1%).

The main difference between these two criteria is that the AIC is more explorative, while the BIC is more conservative. The BIC criterion penalises complex models to a greater extent while simultaneously favouring simpler models (i.e., those with fewer parameters)¹⁸. Subsequently, we opted to analyse model 4 to understand why the AIC criterion is underlining a difference between this experiment and the previous one. As depicted in Table 3, the interactions between the differences in temperature and the type of condition (previous experiment, congruent condition of the current experiment, or incongruent condition of the current experiment) are statistically significant. The post-hoc analysis revealed how the accuracy of participants' answers was higher in the previous experiment in comparison with the congruent condition (p -value < 0.01) and the incongruent condition (p -value < 0.001) of the current experiment (see also Fig. 1). Finally, this model has a high goodness of fit, explaining over 60% of the data variance (R^2 marginal = 61%; R^2 conditional = 64%).

Moreover, we calculated the PSE, JND and JND⁹⁵ of this experiment (Table 4) and compared them with the values from the previous study¹⁷ by using the Wilcoxon test (due to the non-normal distribution of the data, precluding the use of a t-test). In particular, the test highlights a statistically significant difference between the JND and JND⁹⁵ of the previous experiment and the congruent condition of the current one (p -value < 0.01) and between the JND and JND⁹⁵ of the previous experiment and the incongruent condition of the current one (p -value < 0.001). However, there is no significant difference between the JND and JND⁹⁵ of the congruent and incongruent conditions (p -value = 0.29). These results suggest a greater accuracy when there were no

Model	AIC	BIC
glm0: Answer ~ DT + (1 Participants)	5542.1 (<0.1%)	5562.3 (<0.1%)
glm1: Answer ~ DT + (DT Participants)	5472.0 (0.7%)	5505.7 (98.1%)
glm2: Answer ~ DT + Test + (DT Participants)	5473.2 (0.4%)	5513.6 (1.9%)
glm3: Answer ~ DT + Test + (DT + Test Participants)	5476.7 (<0.1%)	5537.3 (<0.1%)
glm4: Answer ~ DT * Test + (DT + Test Participants)	5462.4 (92.6%)	5529.8 (<0.1%)
glm5: Answer ~ DT * Test + (DT * Test Participants)	5467.8 (6.2%)	5562.1 (<0.1%)

Table 2. Results of the model comparison for the second experimental question. In parentheses, information criteria weights are reported.

	Chi square	Df	p -value
DT	658.58	1	<2*10 ⁻¹⁶ ***
Test	2.38	2	0.30
DT*Test	23.51	2	7.87*10 ⁻⁶ ***

Table 3. Analysis of deviance of model 4. Df = Degree of freedom. DT = differences in temperature. Test = categorical variable indicating whether the results belong to the previous experiment (Battistel et al., 2023), or the congruent condition of the current one, or the incongruent condition.

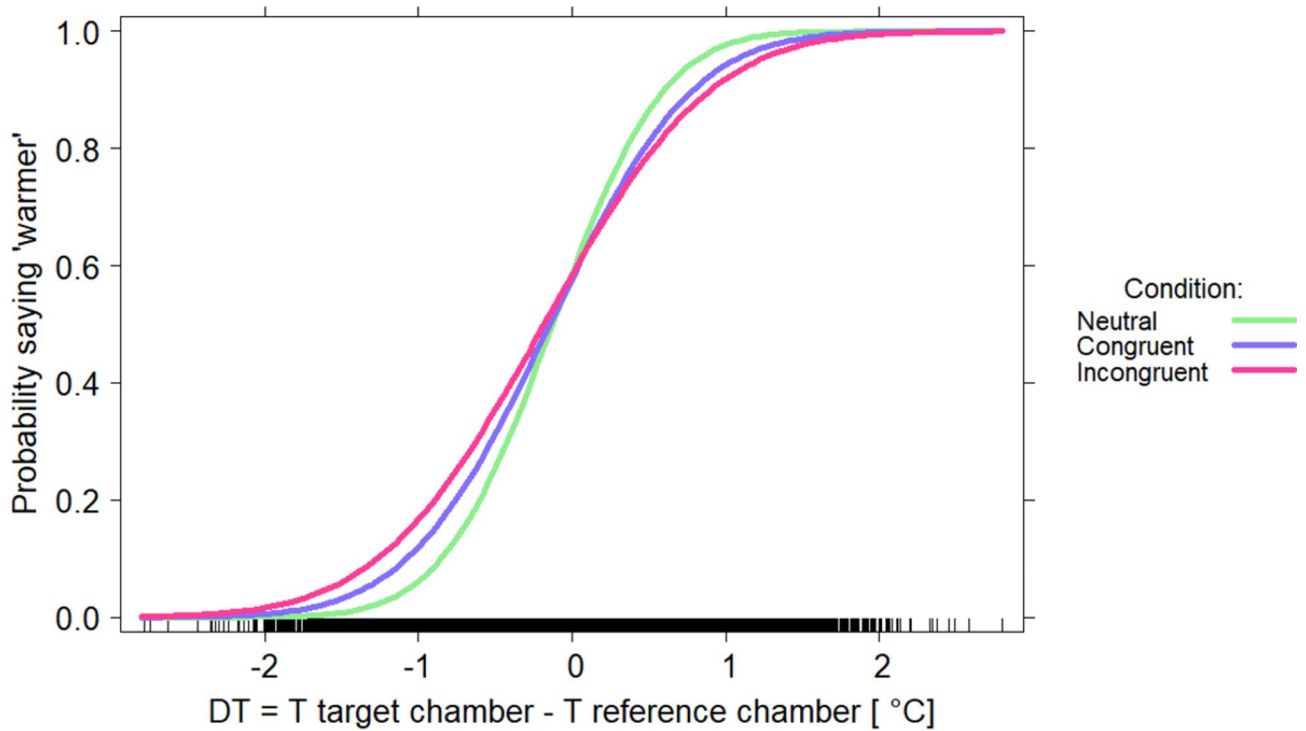


Fig. 1. Interaction effect between the differences in temperature and the type of condition. The black marks on the x-axis indicate the distribution of the data along the tested temperature range.

Test	PSE	JND	JND ⁹⁵
No colour	-0.13	0.40	0.97
Congruent colour	-0.13	0.51	1.24
Incongruent colour	-0.14	0.67	1.62

Table 4. Psychometric value for the two experiments.

differences in the colour of the lights compared to when they were congruent and incongruent with the temperature differences.

Blue target chamber vs. red target chamber

Given the observed general decrease in participants’ performance in this experiment compared to the previous one¹⁷, we conducted an explorative analysis to identify the factors that may have impacted the manipulation of the colour of the lights. Namely, we examined the detailed outcomes when the target chamber was illuminated with either blue lights or red lights. The model comparison in Table 5 indicates a discrepancy between the more explorative AIC criterion, which favours model 3 (65.3%), and the more conservative BIC criterion, which favours model 1 (44.4%). We proceeded with the analysis using model 3, which explains 50% of the data variance (R² marginal = 47.6%; R² conditional = 51.9%). This model indicates that there is a difference in the responses

Model	AIC	BIC
glm0: Answer ~ DT + (1 Participants)	3109.6 (<0.1%)	3127.8 (30.1%)
glm1: Answer ~ DT + (DT Participants)	3096.8 (0.6%)	3127.0 (44.4%)
glm2: Answer ~ DT + Colour + (DT Participants)	3091.9 (7.3%)	3128.1 (25.4%)
glm3: Answer ~ DT + Colour + (DT + Colour Participants)	3087.5 (65.3%)	3141.8 (<0.1%)
glm4: Answer ~ DT * Colour + (DT + Colour Participants)	3089.3 (26%)	3149.7 (<0.1%)
glm5: Answer ~ DT * Colour + (DT * Colour Participants)	3096.4 (0.8%)	3180.9 (<0.1%)

Table 5. Results of the model comparison for the third experimental question. In parentheses, information criteria weights are reported.

when the target chamber was illuminated with red lights compared to blue lights. Although the effect of colour is not statistically significant, it approaches the threshold of statistical significance (p -value = 0.08), as shown in the fixed effect (Table 6). Plotting the effect (Fig. 2), it is evident that, in line with the hue-heat hypothesis, the red lights increase the probability of indicating warmer, whereas blue lights increase the probability of indicating colder. Moreover, model 3 incorporates the colour of the lights also as random effect, highlighting the presence of individual differences in the effect of light colours. To better understand why this occurred, we analysed the behaviour of individual participants.

Single participant analysis

Given the discrepancy in the analysis of the effect of the colour of the target chamber and recognising the importance of treating this variable as a random effect, we opted to delve into the single participants' responses to better understand the variations in their behaviour. We conducted an explorative analysis by separating the congruent and incongruent conditions, and calculating each participant's JND and JND⁹⁵. We used a Generalised Linear Model (GLM) to calculate the probability of responding warmer as a function of the temperature differences. The results are detailed in the Supplementary Materials, Table S1. As evident in Fig. 3, a subset of participants exhibited a behaviour contrary to expectations (data framed in black). In particular, they exhibited smaller JND in the incongruent condition than in the congruent one, indicating better performance when the colour of the lights did not align with the differences in temperature.

Given this unexpected result, we reanalysed the data separated for the two groups using Generalised linear mixed models to investigate how light colours differently affected the temperature judgments for the two groups (see Table 12). In particular, the two groups were formed by the participants that behaved as expected by the hue-heat effect (i.e., the ones with smaller JNDs in the congruent condition: P1, P2, P4, P6, P7, P8, P11, P12, P13, P15, P16, P17, P19, P20, P21, P25) and the participants who exhibited the opposite pattern (i.e., the ones with smaller JNDs in the incongruent condition: P3, P5, P9, P10, P14, P18, P22, P23, P24, P26).

In the model comparison for the group that behaved according to expectations (Table 7) both information criteria AIC (93.5%) and BIC (> 99.9%) favour model 2, indicating that participants behaved differently based on the colour of the target chamber. This model explains more than 50% of the data variance (R^2 marginal = 48.3%; R^2 conditional = 53.3%) and shows a highly significant effect of the colour of the lights (p -value < 0.0001, Estimate = 0.41) with red lights prompting the answer "warmer" and blue lights prompting the answer "colder" (Fig. 4).

	Chi square	Df	p -value
DT	364.11	1	< 2×10^{-16} ***
Colour	2.99	1	0.08

Table 6. Analysis of deviance of model 3. Df = Degree of freedom. DT = differences in temperature. Colour = categorical variable indicating whether the target chamber was illuminated with blue lights or red ones.

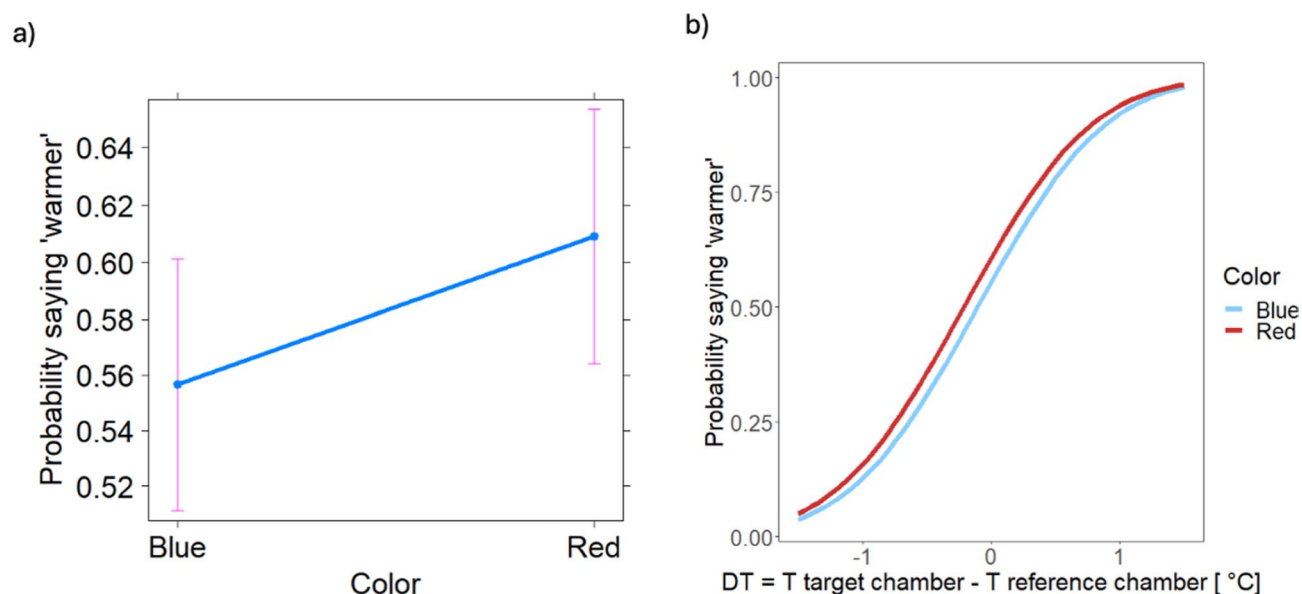


Fig. 2. Panel (a) shows the effect of colour on participants' probability of saying "warmer". Panel (b) shows the psychometric functions when the target chamber had blue versus red lights.



Fig. 3. JND in the congruent and incongruent conditions for each participant. In black are highlighted the participants who behaved opposite to what was expected (i.e., those who JND in the incongruent condition is smaller than in the congruent one).

Model	AIC	BIC
glm0: Answer ~ DT + (1 Participants)	1917.7 (<0.1%)	1934.4 (<0.1%)
glm1: Answer ~ DT + (DT Participants)	1903.8 (<0.1%)	1931.5 (<0.1%)
glm2: Answer ~ DT + Colour + (DT Participants)	1869.5 (93.5%)	1902.8 (>99.9%)
glm3: Answer ~ DT + Colour + (DT + Colour Participants)	1875.5 (4.7%)	1925.4 (<0.1%)
glm4: Answer ~ DT * Colour + (DT + Colour Participants)	1877.5 (1.7%)	1932.9 (<0.1%)
glm5: Answer ~ DT * Colour + (DT * Colour Participants)	1884.6 (<0.1%)	1962.2 (<0.1%)

Table 7. Results of the model comparison for the group of participants who behaved as expected.

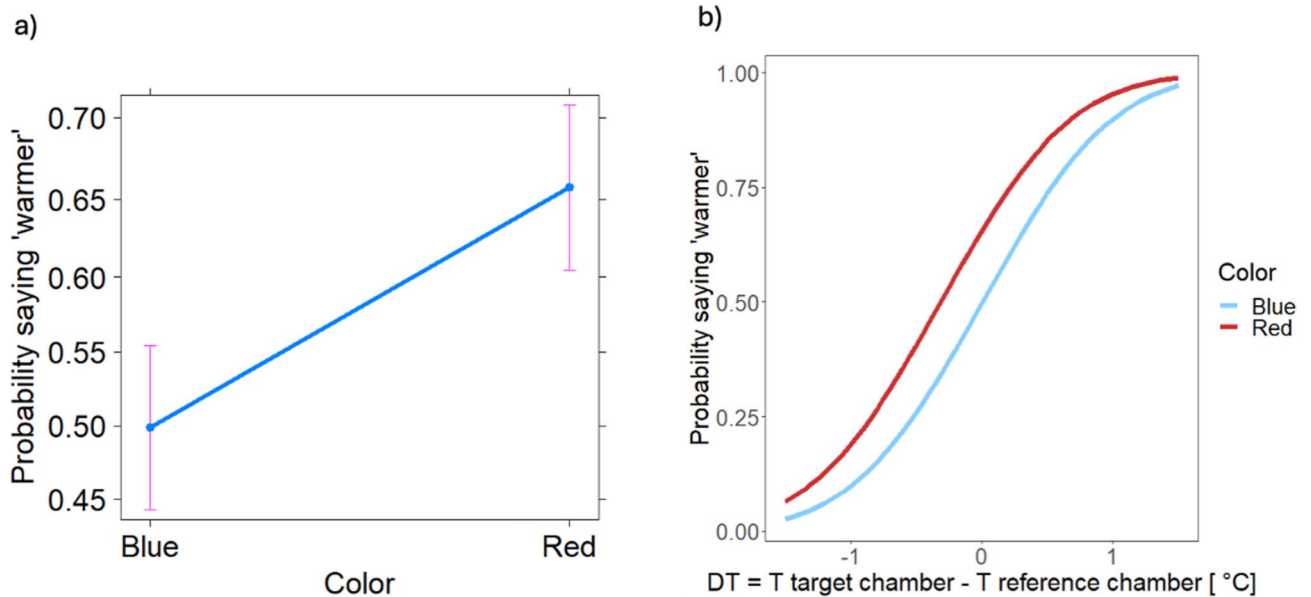


Fig. 4. Panel (a) shows the effect of colour on participants' probability of saying "warmer" for the group who behaved as expected. Panel (b) shows the psychometric functions when the target chamber had blue versus red lights for the group who behaved as expected.

When considering the group of participants that behaved contrary to expectations, the model comparison reveals a discrepancy between the AIC information criterion, which favours model 2 (85.0%) and the BIC one, which favours model 0 (99.1%; see Table 8). To gain a better understanding of the possible effect of the colour, we proceeded with the analysis using model 2, indicating that participants' temperature judgments changed depending on the colour of the target chamber. This model explains 50% of the data variance (R^2 marginal = 49.3%; R^2 conditional = 50.2%) and demonstrates a highly significant effect of the colour of the lights (p -value < 0.01, Estimate = -0.28) with red increasing the probability of participants answering "colder" and blue "warmer" (Fig. 5).

Discussion

The aim of this study was to investigate the potential impact of the hue-heat effect⁷ on thermal sensitivity. Specifically, our hypothesis posited that congruent lights, involving the use of red lights in the warmest chamber and blue lights in the coldest chamber, would enhance participants' sensitivity to temperature differences. This hypothesis is grounded in previous research indicating that warm colours (e.g., yellow and red) create the perception of a warmer environment, whereas cool colours (e.g., green and blue) evoke a sense of coldness (e.g.,¹⁹). We anticipated superior performance in the congruent condition, where the colour of the lights should accurately amplify thermal perception, enhancing accuracy. On the contrary, in the incongruent condition, we expected to observe diminished performance, as the colour of the lights would create a mismatch between participants' thermal and visual information, leading to potential confusion and an increased likelihood of errors in their responses.

Differently from what was expected, we did not observe any statistically significant difference between the congruent and incongruent conditions (p -value = 0.29). The generalised linear mixed model that provided the best fit for the data included only differences in temperature as fixed effect (AIC weights = 63%; BIC weights = 58.9%; R^2 marginal = 47%; R^2 conditional = 51%). This suggests that the introduction of different colours of lights within the climate chambers did not have a significant impact on participants' perception of the environmental temperature.

Model	AIC	BIC
glm0: Answer ~ DT + (1 Participants)	1196.5 (5.2%)	1211.8 (99.1%)
glm1: Answer ~ DT + (DT Participants)	1199.9 (0.9%)	1225.4 (0.1%)
glm2: Answer ~ DT + Colour + (DT Participants)	1190.9 (85.0%)	1221.5 (0.8%)
glm3: Answer ~ DT + Colour + (DT + Colour Participants)	1196.2 (6.0%)	1242.0 (<0.1%)
glm4: Answer ~ DT * Colour + (DT + Colour Participants)	1197.7 (2.8%)	1248.6 (<0.1%)
glm5: Answer ~ DT * Colour + (DT * Colour Participants)	1206.9 (<0.1%)	1278.2 (<0.1%)

Table 8. Results of the model comparison for the group of participants who behaved opposite to what was expected.

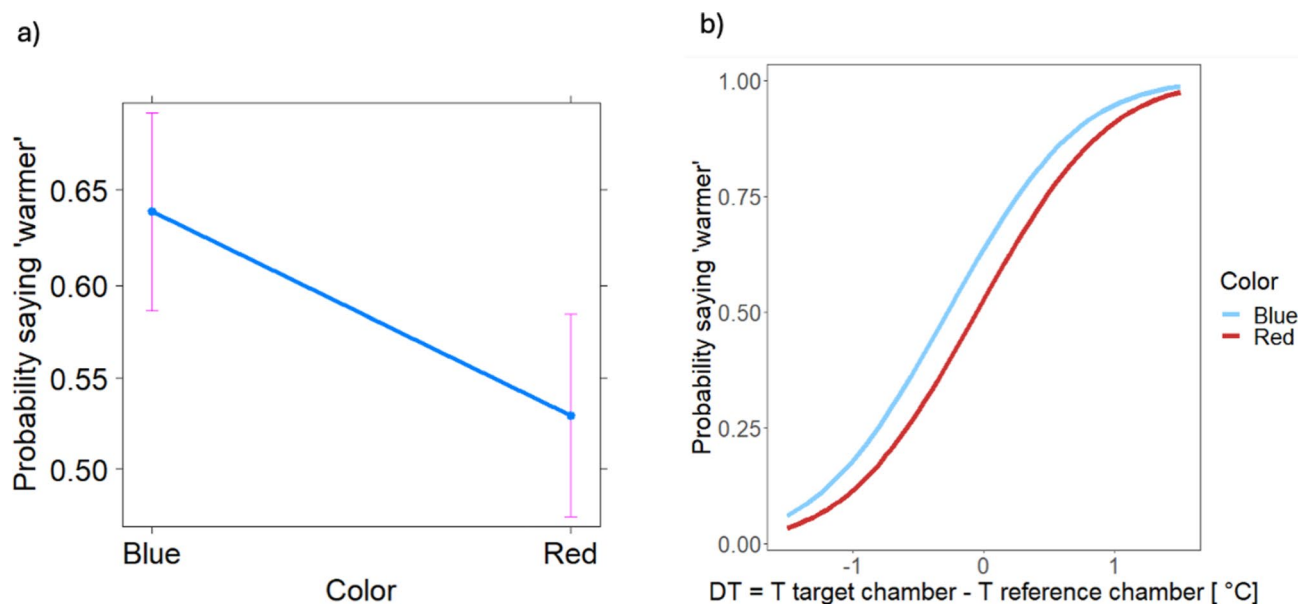


Fig. 5. Panel (a) shows the effect of colour on participants' probability of saying "warmer" for the group who behaved opposite to what was expected. Panel (b) shows the psychometric functions when the target chamber had blue versus red lights for the group who behaved opposite to what was expected.

To further investigate the effectiveness of the colour manipulation, we compared the current results with those obtained in our previous work¹⁷. Such a comparison showed that while adding different colours of the lights led to an effect, it resulted in a general decrease in participants' performance, as shown by the higher JND and JND⁹⁵ of this experiment compared to the previous one (previous experiment versus congruent condition: p -value < 0.01; previous experiment versus incongruent condition: p -value < 0.001). The expected difference between the congruent and incongruent conditions was not found. However, the results revealed an overall decline in performance in the current experiment when compared to the condition without different colours of the lights (i.e., the previous experiment). Although this effect was not anticipated, it could be explained by considering the possibility that our previous experiment exhibited a ceiling effect. In other words, it is plausible that our sensitivity to the environmental temperature under the previously tested conditions is already highly accurate, making the addition of one more piece of information (i.e., the visual cue given by different colours of the lights) redundant. Alternatively, the addition of information could potentially distract participants, thereby reducing their accuracy. Strelnikov and colleagues²⁰ demonstrated a similar phenomenon, illustrating that multisensory information can impair inhibitory processing. They proposed that when information is presented through multiple stimuli from different sensory modalities, it may be perceived as concurrent stimuli rather than a unified object. In such cases, the cognitive load required to make a decision increases, and the multisensory stimulus hinders the ability to revise the answer. This example suggests that in our previous experiment, we might have identified the ideal conditions for enhancing human thermal sensitivity. Conversely, in the present study, we might have increased participants' cognitive load, reducing their performance capabilities. Researchers are currently exploring the ideal environmental conditions for humans to optimise their performance. For instance, companies like NASA, Nike, Biostrap, Strobilo.life, and ThermHuman are actively studying the impact of environmental temperature on cognitive functions and athletic abilities to determine the most efficient settings.

An alternative explanation could be that the explicit association between colours and temperature²¹ may have influenced participants' behaviour. Despite being instructed to ignore the colour of the lights, participants may have engaged in reasoning processes or mental associations that diverted their attention from the core task of making thermal judgments. This potential cognitive bias could have interfered with their performance and affected the outcomes of the experiment.

Our data did not provide significant support in favour of the hue-heat hypothesis. When examining the data from the perspective of the colour rather than the condition (i.e., dividing the data between trials where the target chamber was illuminated in blue and those where it was red), the best-fitting Generalised linear mixed model includes the variable colour as both fixed and random effect (AIC weights = 65.3%; R^2 marginal = 47.6%; R^2 conditional = 51.9%). This suggests that our participants behaved differently when judging the temperature inside a red or blue chamber. In particular, examining the plotted data (Fig. 3) it is apparent that a red target chamber generally increased the probability of participants reporting it as warmer than the reference chamber. Conversely, a blue target chamber increased the probability of answering colder. Nonetheless, this effect is not significant, hovering close to the statistically significant threshold (p -value = 0.08), not allowing to obtain conclusive results on the role of light colours.

We further investigated the hue-heat effect by looking into model 3 (see Table 5), where the variable colour is a random effect, indicating that different participants exhibited different behaviours to the colours. Therefore, we delved into single participants' answers and identified two different populations: one adhering and one not to the hue-heat hypothesis. One possible explanation emerged during a debriefing session with one participant. This participant reported adopting a defined strategy when uncertain about the perceived temperature: the participant intentionally answered in the opposite direction of the colour of the lights. Aware of the usual association of red with warmth and blue with cold, this participant adopted this approach to avoid potential deception. Consequently, if the target chamber was illuminated with blue lights, this participant responded "warmer", whereas if it was illuminated with red lights, they responded "colder". As a result, this participant consistently provided correct answers in the incongruent condition and consistently incorrect answers in the congruent condition, leading to smaller JNDs in the former and larger JNDs in the latter.

While it cannot be generalised that all participants displaying behaviour contrary to expectations employed the same reasoning (to ensure this aspect, we later asked participants to perform the Balanced Inventory of Desirable Responding (BIDR-16) and ensure that none of them was inclined to behave as they thought the experimenter hoped. Moreover, in the post-experiment interview, we asked participants what they thought the purpose of the study was. While the majority believed the lights were somehow involved, almost none understood the real aim), this example suggests that participants may have been aware of the colour-temperature association and may have been influenced by it. Some participants may have been biased in the expected direction (responding according to the colour when uncertain about temperature), while others may have been biased in the opposite direction (responding contrary to the colour when uncertain about temperature). The stark difference in the colour of the lights may therefore represent a limitation of the current study, and future research could consider replicating the experiment using warm and cold white lights instead of blue and red ones to minimise potential biases in participants' responses. Another potential approach to further investigate the potential influence of the hue-heat effect on thermal perception would be to modify the current methodology. For example, both the reference and target chambers could be illuminated with the same colour (e.g., both red or both blue). This modification would help to determine whether colour alone biases participants' thermal perception, thereby isolating the effect of colour from the hue-heat interaction. Moreover, researchers could employ alternative measures, such as implicit tests based on reaction time, to assess participants' susceptibility to the hue-heat effect. This strategy would help ensure that participants remain unaware of the association between colours and lights under investigation, thereby reducing potential bias in their behaviour and enhancing the ecological validity of the findings.

Furthermore, additional investigations could aim to address the limitation of having participants who were likely aware of the hue-heat association occurring during the experiment. This awareness may have led to the

use of different strategies in responding to the task, resulting in noticeable interindividual differences. Variations among individuals could be a factor contributing to the complexity observed in the thermal comfort literature, with some studies proving the effectiveness of the hue-heat hypothesis and others failing in this intent. For this reason, future experiments are crucial to further elucidate whether the hue-heat effect can manifest a tangible impact in real-life scenarios. For instance, future studies could investigate which personality traits, along with other participant characteristics, may influence the effectiveness of the hue-heat effect. Identifying these factors could benefit researchers in the field of thermal comfort by providing alternative solutions to enhance thermal perception without directly altering the environmental temperature. Furthermore, future studies aiming to assess the individual differences we observed could benefit from larger sample sizes. Lastly, future studies could explore the ceiling effect identified in our prior research¹⁷ and examine whether alternative manipulations could enhance our thermal sensitivity.

Conclusion

In this experiment, we investigated the validity of the hue-heat effect in relation to thermal sensitivity. Previous research in the field of thermal comfort has suggested that red is associated with warmth and blue with cold. Nevertheless, inconsistent findings in past studies and potential confounds introduced by subjective scales used to assess thermal comfort prompted us to focus on exploring the hue-heat effect on thermal sensitivity. Our study involved participants comparing perceived temperatures inside climate chambers illuminated by either red or blue lights. The congruent condition had red lights in the warmest chamber and blue lights in the coldest chamber, while the incongruent condition had the opposite arrangement. Our hypothesis posited that participants would exhibit superior performance in the congruent condition, as the colour would align with the expected temperature meaning. However, our analysis did not support this hypothesis, revealing comparable performance in both conditions, which was also inferior to our previous study¹⁷. These findings may suggest a potential ceiling effect in the previous experiment. Instead, the additional visual information may have led to an increase in the cognitive load, leading to interference and diminished performance. Notably, two distinct participant groups were identified, one showing better performances in the congruent condition than in the incongruent one, and another displaying the opposite pattern. While the reason for these distinct groups remains unclear, it could be indicative of the existence of a conscious bias for the association between red and warm and blue and cold. Nevertheless, our primary findings suggest that human thermal sensitivity remains highly accurate under the examined conditions, and additional cues, such as variations in light colour, do not appear to significantly influence the formation of thermal judgments.

Methods

Participants

A total of 26 participants took part in this study (50% females). Their demographic characteristics are detailed in Table 9. A priori power analysis determined the sample size, aligning with our previous research methodology¹⁷. Inclusion criteria for participants comprised an age range of 18–65 years old, and the ability to provide informed consent. Exclusion criteria included a history of psychiatric or neurological conditions, cardiac illness, health or sensory conditions that could lead to skin alterations (e.g., psoriasis), claustrophobia, and colour-blindness (assessed through subjective self-report from participants). The study was approved both by the ethical committee of the University of Trento and by the ethical committee of the Azienda Sanitaria of the province of Bozen, and was conducted in compliance with the principles outlined in the Declaration of Helsinki (Fortaleza, 2013).

Following the same methodology as in our previous work¹⁷, participants completed a list of questionnaires designed to assess pertinent psychological information and habits. In particular, they filled in the Experienced Temperature Sensitivity and Regulation Survey (ETSRS²²), the Empathy Quotient (EQ²³), the Body Perception Questionnaire (BPQ²⁴), and the Global Physical Activity Questionnaire (GPAQ²⁵). The ETSRS was used to categorize participants based on their preferences for either cold or warm temperatures. The EQ is a valuable tool for obtaining participants' empathy levels, enabling subsequent analysis to explore potential correlations between this psychological construct and temperature perception. Similarly, the BPQ enables to investigate whether varying degrees of self-awareness concerning one's body may influence temperature sensitivity. Lastly, the GPAQ allows the evaluation of participants' daily physical activity levels, considering the substantial movement required

26 participants	Age	Sex	BMI	Place of birth	Temperature preferences	EQ	BPQ_BOA	BPQ_ASR	GPAQ_m	GPAQ_i
characterisation	max 63; min 23	50% females	max 27.89; min 18.59	22 born in north Italy, 3 born in south Italy, 1 born in Albania	5 prefer warm, 12 no preferences, 9 prefer cold	4 subj. < cut-off	9 subj. < cut-off	5 subj. > cut-off	3 subj. < cut-off	8 subj. < cut-off
Average	34	/	21.81	/	/	42	20	15	478	183
St. deviation	11	/	2.13	/	/	9	6	3	384	173

Table 9. Participants' (n = 26) demographic information. EQ = Empathic Quotient (cut-off < 33); BPQ_BOA = Body Perception Questionnaire_Body Awareness (cut-off < 18); BPQ_ASR = Body Perception Questionnaire_Autonomous System Stress Response (cut-off > 16); GPAQ_m = Global Activity Questionnaire_moderate level of activity (cut-off < 150 min); GPAQ_i = Global Activity Questionnaire_intense level of activity (cut-off < 75 min).

during the experiment. For a deeper explanation of the rationale behind these questionnaires, we refer to our previous work¹⁷.

All participants were instructed to wear the same clothes (i.e., long jeans and T-shirt) to ensure the same level of thermal insulation and allow the comparison.

Apparatus

We used four climate chambers connected through an airlock (see Figure S1 for a more detailed description of its temperature) to perform our experiment. In particular, within these chambers, the temperature continuously fluctuated between 23 and 25 °C, monitored through three PT100 temperature sensors per chamber. For a more detailed explanation of the setup, we kindly direct readers to our previous publication¹⁷. Moreover, in the present experiment, we introduced an additional manipulation involving the colour of the lights (see Fig. 6). In particular, the colour of the lights was either red (wavelength = 730 nm) or blue (wavelength = 475 nm), with their radiative power maintained at a constant 30 W to prevent any impact of LED-induced on participants' thermal judgments. To implement this light manipulation, we developed an algorithm designed to automatically compare the temperature of two specified climate chambers, determining which one was warmer to activate either the blue or red LED lights. Following a series of trials where room temperature and light colours were randomised, the experimenter selected which chambers to compare and whether the relationship between the colour of the lights and the temperature difference should be congruent or incongruent. Consequently, the algorithm turned on the red lights in the warmest chamber and the blue lights in the coldest (congruent condition), or the blue lights in the warmest chamber and the red lights in the coldest (incongruent condition).

Procedure

Before starting the experiment, participants signed the informed consent forms. Subsequently, they received a T-shirt from the experimenter and were then invited to enter the airlock. Within the airlock, participants underwent a comprehensive briefing session, during which the experimenter provided a detailed explanation of their task and an overview of the experiment's procedures. In particular, the experimenter explained to them that their task involved transitioning between two climate chambers: a reference chamber and a target chamber, wherein the temperature was continuously changing in both environments. Participants were required to indicate whether the target chamber felt warmer or colder than the reference chamber. The experimenter emphasised the random changes in the colour of the lights and underscored that participants should not focus on this aspect. In particular, during the experiment, the lights inside the chambers could be either blue or red, following congruent and incongruent conditions. In the congruent condition, the chamber determined to be the warmest had red lights and the coldest had blue lights. Conversely, in the incongruent condition, the warmest chamber had blue lights, and the coldest had red lights. Notably, the hue-heat effect was respected in the congruent condition but not in the incongruent one. Following the experimenter's explanation, participants were given a 5-min acclimatisation period before the start of the experimental procedure.

More specifically, the experimental task was structured into the following steps: (i) participants were instructed to enter the reference chamber and focus on the temperature within it for a duration of 5 s; (ii) subsequently, they were instructed to move to the target chamber and once again focus on its temperature for additional 5 s; (iii) once left the target chamber, participants utilised a walkie-talkie to communicate with the experimenter and report whether the target chamber felt warmer or colder compared to the reference chamber.

Each of the five experimental blocks consisted of 24 trials, with 12 trials in the congruent condition and 12 trials in the incongruent condition. This resulted in a total of 60 trials for the congruent condition and 60 trials for the incongruent one across the experiment, amounting to 120 trials overall for each participant. To minimise potential biases, the order of the congruent and incongruent conditions within each block was randomised, ensuring that no more than 5 consecutive trials of the same condition occurred. This randomisation strategy

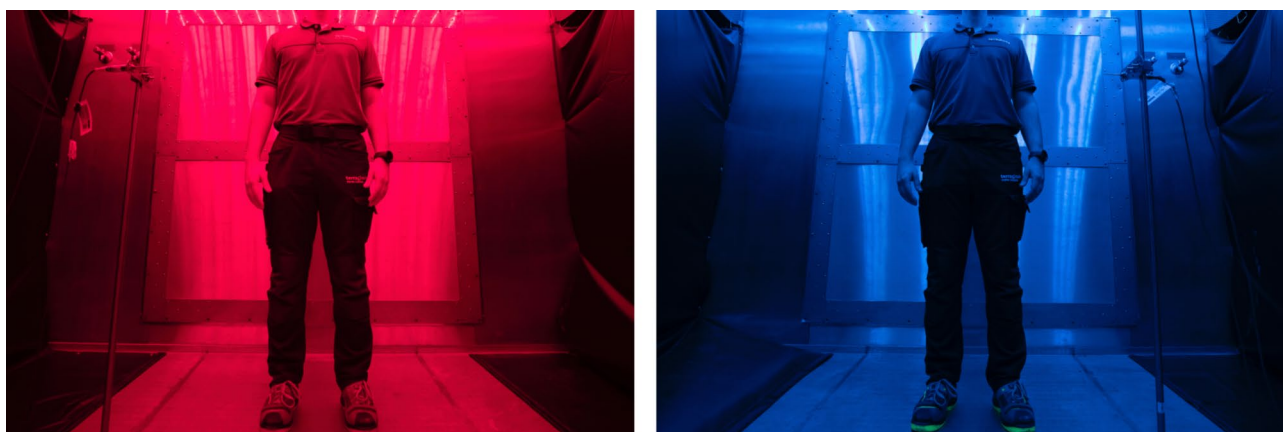


Fig. 6. Example of how the climate chambers looked like with the red (left) and blue lights (right) turned on © Eurac Research | Andrea De Giovanni.

aimed to prevent participants from recognising any discernible relationship between the colour of the lights and the temperature differences.

The experiment consisted of 5 blocks, with each block comprising 24 comparisons, resulting in a total duration of 15 min per block. Including proper breaks, as well as initial and final preparation and briefing time, the overall duration of the experiment extended to approximately 120 min. Throughout the entire experiment, a reliable connection was maintained between the experimenter and the participants using two walkie-talkies and five video cameras.

Analysis

For each trial, we gathered data on the temperature differences between the target and the reference chamber and the corresponding answer, with 0 meaning “colder” and 1 meaning “warmer”. Moreover, we classified each trial as belonging to either the congruent or incongruent condition. Overall, our data set comprises 3096 observations, collected from 25 participants who completed all 5 experimental blocks and 1 participant who completed only 4 blocks (due to personal reasons that led to the interruption of the test), resulting in 96 trials instead of the regular 120. The dataset includes 4 variables: participant (i.e., subject’s ID), temperature difference (DT), condition (i.e., congruent or incongruent), and answer.

We then proceeded to address the first main research question: is there a difference between the congruent and incongruent conditions? Namely, we evaluated how participants’ answers were affected by the interaction between the difference in temperature and the congruency or incongruency of the colour of the lights. To do that, Generalised Linear Mixed Models (GLMMs^{26,27}) were used. GLMMs allow to model non-normally distributed data using appropriate probability distributions that reflect the characteristics of the data. Specifically, we used probit regression to model the participants’ probability of answering “warmer”. Moreover, Mixed Models were used to account for the repeated measures design of the experiment (i.e. observations nested within subjects). In particular, we compared different models, going from the simplest (considering only the temperature differences as fixed effect and the participants’ ID as random effect) to the most complex (considering the interaction between the differences in temperature and the condition as both fixed effect and random effect depending on participants’ ID) (see Table 10). The obtained models were compared based on their support by the data and complexity using the information criteria AIC²⁸ and BIC²⁹ with lower values indicating a better model¹⁸. Subsequently, the selected model was assessed by considering goodness-of-fit indices Marginal R² (i.e., variance explained by fixed effects) and Conditional R² (i.e., variance explained by both fixed and random effects³⁰).

The second question analysed was: is there a difference between the current results and our previous ones¹⁷? In other words, we investigated whether introducing different light colours enhances sensitivity in the congruent condition compared to the condition with neutral white lights, and conversely, whether it diminishes participants’ accuracy in the incongruent condition compared to the condition with neutral white lights. The same experimental design was used in both studies, with the only difference of the light colours (fixed white neutral lights in the previous experiment, blue-red lights colour in the current one). For a comparison of descriptive statistics of the two samples, see Table S5. Again, we estimated different Generalised linear mixed models (see Table 11) and

glm0: Answer ~ DT + (1 Participants)
glm1: Answer ~ DT + (DT Participants)
glm2: Answer ~ DT + Condition + (DT Participants)
glm3: Answer ~ DT + Condition + (DT + Condition Participants)
glm4: Answer ~ DT * Condition + (DT + Condition Participants)
glm5: Answer ~ DT * Condition + (DT * Condition Participants)

Table 10. The six Generalised linear mixed models employed to analyse the effect of the difference in temperature and the condition on the participants’ accuracy. Answer = participants’ answers. DT = Differences in temperature. Condition = congruent condition vs incongruent condition. Participants = Participants’ ID.

glm0: Answer ~ DT + (1 Participants)
glm1: Answer ~ DT + (DT Participants)
glm2: Answer ~ DT + Test + (DT Participants)
glm3: Answer ~ DT + Test + (DT + Test Participants)
glm4: Answer ~ DT * Test + (DT + Test Participants)
glm5: Answer ~ DT * Test + (DT * Test Participants)

Table 11. The six Generalised linear mixed models employed to analyse the difference between the conditions of this experiment and the previous one (Battistel et al., 2023). Answer = participants’ answers. DT = Differences in temperature. Test = categorical variable indicating whether the results belong to the previous experiment (Battistel et al., 2023), or the congruent condition of the current one, or the incongruent condition. Participants = Participants’ ID.

glm0: Answer ~ DT + (1 Participants)
glm1: Answer ~ DT + (DT Participants)
glm2: Answer ~ DT + Colour + (DT Participants)
glm3: Answer ~ DT + Colour + (DT + Colour Participants)
glm4: Answer ~ DT * Colour + (DT + Colour Participants)
glm5: Answer ~ DT * Colour + (DT * Colour Participants)

Table 12. The six Generalised linear mixed models employed to analyse the difference between entering a blue target chamber or a red one. Answer = participants' answers. DT = Differences in temperature. Colour = categorical variable indicating whether the target chamber was illuminated with blue lights or red ones. Participants = Participants' ID.

compared them using the AIC and BIC information criteria. Finally, we calculated the different psychometric values, including the Point of Subjective Equality (PSE), the Just Noticeable Difference at 75% of accuracy (JND), and the Just Noticeable Difference at 95% of accuracy (JND⁹⁵) and compared them through Wilcoxon test.

Subsequently, we conducted a more detailed analysis within the congruent and incongruent condition, asking: is there a difference between the effect caused by red lights and by blue ones? Namely, we analysed whether entering a target chamber with blue lights conveys a feeling of cold with respect to red, which should transmit a sensation of warmth. Once again, we computed different Generalised linear mixed models (see Table 12) and compared them through means of the information criteria AIC and BIC.

Analyses were conducted with R (version 4.1.2; R Core Team, 2021). Statistical analyses were conducted with the following package: tidyverse, lme4, mgcv, ggplot2, ggdist, mixedpsy, readxl, effects.

Data availability

Anonymous data and analysis script can be shared on request by contacting the first author Laura Battistel at her personal email address: laura.battistel@eurac.edu.

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Author contributions

L.B.: experiment conceptualisation, investigation, software, data analysis, writing—original draft and editing; Z.C.C.: data analysis, writing—review and editing; M.Z.: experiment conceptualisation, writing—review and editing; R.P.: experiment conceptualisation, writing—review and editing, funding acquisition.

Competing interests

The authors declare no competing interests.

Additional information

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