The effects of the correlated colour temperature of light on thermal sensation in the built environment: a systematic review and meta-analysis

The effects of the correlated colour temperature of light on thermal sensation in the built environment: A systematic review and meta-analysis

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Highlights:

- Systematically reviewed correlated colour temperature impact on thermal sensation;
- The heterogeneity sources of existing studies were identified;
- Higher CCT induces cooler sensations in neutral and warm environments;
- The effect of CCT on thermal sensation only occurs in a short time of exposure;
- Illuminance levels do not affect the effect of CCT on thermal sensation.

Abstract:

Recently, the effect of the correlated colour temperature (CCT) of light on human thermal sensation has drawn much attention from the built environment area because of its potential application to change indoor comfortable temperature set points and save energy in buildings. Many studies have been conducted on this topic, and the results have proved inconsistent, making them difficult to use in actual practice. To further understand the validity and application range of the effect, it is urgent to research and reflect on a heterogenous selection of relevant studies. Thus, this paper aims to conduct a systematic review of existing studies, investigate the reasons for heterogeneity and explore the effect of moderators on experimental results. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used for the systematic review, while the method of Meta-analysis was utilised to investigate the reasons for heterogeneity and the effect of moderators. The meta-analysis found that a higher CCT can lead to a cooler thermal sensation, while environmental factors, such as the background thermal environment, temperature and exposure duration, moderate the effect's magnitude. The results of the meta-analysis suggest that in the thermally neutral environment, the effect of CCT on thermal sensation is most significant. Meanwhile, the magnitude of the effect diminishes with the duration of exposure. For the first time, this study explains the reasons for the heterogeneity of existing studies and reveals the influence of moderators on the thermal effect of CCT.

Keywords:

Non-visual effects, IEQ, Hue-Heat Hypothesis, CCT, Thermal comfort, Thermal sensation

Abbreviations:

CCT

Correlated Colour Temperature

HHH

Hue-Heat Hypothesis

HVAC

Heating, Ventilation and Air-Conditioning

TSV

Thermal Sensation Vote

1 Introduction

1.1 Background

Under the climate change and the global energy saving and carbon neutrality movement [1, 2], recently, the effect of light's correlated colour temperature (CCT) on human thermal sensation has drawn much attention from the built environment area because of its potential application to change indoor comfortable temperature set points and save energy in buildings.

The building sector consumes approximately 40% of energy worldwide [3], with the heating, ventilation and air-conditioning (HVAC) system accounting for about half of such consumption [4]. One major factor impacting HVAC systems' energy consumption is the indoor setting temperature, which depends on people's comfort level [5, 6]. In this case, efforts (such as the well-established thermal adaptive model [7, 8]) were made to increase comfort temperature in the cooling season and reduce it in the heating season while guaranteeing acceptable thermal conditions. Studies have shown that expanding the range of indoor setting temperatures in office buildings can achieve 27-29% HVAC energy savings [9] and reduce annual energy demand by up to 9.9% [10].

Light, one of the most powerful stimuli affecting human perception in the built environment, is also considered to impact thermal sensation, known as the Hue-Heat Hypothesis (HHH). According to this theory, humans' subjective sensation of thermal condition relies partly on ambient colour [11]: people exposed to light with high CCT will feel colder at the same air temperature, whereas they may feel warmer when exposed to light with a low CCT. This suggests the possibility of maintaining the same level of indoor thermal comfort with a relatively wider range of temperatures by simply adjusting the CCT level of lamps, thus reducing energy consumption [12, 13]. A study by Bellia et al. [14] indicated results that closely aligned with HHH, while subsequent dynamic daylighting simulations highlighted the energy-saving potential of implementing HHH alongside an integrated indoor lighting control strategy.

On the other hand, the discovery of non-visual effects of light enhances the interest in the thermal effect of CCT: neurophysiology evidence suggests the influence of light on human physiological and subjective responses. The non-visual effects of light encompass a wide spectrum of interactions with humans in terms of impact on circadian rhythms, sleep, cognition and thermophysiology [15-17]. It results from intrinsically photoreceptive retinal ganglion cells (ipRGCs), discovered by D. Berson in 2002 [18], which are sensitive to short-wavelength light [19]. The suprachiasmatic nucleus (SCN) receives signals from different light spectrums through ipRGCs. It adjusts the generation of hormones such as melatonin [20], vital in regulating human circadian rhythm and core body temperature [21]. Thus, as a main driver in changing the light spectrum, CCT may considerably affect human thermal perception.

1.2 The heterogeneity of current research

The early records aiming to identify the Hue-Heat Hypothesis with artificial light may be traced back half a century. In 1961, P.C. Berry *et al.* investigated the effect of coloured light on the levels of heat that people would tolerate, with results which suggested that there were no associations between them [22]. In 1977, P.O. Fanger *et al.* [23] conducted experiments to compare the preferred temperature of occupants exposed to red and blue light and found that subjects preferred a slightly lower (0.4°C) temperature in the extreme red light than in the others.

Most of the papers regarding this topic were shown to have been published within the last 10 years [24]; however, heterogeneity was found in their results. Some studies indicate that people perceived colder in higher ambient CCT [12, 13, 25-27], while results from others showed no difference at all in each scenario [28-30]. The reasons for the heterogeneity are complex. First, the magnitude of the impact of CCT may hinge on the ambient thermal environment. Brambilla *et al.* [31] concluded that CCT affects subjects' thermal sensation only in a warmer but not in a thermally neutral or colder environment. Likewise, J. Toftum *et al.* [32] suggested that CCT exerts its effects only in thermally neutral environments. Secondly, the impact of illumination level and exposure duration on experimental results is also deemed significant due to their influence on non-visual effects [33-36], which will be further discussed in later sections. Then, the difference in sample size and study design also increased ambiguity when comparing different studies [31]. Moreover, due to the difference in research purposes, not all experiments are conducted in a typical climate chamber or simulated office environment. For instance, several studies [37, 38] are conducted in simulated aircraft cabins with coloured light (rather than white light with different levels of CCT). Furthermore, as pointed out by Bellia et al. [26], the inadequate control of indoor thermo-hygrometric parameters is an important reason that leads to heterogenous results, such as insufficient regulation of luminance levels, poor measurement or control of microclimatic conditions, and other factors affecting thermal comfort. In fact, only a few studies offered all a complete characterisation of the key indoor parameters (e.g. indoor air temperature, humidity, the mean radiant temperature and the air velocity) that should be considered.

Scientists from multiple disciplines have reviewed this subject. M. te Kulve *et al.* [17] reviewed studies pertinent to the impact of light on subjects' thermal responses, discussing both thermal-physiological mechanisms and non-visual effects. This review supported the idea that light significantly impacts thermophysiological responses. Meanwhile, they pointed out that "how the conditions and the different parameters interact and influence human thermal responses" is unclear. N. Wang *et al.* [24] summarised the findings of 18 studies concerning the acute thermal effects of artificial light in the daytime. They reviewed experimental designs and settings and noted that the support for the Hue-Heat Hypothesis varied across these studies. H.S Mayes *et al.* [39] carried out a literature review of studies related to the visual environment and thermal perception, noting that "the methodological heterogeneity limits the generalizability of the findings". These reviews all pointed out the heterogeneity of results in existing studies. However, none of them investigated its possible reasons nor explored the associations between the results and moderators.

The heterogeneity of existing studies may make practitioners, such as designers, engineers and policymakers, hesitate to apply the thermal effect of CCT to actual practice because they cannot ensure the effectiveness of the application. Nevertheless, given that the heterogeneity can be attributed to experimental conditions and various moderators, it is reasonable to assume that by identifying the source of heterogeneity and further investigating the effect of moderators, we can delimit the applicability of existing studies, making their results applicable in actual practice. Thus, it is important to research the heterogeneity of studies on the effect of CCT on thermal sensation.

1.3 Aims of this study

This study aims to systematically review existing studies and conduct a meta-analysis to (i) reach a general conclusion about the effects of CCT of light on occupants' thermal sensation；(ii) identify the source of heterogeneity of studies；(iii) investigate the effect of moderators (i.e. temperature, exposure duration, illuminance level) on experiment results.

2 Methodology

The methodology of this study consists of three sections. First, we searched and selected target studies from scientific databases with keywords and rigorous criteria. Then we systematically reviewed the key characteristics of eligible studies. Third, we used the meta-analysis method to gather and synthesise data from independent studies while providing collective insights (i.e. the summary effect) [40]. This involves the identification of potential moderators that may influence the research outcomes and the exploration of potential mechanisms underlying these effects [40].

2.1 Literature and Studies Selection

The literature search process followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines [41], which are widely used to improve the transparency and quality of reporting for systematic reviews and meta-analyses. We used online databases, including PubMed, Web of Science, ScienceDirect, Scopus, Wiley, and Taylor & Francis, to search for peer-reviewed articles. Literature was searched from inception to March 31st, 2024. The search terms used were listed as follows: "correlated colour temperature", "CCT", "colour temperature", "Hue-Heat Hypothesis", combined with "thermal sensation", "thermal comfort" and "thermal perception". We also reviewed all sources cited in the original studies and reviews about this subject to avoid omitting relevant papers.

Only original research with full text available was included in the systematic review, while studies irrelevant to the effect of CCT on thermal sensation in built environments were excluded.

Furthermore, studies that did not meet the following criteria were excluded from the meta-analysis:

(i) Experiments that do not use artificial white light - to ensure greater consistency with real-world conditions, the meta-analysis includes only experiments conducted with artificial white light (rather than coloured light or natural light) since artificial white light is most commonly used in built environments.

(ii) Articles that do not allow for the calculation of the effect size - to guarantee that studies provide quantifiable data for comparison across research.

(iii) Studies that add extra intervening variables - to identify the effect of the primary variable by excluding studies with confounding factors.

The PRISMA flow chart summarising the study selection and exclusion process is shown in Fig. 1. Initially, 1,513 records were identified through database searches, supplemented by five additional records from other sources, making a total of 1,518 records. The next step was to remove duplicate records, resulting in 1,289 unique records. These records underwent a screening process where 1,266 were excluded based on their title and abstract, indicating they were irrelevant for the review. By reviewing the full text, in total 18 articles were included in the systematic review. Among them, 11 articles were deemed eligible and retained for use in the meta-analysis. Studies excluded from the meta-analysis for not meeting the inclusion criteria are listed in Table S1 (Supplementary Materials).

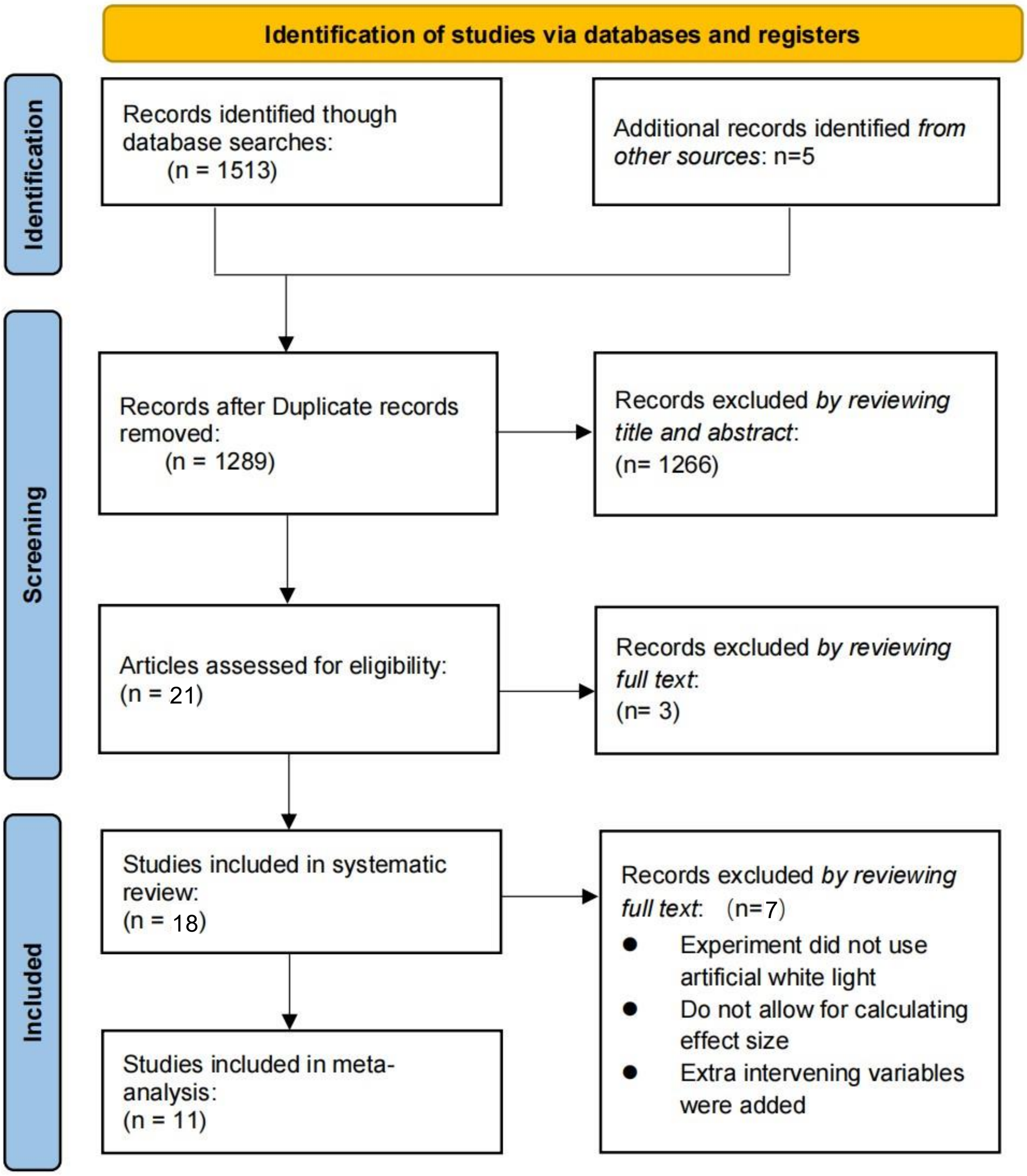


Figure 1: PRISMA flow chart showing the searching and selection process

2.2 Systematic review

The systematic review allowed us to meticulously summarise the key characteristics of studies about the thermal effects of light in the built environment. Then, we discussed factors potentially contributing to the heterogeneity in existing results. Based on this, moderators deemed essential for inclusion in the meta-analysis were identified. This systematic approach ensures a thorough understanding of the research landscape, helps the identification of pertinent moderators, and thus enhances the methodological rigour of the subsequent meta-analysis.

2.3 Meta-analysis

Meta-analysis is a statistical technique used to synthesise and analyse data from multiple studies to identify patterns, inconsistencies and overall effects. This method is particularly valuable in research fields where individual studies may have small sample sizes or varied findings, such as in medical, social and behavioural sciences. By aggregating data from various sources, meta-analysis increases the statistical power and reliability of conclusions drawn from the research literature.

The meta-analytical technique has become increasingly prevalent across various disciplines, such as medicine, psychology, social sciences, environmental sciences and, recently, the thermal comfort field. In 2018, A. J. Yeganeh [42] reviewed the relationship between ambient air temperature and cognitive performance and used meta-analysis to investigate the heterogeneity of individual studies. In 2021, J. A. Porras-Salazar [43] conducted a meta-analysis across 35 studies to examine the effect of indoor temperature on office work performance. In 2022, W. F. Song [44] conducted a systematic review and meta-analysis to look into personal comfort systems' thermal comfort and energy performance. In 2023, Y. J. Fan [45] performed a meta-analysis to investigate the effect of short-term exposure to indoor carbon dioxide on cognitive task performance.

The primary objective of a meta-analysis is to quantitatively combine the results of multiple studies addressing a similar question, providing a more comprehensive understanding of the effect or phenomenon being studied. This process involves several key steps: identifying and selecting relevant studies, extracting and coding data from these studies, and then statistically analysing the combined data. The outcomes of this analysis are often presented in the form of effect sizes, which offer a standardised measure of the magnitude of the observed effect across different studies.

One critical aspect of conducting a meta-analysis is selecting the appropriate statistical model. Two primary models are used: the fixed-effects model and the random-effects model. The fixed-effects model assumes that the effect size is constant across all the studies, while the random-effects model accounts for variability in effect sizes between studies. The choice between these models depends on the degree of heterogeneity in the analysed studies.

In this study, comprehensive Meta-Analysis (CMA) V3 software (Biostat, NJ) [46] was utilized to carry out the meta-analysis. The effect sizes were calculated to estimate the magnitude of observed effects quantitatively and summarise the results of a study [47]. In this study, effect size was expressed as Hedge's g and 95% confidence interval (CI), as it helps mitigate biases associated with small sample sizes [40]. The means and standard deviation (SD) are required to calculate Hedge's g. According to X. Wan *et al.* [48] and S.Y. Cai *et al.* [48, 49], if means and SD were not available, they were converted from other statistics (i.e. standard error, p-value). According to Cohen's definitions [50], Hedge's g values falling within 0-0.19, 0.2-0.49, 0.5-0.79, and above 0.8 indicate trivial, small, moderate and large effects, respectively. In the current study, Hedge's g with a negative sign represents that a higher level of CCT leads to a reduction of Thermal Sensation Vote (TSV); otherwise, the opposite.

Heterogeneity was evaluated through Cochran's Q-test and Higgins's I^2-test [51]. In Cochran's Q-test, a significant p-value refers to heterogeneity, and in Higgins's I^2-test, percentages of I^2 around 25%, 50%, and 75% would mean low, medium, and high heterogeneity, respectively. To ensure the reliability of the heterogeneity analysis, the results were considered heterogeneous with $p < 0.1$ and $I^2 > 50\%$ in the meta-analysis [52, 53]. When the results exhibited heterogeneity, the random-effects model was employed for the meta-analysis; otherwise, the fixed-effects model was utilised. A sensitivity analysis was performed using the one-by-one elimination method to assess the impact of individual studies on the overall results. This involves removing individual studies and re-checking the analysis results [54]. Funnel plots and Egger’s regression test were used to evaluate publication bias for the meta-analysis. The funnel plot with an asymmetrical shape and the p-value of Egger's test lower than 0.05 indicate the significance of publication bias [55, 56].

Sub-group analysis [57] was performed to identify the variety of magnitude of the thermal effect of CCT under different environmental thermal conditions. To explore the effect of moderators, random-effects meta-regression models were established using restricted maximum likelihood estimation (RMLE) [58]. Knapp-Hartung adjustment was applied to the model for advantages in dealing with uncertainty regarding between-study heterogeneity [59].

3. Systematic review

3.1 Overview of existing studies

After the screening process, 18 articles were included in the review. In the systematic review, the main characteristics of these studies (e.g. author, publish year, subjects, experimental environment, experimental method, light manipulation, thermal environment, exposure duration, results) were extracted (Table 1). Based on this, how the characteristics of the experiments may influence research results were examined and the specific traits that should be considered in meta-analysis were identified.

Amongst the 18 articles, 11(61.1%) reported statistical significance of the effect of CCT on thermal sensation. Most studies utilised the ASHRAE 7-point scale for evaluating thermal sensation, except for [23] (P.O. Fanger, 1977), which, to explore variations induced by different colours of light, adjusted indoor temperatures based on participants' expectations and [25] (R. R. Baniya, 2018), which employed a 9-point scale.

All the studies indicating significant results confirmed a negative correlation between CCT and thermal sensation, indicating that higher (cooler) CCT values result in cooler thermal sensations. Several studies also reported the magnitude of variation in thermal sensation or the equivalent temperature change caused by changes in CCT. P.O. Fanger [23] reported that subjects preferred a slightly lower (0.4°C) temperature under red lights and suggested that this difference could be negligible practically. Moreover, J. Toftum [32], L. Bellia [26] and I. Golasi [13] reported more significant results. I. Golasi *et al.* [13] discovered that thermal sensation decreased by approximately 0.5 units under cooler light compared to warmer light whilst J. Toftum *et al.* [32] observed that at 22°C, CCT significantly influenced thermal sensation, resulting in a variation of 0.35 units, equivalent to a 1.7°C change in temperature. Additionally, L. Bellia *et al.* [26] found that, compared to 3,000K, thermal sensation decreased by 0.4 units during winter (with a set temperature of 20°C) and by 0.48 units during spring (with a set temperature of 25°C) at 6,000K. This change is equivalent to a 1.7°C difference in operative temperature in both conditions. The most significant variation in thermal sensation affected by CCT was reported by C. Liu [60], indicating a reduction in thermal sensation of 1.65-2.75 units with increasing CCT.

Regarding the potential energy-saving benefits associated with the thermal effects of CCT, nearly all studies have affirmed the capacity for energy conservation by utilising CCT to influence thermal sensation in the built environment. According to quantitative estimates by J. Toftum [32], buildings' total annual energy consumption in Denmark could decrease by approximately 8% by adjusting the heating set point to 21.2°C at a CCT of 2,750 K while maintaining an unchanged mean thermal sensation.

3.2 Effects of experimental characteristics

Does CCT affect human thermal sensation? Different studies have provided varying answers.

Cross-modal effects between CCT and thermal sensation may lead to heterogeneity, which could be influenced by environmental characteristics such as experimental circumstances, light manipulation, ambient thermal conditions, illuminance level and exposure duration.

First, experimental circumstances across different studies vary considerably due to variations in research objectives and available experimental equipment. The majority of studies were conducted in climate chambers [12, 23, 27, 29-32, 60, 61], environmental laboratories [28, 62], or controlled test rooms [13, 25, 26, 63-65], where environmental parameters could be strictly controlled. Additionally, Y. Wu [61] created a high-humidity environment in the laboratory to simulate an underground environment. F. Albers [37] and J. Winzen [38] utilised a single-aisle jet mock-up with a complete cabin interior, representing an aircraft cabin. In 2018, G. Chinazzo [64] conducted experiments in an office-like test room equipped with coloured windows and, in 2021, this research was expanded by conducting experiments using Virtual Reality headsets [66]. Considering that several studies have suggested that building types or indoor interiors may influence thermal sensation [63, 67, 68], it becomes important to consider experimental conditions that represent specific types of buildings when interpreting conclusions from studies on the effects of CCT on thermal sensation.

Secondly, light manipulation is another crucial factor that may influence experimental results. In this review, all studies, except for the experiment conducted by Fanger [23] in 1977 using fluorescent lighting tubes, utilised LED lighting to create the light environment. Therefore, it appears that differences in lamps and lanterns are not the main reason for case heterogeneity. However, an important distinction in light manipulation lies in the types of light. Some studies [23, 37, 38, 64, 66] conducted experiments using coloured light, such as monochromatic blue or red light, while others used artificial white light, which is composed of multiple wavelengths across the visible spectrum and is common in most built environments such as workplaces or classrooms. Particularly noteworthy, G. Chinazzo used coloured windows in 2018 [64] and virtual reality technology in 2021 to create light environments [66]. Considering that light manipulation significantly influences the independent variable CCT, it is necessary to differentiate between light types when comparing results from different studies.

Ambient thermal conditions, the foremost determinant of occupants' thermal sensation, likely exhibit cross-modal effects with CCT. Among the experiments in the 20 articles reviewed, 13 applied more than one temperature condition to explore and investigate the thermal effect of CCT in different background temperatures. Notably, Y. Wu [61] and Z. Wang [63] employed multivariate analysis of variance (MANOVA) and generalized linear mixed models (GLMM) to analyse the interactions among CCT, illuminance and temperature. The influence of ambient thermal conditions on the thermal effects of CCT will be further discussed in Section 4, drawing insights from the meta-analysis results.

Other reasonable aspects to be considered as moderators affecting the thermal effect of CCT include illuminance level and exposure duration. Studies indicate that human pupil size significantly correlates with brightness perception [69, 70], mainly affected by illuminance levels in the built environment [71, 72]. This correlation may affect the amount of light that enters human eyes per unit of time, consequently influencing the amount of blue light (which is influenced by CCT) that enters human eyes. Similarly, exposure duration also determines how much light enters the human eye. Additionally, psychological adaptation [73] and changes in body temperature [17] may occur over time. Therefore, when assessing the thermal effects of CCT, it is essential to consider the CCT itself and factors such as illuminance level and exposure duration.

Table 1: Study characteristics

Author, year	Subjects	Experimental environment	Experimental method	Light manipulation	Thermal environment	Exposure duration	If CCT has an effect on thermal sensation (Y/N); Thermal sensation variation caused by changing CCT
P.O. Fanger, 1977 [23]	16 (8M, 8F)	Climate chamber.	Within-subjects design; Change ambient temperature according to the subject's preference every 10 minutes.	Fluorescent lighting tubes; 2 Coloured light: Extreme blue light (150 lx), extreme red light (190 lx);	25°C.	150 mins	Y. The subject preferred a slightly lower (0.4°C) ambient temperature in the extreme red light than in the extreme blue light.
G. Chinazzo, 2018 [64]	75 (45M, 30F)	Two office-like test rooms with coloured window.	Mixed-subjects design; Full factorial design (3 × 3).	3 coloured daylight: blue, orange and neutral.	19°C, 22°C and 26°C.	30 mins	Y. Blue daylight results in a colder thermal sensation.
M. te Kulve , 2018 [62]	16F	Experimental laboratory (controlled indoor environment).	Randomized within-subjects crossover design; 2 sessions with different CCT.	LED; Artificial white light, 2 levels of CCT: 4,000 K (250lx) as the baseline, 2700 K (55 lx) and 5,800 K (55 lx).	26°C, 29°C and 32°C.	75 mins	N.
A. Brambilla, 2020 [31]	45 (21M, 16F, 8 unknown)	Climate chamber (furnished to simulate a real office environment).	Within-subjects design; Full factorial design (3 × 3).	LED; Artificial white light, 3 levels of CCT: 3,968 K (371.3 lx), 2,762 K (374.5 lx) and 6,253 K (373.0 lx).	21°C, 24°C and 26°C.	30 mins	Y. Subjects feel cooler under higher CCT in a warmer ambient temperature (26°C).
G. Chinazzo, 2021 [66]	57 (28M, 29F)	Virtual Reality headset	Between-subjects design (each condition 9-10 participants).	Three daylight colours displayed in VR:	24°C and 29°C.	10 mins	Y. Orange daylight resulting in estimated

			Randomized full factorial design (3 × 2).	blue, orange and neutral.			warmer temperatures at 24 °C but not at 29 °C.
C. Liu, 2022 [60]	32 (10M, 22F)	Climate chamber (to simulate a classroom environment).	Within-subjects design; Full factorial design (6 × 3).	LED; Artificial white light, 6 levels of CCT: 3,000K, 3,700K, 4,400K, 5,100K, 5,800K, and 6,500K. Illumination was constant at 250lx.	23°C, 26°C and 29°C.	10 mins	Y. The thermal sensation decreased gradually with increasing CCT, creating a thermal sensation redaction of 1.65–2.75 units (7-pt scale).
Y. Wu, 2022 [61]	19 (10M 9F)	Climate chamber (high humidity to simulate an underground environment).	Mixed-subjects design (each subject participates in 4 -8 experiments); 5 (temperature) × 5 (illuminance) × 3 (CCT) mixed design.	LED; Artificial white light, 3 levels of CCT: 4,000, 5,000, and 6,000 K; 5 levels of illuminance: 200, 300, 500, 750, and 1,000 lx;	22, 24, 26, 28, and 30°C	30 mins	N.
C. M. Chou, 2016 [28]	8 M	Experimental laboratory (to simulate an office environment).	Within-subjects design; 10 thermal/lighting conditions (5 × 2).	LED and fluorescent lamp (FL) ceiling lights; Artificial white light, 4 levels of CCT: 3,000, 4,000, 5,000, and 6,500 K (LED and FL); Illumination was set at 500lx.	28 and 30°C	100 mins	N.
G. M. Huebner, 2016 [12]	32 (18M 14F)	Climate chamber.	Between-subjects design; Full factorial design (2 × 2).	LED; Artificial white light, 2 levels of CCT: 2,700 K (550lx) and 6,500	Cooling cycle: 24 to 20°C Warming cycle: 20 to 24°C	60 mins	Y. Participants felt warmer under 2700K at cooling cycle.

				K (495 lx).			
R. R. Baniya, 2018 [25]	16 (7M 9F)	A test room (controlled indoor environment).	Within-subjects design; 2 temperature scenarios; step-changed CCT (14 levels).	LED; Artificial white light, 14 levels of CCT step-change from 2,733 K to 6,208 K; Illumination was set at 500lx.	20 and 25°C	10 mins	N.
J. Toftum, 2018 [32]	16 (7M 9F)	Climate chamber.	Within-subjects design; Full factorial design (3 × 2).	LED; Artificial white light, gradually changed CCT: Scenario 1: nominally vary from 2,700K to 6,200K; Scenario 2: nominally vary from 6,200K to 2700K; Illumination was set at 1,000lx.	19°C, 22°C and 27°C.	90 mins	Y. A significant effect of CCT on thermal sensation was seen only at 22 °C; 0.35 units variation of thermal sensation (7-pt scale) between the CCT level of 2700K and 6200K (equivalent to a difference in operative temperature of 1.7 °C at 22°C).
F. R. D'Ambrosio Alfano, 2019 [65]	81 (40M 41F)	Experimental laboratory (controlled indoor environment).	Within-subjects design.	LED; Artificial white light, 2 levels of CCT: 3,000K and 6,000K; Illumination was constant at 300lx.	20°C	10 mins	Y. Cooler light (6000 K) led to a cooler thermal sensation.
I. Golasi, 2019 [13]	42 (24M 18F)	A test room (controlled indoor environment).	Within-subjects design.	LED; Artificial white light, 3 levels of CCT: 1,772K, 4,000K and 11,530K; Illumination was constant at 500lx.	22°C	30 mins	Y. Compared to warmer light, thermal sensation decreased by about 0.5 units (7-pt scale) under cooler light.

L. Bellia, 2019 [26]	128 (63M 63F)	Experimental laboratory (controlled indoor environment).	Mixed-subjects design; 2 temperature scenarios in winter and spring; 2 CCT scenarios.	LED; Artificial white light, 2 levels of CCT: 3,000K and 6,000K; Illumination was set at 300lx.	20 and 25°C	15 mins	Y. Compared to 3,000K, thermal sensation decreased by 0.4 units during winter (with a set temperature of 20°C) and by 0.48 units during spring (with a set temperature of 25°C) at 6,000K, equivalent to a 1.7°C difference in operative temperature in both conditions.
M. E. Kompier, 2021 [29]	23 (10M 13F)	Climate chamber (Office-like setting).	Within-subjects design; 2 (Illuminance: bright vs. dim) by 2 (CCT: cool vs. warm) factorial design.	LED; Artificial white light, CCT: 3,000K and 6,000K; Illuminance: 100lx and 1000lx.	18°C	45 mins	N.
Y. Yang, 2021 [27]	20 (16M 4F)	Climate chamber.	Within-subjects design; Full factorial design (3 × 3).	Fluorescent tubes; Artificial white light, 3 levels of CCT: 3,000K, 4,000K and 6,000K; Illumination was set at 300lx.	26°C, 28°C, and 30°C	10 mins	Y. A negative correlation between CCT and the thermal sensation was found at 26 °C and 28 °C
W. Luo, 2023 [30]	16 (8M 8F)	Climate chamber (Office-like setting).	Within-subject design.	LED; Artificial white light, 2 levels of CCT: 2,700K and 5,700 K; Illumination was constant at 500lx.	17°C	70 mins	N.
Z. Wang, 2024 [63]	36 (24M 12F)	A test room (Office-like setting, controlled indoor	Mixed-subjects design. 2 (temperature) × 2	LED; Artificial white light, CCT:	23 and 29°C	30 mins	N.

		environment).	(illuminance) × 3 (CCT) mixed design.	2.700K, 4.000K and 7.800K; Illuminance: 300lx and 750lx.			

4 Results of Meta-analysis

4.1 Included studies

After the selection process, 11 eligible studies ([12, 13, 25-30, 32, 62, 65]) were included in the current meta-analysis. In some studies, experiments were performed in several temperature conditions. In this meta-analysis, an experiment conducted under one specific environmental temperature condition is considered as a “trial”. The main characteristics of these trials can be found in Table 2.

The following information on trials was extracted from the included studies: author names, year of publication, sample size, level of CCT, level of illuminance, temperature, exposure duration, TSV and the statistics for calculating effect size for meta-analysis. It is worth noting that “sample size” is different from “subjects” in Table 1, since the calculation of “sample size” is relevant to the study design method (within-subjects *vs*. between subjects) [40]. WebPlotDigitizer Software Version 4.5 was utilised to extract data when provided by figures.

To ensure the quality of studies involving the meta-analysis, a quality assessment process for individual studies was performed using the Quality Assessment with Diverse Studies (QuADS) tool [74]. The QuADS is the refined version of the Quality Assessment Tool for Studies with Diverse Designs (QATSDD) that was developed to assess the study quality with mixed or multi-method designs primarily in psychology research. It evaluates the quality of studies across different aspects with 13 criteria (listed in Appendix, Table S2) and applies a four-point scale [74]. To avoid subjectivity, the two authors independently conducted the quality assessment process, with any disagreements resolved through a discussion to reach a consensus.

Although some studies reported experimental results under moderate CCT levels, to enhance comparability, only trials conducted under "cool light" and "warm light" conditions were included.

Here, "cool light" is defined as light with a CCT level higher than 5,300K, while “warm light” is characterised by a CCT level below 3,300K (as per GB 50034-2013 [75]).

The outcomes of the quality assessment for 11 studies are provided in Table S2 (Supplementary materials).

Table 2: Main characteristics of trials included in the meta-analysis

Reference	Trails	CCT range	Exposure duration (min)	Sample size	Illuminance (lx)	Temperature (°C)	Thermal conditions
[12]	G.M. Huebner 2016 (1)	2,700K-6,500K	60	16	500	20-24 (cycle)	Cool
	G.M. Huebner 2016 (2)	2,700K-6,500K	60	16	500	24-20 (cycle)	Cool
[28]	C.M. Chou 2016 (1)	3,000K-6,500K	100	8	500	28	Warm
	C.M. Chou 2016 (2)	3,000K-6,500K	100	8	500	30	Warm
[29]	M. te Kulve 2018 (1)	2,700K-5,800K	75	18	50	26	Cool
	M. te Kulve 2018 (2)	2,700K-5,800K	75	18	50	29	Neutral
	M. te Kulve 2018 (3)	2,,700K-5,800K	75	18	50	32	Warm
[32]	J. Toftum 2018 (1)	2700K-6,300K	90 (with cycling CCT)	43	1000	19	Cool
	J. Toftum 2018 (2)	2,700K-6,300K	90 (with cycling CCT)	22	1000	22	Neutral
	J. Toftum 2018 (3)	2,700K-6,300K	90 (with cycling CCT)	43	1000	27	Warm
[25]	R.R.Baniya 2018 (1)	2,700K-6,200K	10 (with step-changed CCT)	16	500	20	Cool
	R.R.Baniya 2018 (2)	2,700K-6,200K	10 (with step-changed CCT)	16	500	25	Neutral
[13]	I. Golasi 2019	2,700K-11,530K	30	42	500	22	Neutral
[65]	F.R. D'Ambrosio Alfano 2019	3,000K-6,000K	10	81	300	20	Warm
[27]	Y. Yang 2021 (1)	3,000K-6,000K	10	20	300	26	Neutral
	Y. Yang 2021 (2)	3,000K-6,000K	10	20	300	28	Neutral

	Y. Yang 2021 (3)	3,000K-6,000K	10	20	300	30	Warm
[26]	L. Bellia 2021 (1)	3,000K-6,000K	15	70	300	20	Neutral
	L. Bellia 2021 (2)	3,000K-6,000K	15	58	300	25	Warm
[29]	M.E. Kompier 2021 (1)	2,700K-5,900K	45	23	100	18	Cool
	M.E. Kompier 2021 (2)	2,700K-5,900K	45	23	1000	18	Cool
[30]	W. Luo 2023	2,700K-5,700K	70	16	500	17	Cool

4.2 Publication bias

Publication bias is a critical factor to consider in meta-analysis as it can significantly skew the results and conclusions of the study. This form of bias occurs when the likelihood of a study being published is influenced by the nature or direction of its results. Typically, studies that find significant or positive results are more likely to be published than those that do not, leading to an overrepresentation of these findings in the literature. This can create a distorted view of the research in a particular field, making it appear that a certain effect is stronger or more consistent than it is.

Evaluating and adjusting for publication bias is therefore essential in meta-analysis to ensure the accuracy and reliability of its conclusions. The funnel plot and Egger's test are two common methods for assessing publication bias. A funnel plot is a scatterplot that visualises the relationship between study size (usually on the vertical axis) and effect size (on the horizontal axis). In the absence of bias, the plot resembles a symmetrical inverted funnel, as studies which have less scatter in results cluster at the top, and studies which show more variation spread out at the bottom. Asymmetry in this plot can be indicative of publication bias. Egger's test provides a statistical measure of funnel plot asymmetry. A significant result (usually $p < 0.05$) in Egger's test suggests the presence of publication bias.

This study assessed the publication bias by funnel plot and Egger's test. The shape of the funnel plot exhibits substantial symmetry (Fig. 2), while the outcome of Egger's test was insignificant ($p > 0.05$), indicating that there is no obvious publication bias. No significant change was observed when any single study was deleted (Figure S1). The studies were found to be heterogeneous, with $p < 0.001$ and $I^2 = 66.5$. As a result, the random-effects model was employed in the analysis.

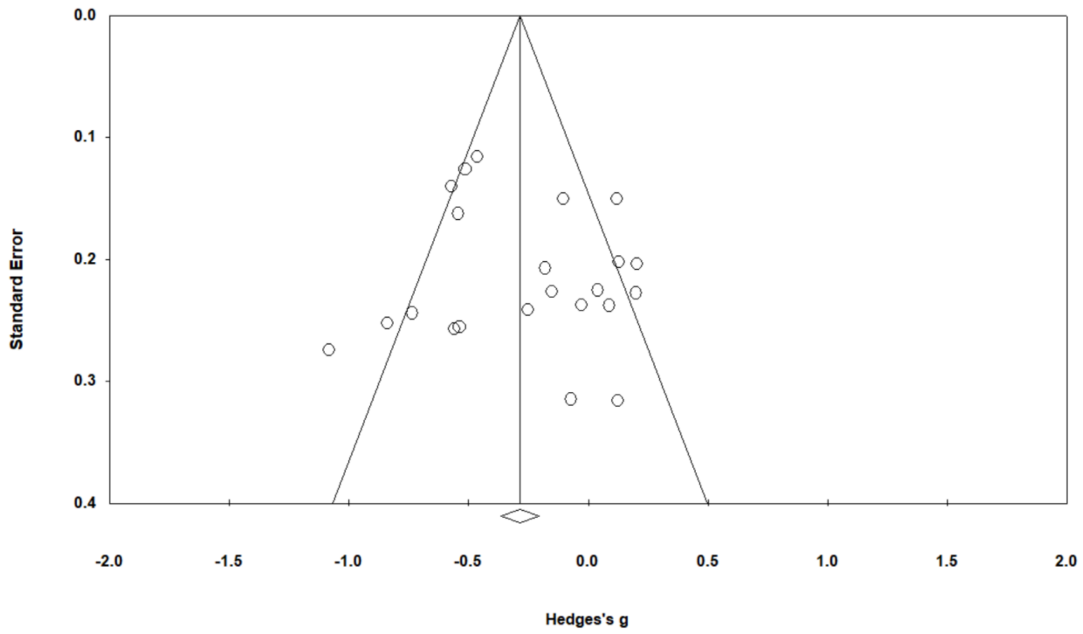


Figure 2: Funnel plot of publication bias analysis

4.3 The summary effect

The results of the meta-analysis examining the effect of CCT on thermal sensation are illustrated by a forest plot. A forest plot is a graphical representation commonly used in meta-analyses to display the results of individual studies and the overall summary estimate. In a forest plot, each study included in the meta-analysis is represented by a line and a box. The line extends on either side of the box and represents the 95% confidence interval (CI) of the study's effect size. The box represents the weight of the study in the meta-analysis, which is typically proportional to the inverse of the variance of the effect estimate - larger boxes denote studies with more weight, often due to larger sample sizes or higher methodological quality. At the bottom of the forest plot, a diamond shape represents the overall effect size calculated by the meta-analysis. The position and width of the diamond provide a visual summary of the combined results of all studies, with the centre indicating the average effect size and the width representing its confidence interval.

The plot for the summary effect of CCT on thermal sensation (Fig 3) indicates that there is a small effect (Hedge's g= -0.262, 95% CI: -0.407, -0.117) of cool light on occupants' thermal sensation when compared to warm light. However, the analysis revealed significant heterogeneity among the studies ($p < 0.001$ and $I^2 = 66.5$), indicating considerable inconsistency in the results. Therefore, further investigation is needed to identify the sources of this heterogeneity.

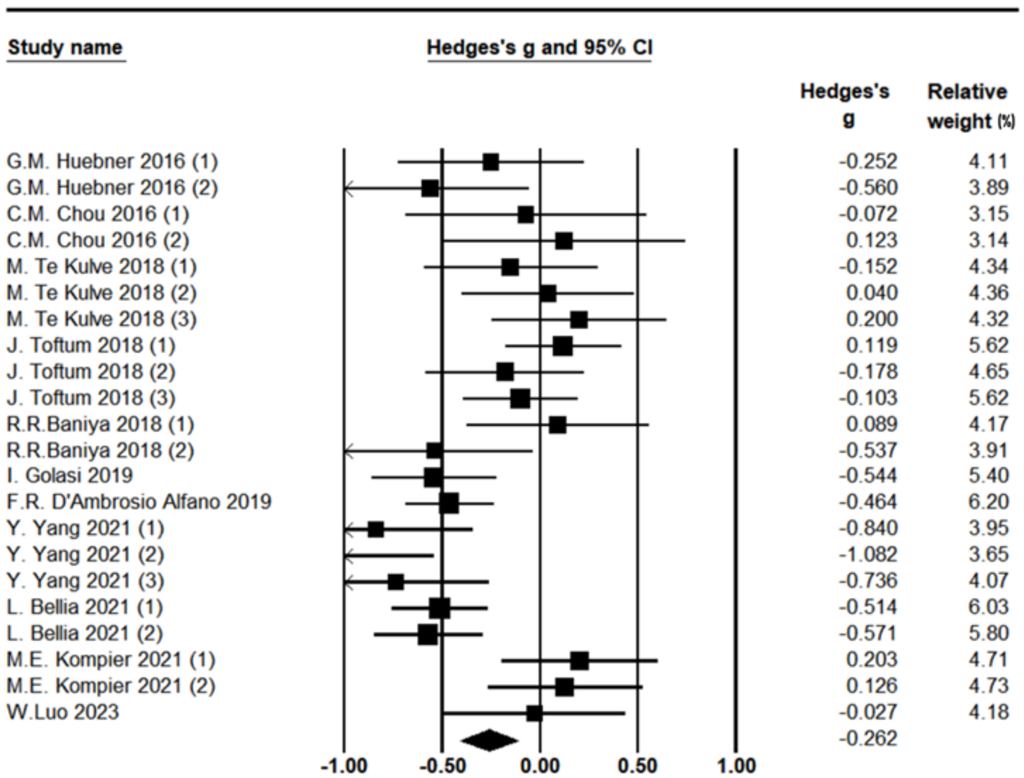


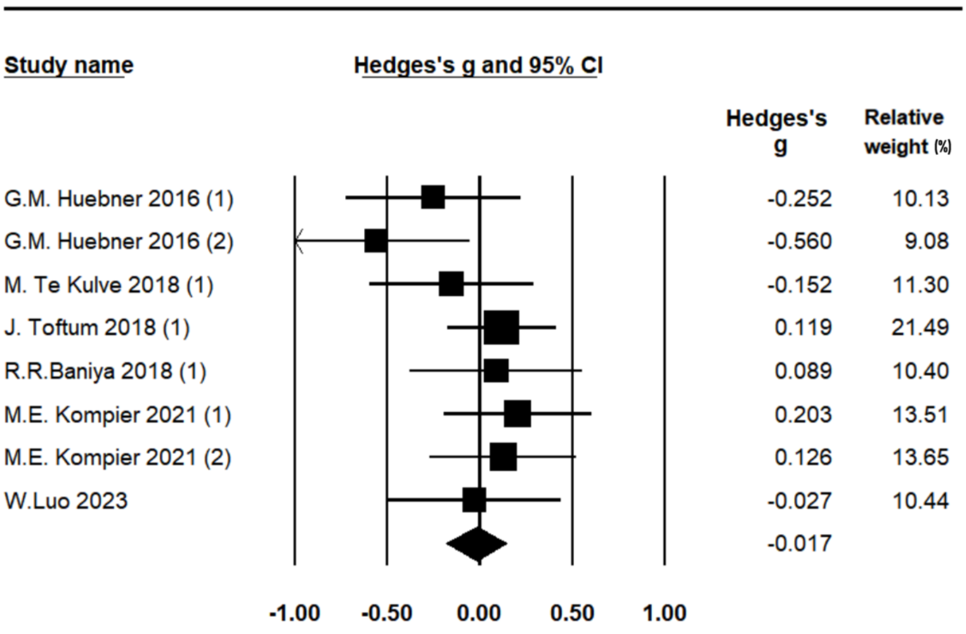
Figure 3: Forest plot illustrating the summary effect of CCT on thermal sensation

4.4 Subgroup analysis

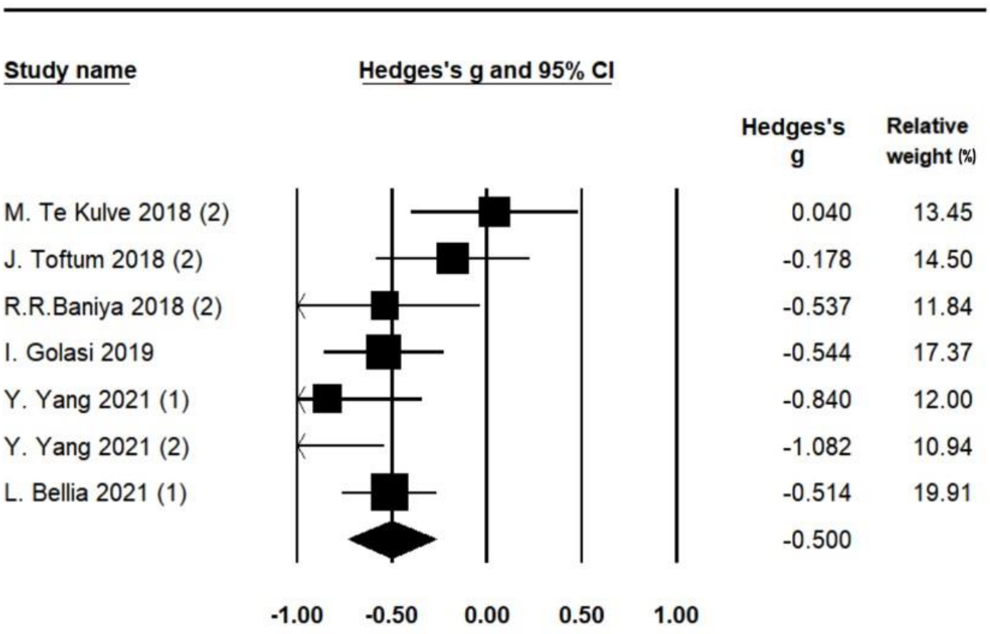
Sub-group analysis in a meta-analysis refers to dividing the overall data set into smaller, relevant categories to determine if the studied effect varies across different categories. This approach is crucial when the impact of specific variables or conditions on the research outcome is of interest. Using sub-group analysis, researchers can discover differences or similarities that may not be apparent in the general analysis.

Across the studies, the same TSV may correspond to different environmental temperatures. The relationship between TSV and temperature depends on the season and the physical activity, and is thus affected by the clothing worn – meaning that the same TSV values can be obtained in different seasons with different temperatures due to clothing [26, 76, 77]. Thus, the thermal conditions were categorised into three groups according to the actual TSV values reported by participants in each study to conduct the sub-group analysis. When TSV values are reported as less than -1, from -1 to 1, and higher than 1, the thermal conditions are considered cool, neutral and warm, respectively.

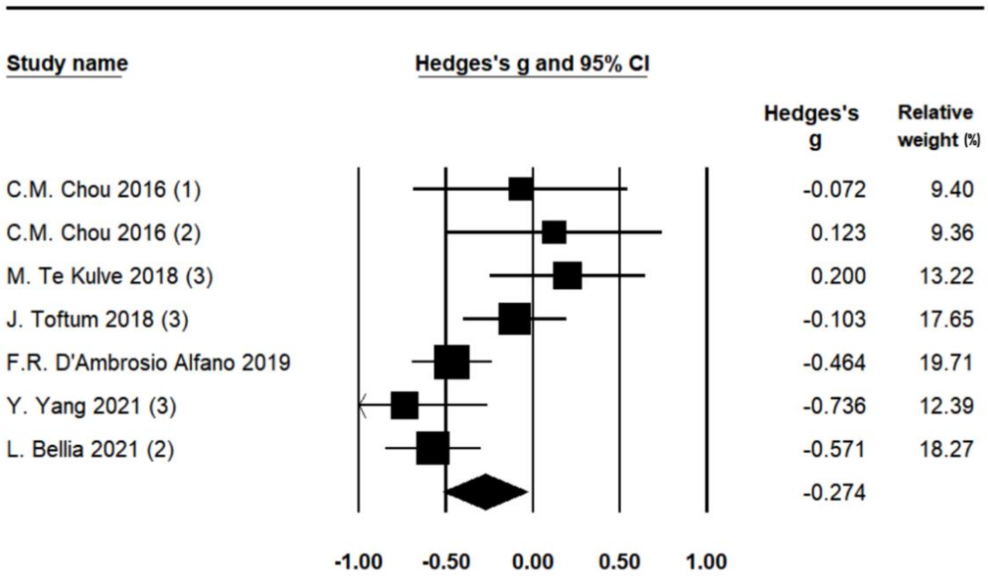
The results of the subgroup analysis are shown in Fig. 4. They indicate that the effects of CCT on thermal sensation turn out to be discrepant in different thermal conditions, as suggested by the between-groups heterogeneity test ($p<0.1$). In the cool environment, the effect of CCT on thermal sensation is trivial (Hedge's g= -0.017, 95% CI: -0.179, -0.145). The $p >0.1$ and I2 = 16.9 results suggest no heterogeneity. On the other hand, CCT has moderate and small effects in the neutral (Hedge's g= -0.500, 95% CI: -0.736, -0.264) and warm environments (Hedge's g= -0.274, 95% CI: -0.517, -0.031), respectively. However, heterogeneity was still found within categories of neutral ($p =0.024$ and $I^2 =58.8$) and warm environments ($p =0.008$ and $I^2 =65.7$).


Study name
Hedges's g and 95% CI
Hedges's g
Relative weight (%)
G.M. Huebner 2016 (1) -0.252 10.13
G.M. Huebner 2016 (2) -0.560 9.08
M. Te Kulve 2018 (1) -0.152 11.30
J. Toftum 2018 (1) 0.119 21.49
R.R.Baniya 2018 (1) 0.089 10.40
M.E. Kompier 2021 (1) 0.203 13.51
M.E. Kompier 2021 (2) 0.126 13.65
W.Luo 2023 -0.027 10.44
-0.017
-1.00
-0.50
0.00
0.50
1.00

(a)


Study name
Hedges's g and 95% CI
Hedges's g
Relative weight (%)
M. Te Kulve 2018 (2) 0.040 13.45
J. Toftum 2018 (2) -0.178 14.50
R.R.Baniya 2018 (2) -0.537 11.84
I. Golasi 2019 -0.544 17.37
Y. Yang 2021 (1) -0.840 12.00
Y. Yang 2021 (2) -1.082 10.94
L. Bellia 2021 (1) -0.514 19.91
-0.500
-1.00
-0.50
0.00
0.50
1.00

(b)



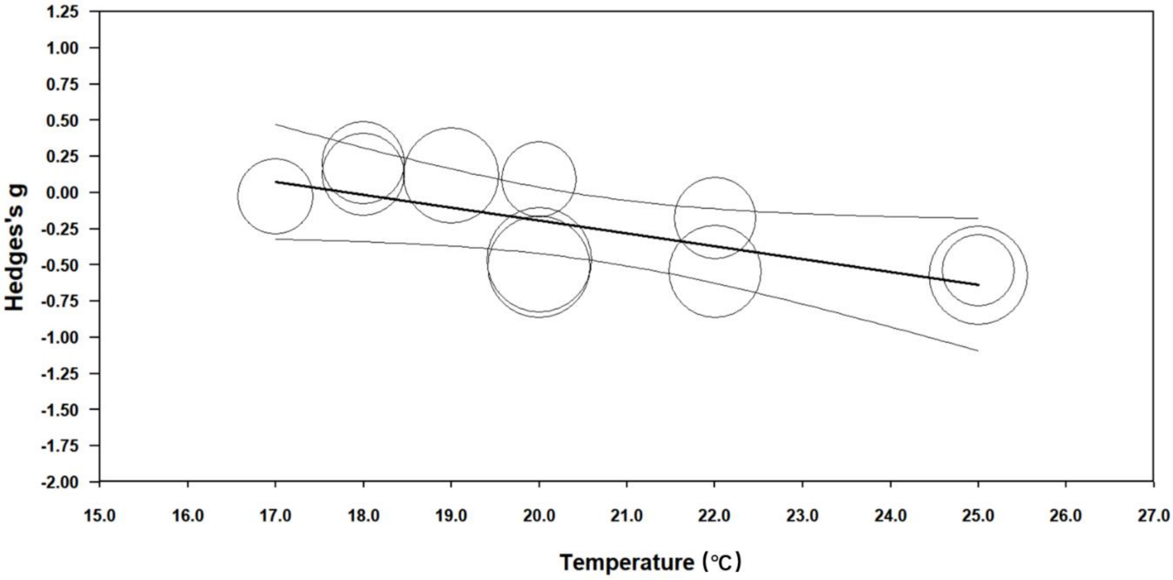
(c)

Figure 4: Forest plot of subgroup analysis: the thermal effect of CCT in (a) the cool environment, (b) the neutral environment and (c) the warm environment

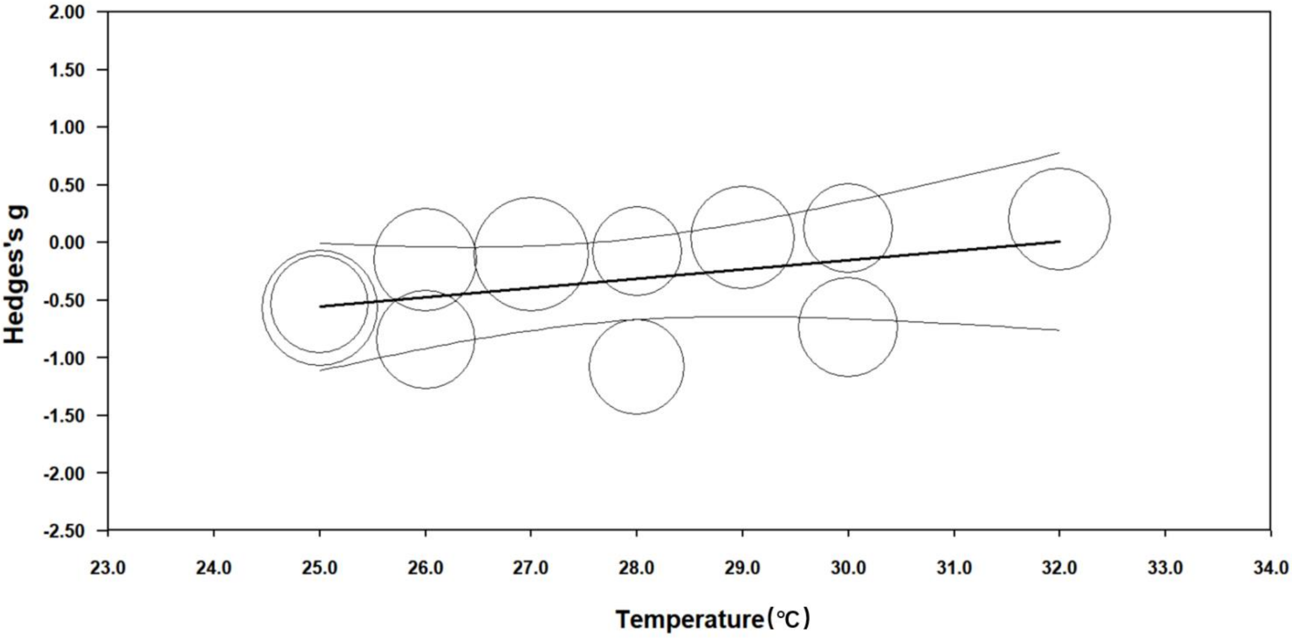
4.5 Meta-regression

Meta-regression is used to explore how study-level factors affect the overall effect size. It differs from sub-group analysis by examining continuous variables across all studies, helping to explain variability in study results. This method provides insights into why studies might yield different outcomes, enhancing the understanding of findings.

No linear relationship was found between temperature and the magnitude of the thermal effect of CCT (2-sided $p > 0.05$), with all trials performed under a temperature range from 17℃ to 32℃. This result indicates temperature setting may not be the source of heterogeneity in the included studies. However, to further investigate the influence of temperature, the trials were subsequently divided into two groups: performed under temperatures below 25℃ and above. The outcomes turned out to be intriguing: the magnitude of the thermal effect of CCT increases with temperature (2-sided $p= 0.0191$) when it is below 25℃ (Fig. 5 a), along with descending Hedge's g. In contrast, the effect of CCT gradually diminishes as the temperature exceeds 25℃ (Fig. 5 b), although there appears to be no statistical significance (2-sided p＞ 0.05). It should be noted that ref. [12] (G.M. Huebner, 2016) was excluded from this analysis because the step-changed temperature setting was utilised in their experiment design.



(a)



(b)

Figure 5: Meta-regression of Hedge's g on temperature: (a) temperature below 25℃ and (b)

above 25℃

The exposure duration involved in the current analysis ranges from 10 to 100 minutes. It suggests a strong relationship between exposure duration and the effect of CCT on thermal sensation. As shown in Fig. 6, with the increase in exposure time, the effect of CCT gradually weakens (2-sided p= 0.0005). It should be noted that [25, 32] (R. R. Baniya, 2018 and J. Toftum, 2018) were excluded from this analysis since the step-changed CCT setting was utilised in their experiment design.

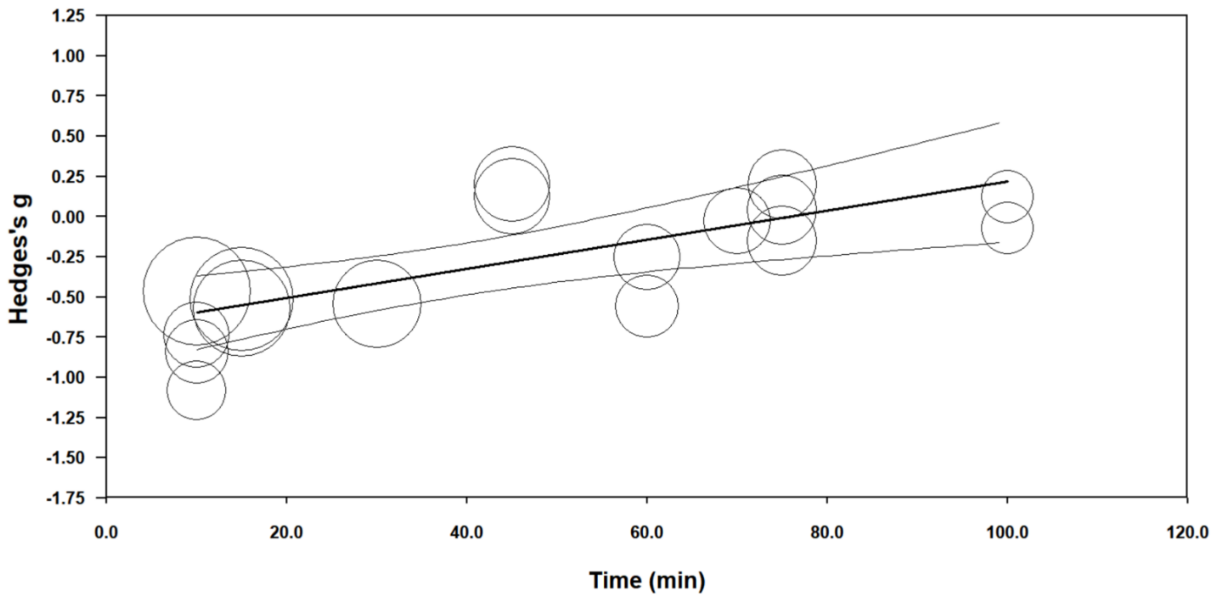


Figure 6: Meta-regression of Hedge's g on exposure duration

The illuminance levels involved in the current analysis range from 50 to 1000 lx. However, no associations were found between illuminance and the thermal effect of CCT (2-sided p＞ 0.05).

5 Discussion

5.1 The effect of CCT on thermal sensation

According to the meta-analysis, we confirmed the influence of CCT on human thermal sensation in the built environment. However, this is not a one-size-fits-all situation. As previously noted, the background thermal environment could be a potential factor that affects the magnitude of the thermal effect of CCT. Thus, a subgroup analysis was carried out to investigate this aspect further. The results of the subgroup analysis suggest that the background thermal environment truly influenced the effect of CCT. In a cool environment, the effect of CCT on thermal sensation can be negligible, while the strongest effect of CCT happens in neutral environments. Meanwhile, the effect also appears in warm environments but is less pronounced than in neutral environments. This finding was substantiated by A. Brambilla *et al.* [31], which aimed to identify the Hue-Heat Hypothesis at three different background temperatures (21℃， 24℃ and 26℃). The results suggested that this hypothesis is valid under warm environments (this study is not included in the meta-analysis due to lack of available data; however, it can be collateral evidence).

To further investigate the associations between the background thermal environment and the thermal effect of CCT, the ambient temperature was used as a continuous moderator to conduct a meta-regression. The results suggest that the magnitude of the CCT effect appears to be associated with gradually changing temperature. The thermal effect of CCT starts to be more apparent when the temperature rises up to 25℃ (which can be considered as a relatively thermal neutral environment). Above this threshold, it begins to diminish. This finding emphasised the importance of the background thermal environment and revealed a possibility of quantifying it in the future.

It is evident that temperature, compared to CCT, is the primary factor influencing human thermal sensation as temperature predominantly dictates whether individuals feel warm or cool. In this case, it is reasonable to suppose that the effect of temperature may overshadow the effects of CCT, meaning that, in scenarios where the temperature does not significantly contribute to a distinct thermal sensation, CCT becomes the influencing factor.

5.2 The effect of exposure duration

According to the meta-regression findings, it is possible to observe the association between exposure duration and the magnitude of the effect of CCT on thermal sensation. The results suggest that exposure duration is a strong moderator that affects the thermal effect of CCT, as well as an important cause that leads to heterogeneous results in existing studies. According to the findings, the effect of CCT on thermal sensation becomes much less significant as experimental times are prolonged, meaning that the effect may only exist at short exposure times.

Among the included studies, all experiments conducted with durations shorter than 15 minutes [25, 27, 65] observed significant effects. However, in experiments lasting longer than 15 minutes, only certain conditions from the included studies demonstrated significant results.

There are two approaches regarding the thermal effect of CCT: psychologically, based on the theory of the Hue-Heat Hypothesis, and physiologically, based on the evidence of non-visual effects of light. The physiological approach suggests that a high CCT with more blue light would suppress melatonin secretions and increase human core body temperature (CBT) [78, 79], which implies that higher CCT will increase the thermal sensation of humans. However, it takes time for the non-visual effects of light to take effect. R. Nagare *et al.* found light exposure duration would affect melatonin suppression, which tends to saturate with increasing exposure time [80]. B. Wood *et al.* found that self-luminous devices would not significantly suppress melatonin levels after exposure for 1h, while this difference reached significance after 2h [35]. In the psychological approach, the colour of light was translated into visual information and directly perceived by humans [17], so it may take effect relatively quickly. This may suggest that the thermal effects of CCT rely more on psychological rather than physiological processes.

5.3 The effect of illuminance

As one of the most important parameters of light design, illuminance is considered to have a significant effect on human perception, cognition and health. Together with CCT, illuminance plays an important role in the control of secretions of melatonin [33, 34]. According to B.L. Myers *et al.* [81], the threshold for significant suppression of melatonin and enhancement of body temperature may be around 500 lx. Given this, illuminance appears to be an influential factor in the results of the experiment. However, no statistical evidence of the relationship between illuminance and the thermal effect of CCT was found in the meta-analysis. In addition, the effect of illuminance on human thermal sensation was studied by M. te Kulve [82]. Also, after conducting various experiments under different illuminance values (5 and 1200 lx, namely), they found no statistical differences in the thermal sensation of subjects. The influence of illuminance and its interaction with CCT on humans are quite complex suggesting that further studies are needed regarding this subject.

5.4 Practical significance of the findings

Researchers used to assume that if the Hue-Heat Hypothesis is true with artificial white light, then it is possible to use CCT to reach a wider comfortable temperature range and thus achieve a lower energy consumption. However, according to this study, even though the Hue-Heat Hypothesis is true, the practical significance of using it to save energy is still limited. CCT can only exert its maximum effect in a neutral thermal environment, while the boundaries of the thermal comfort range always fall in cool or warm conditions. The energy-saving potential of CCT might be used in summer when it still has some impact on the thermal sensation in warm environments.

While it may be a disappointing conclusion that CCT's energy-saving potential is limited, the findings suggest its application value in specific situations. Studies show that human thermal sensation strongly affects productivity, and a neutral thermal sensation may not promise the highest work efficiency. L. Lan *et al.* [83] found that a cooler thermal sensation will provide higher work performance than neutral. In this case, the Hue-Heat Hypothesis can be applied in thermally neutral office environments by using high CCT lighting levels to lower occupants' thermal sensation and subsequently increase productivity without changing air temperature, thus indirectly saving energy from HVAC system operation. Besides, light with high CCT can lead to higher productivity. Studies suggest that light with higher CCT may also improve human cognitive performance [30, 84]. This might be explained by the fact that light with high CCT is rich in blue light, which is effective in suppressing melatonin and enhancing alertness.

On the other hand, the short effect duration of CCT's thermal effect limits its potential applications. To maximise its effectiveness, the most suitable usage scenarios might be in spaces where people only need to stay for short periods, such as transitional built environments like airport jet bridges, platforms or rest areas. Transitional spaces, which often constitute a significant portion of modern buildings, typically accounting for 10% to 40% of the total building volume [85], tend to exhibit a notably higher energy consumption compared to other interior areas, potentially up to three times more [86, 87]. Hence, harnessing the thermal effect of CCT within these regions may hold considerable promise for energy conservation.

6 Conclusions

In the current study, we systematically reviewed existing studies regarding the effect of CCT on thermal sensation in built environments and conducted a meta-analysis. Through the systematic review, we concluded that the reasons for the heterogeneity are complex, regarding the effect of experimental design, conditions, aims of the study and the inadequate control of microclimatic quantities. Further, through the meta-analysis, we identified sources of heterogeneity in existing studies and investigated the effect of moderators. Moreover, we discussed the possible reasons for the heterogeneity and the practical significance of the thermal effect of CCT on improving productivity and saving energy in buildings.

The main findings are summarised as follows:

1) The Hue-Heat Hypothesis was partly identified under artificial white light depending on the background thermal environment. In thermally neutral and warm environments, the higher CCT of artificial white light will influence people's thermal sensation with a cooling effect. However, CCT does not affect people’s thermal sensation in thermally cool environments.
2) Correlations have been uncovered between temperature and the thermal effect of CCT. As temperatures ascend to 25°C, the effect of CCT on thermal sensation strengthens. However, beyond this threshold, the efficacy of CCT begins to wane. Thus, further research is needed to identify and quantify these relationships fully.
3) Exposure duration was identified as the main factor causing the heterogeneity of existing studies. The effect of CCT on thermal sensation only occurs in a short-time exposure, which may imply the mechanism of the thermal effect of CCT is mainly a psychological process.
4) Illuminance was not found to have a relationship with the thermal effect of CCT.

Some limitations of this study should be mentioned. In particular, the effect of some potential moderators, such as the season of the year and the characteristics of the subjects surveyed, were not discussed in this study due to the inadequacy of eligible data. Future research aiming to identify the influence of these intervention factors is thus necessary.

Acknowledgements

This study was supported financially by the National Key Research and Development Program of China, project 2022YFC3801504.

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