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Systematic review: Acute thermal effects of artificial light in the daytime

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ABSTRACT

The acute thermal effects of artificial light during the daytime have the potential to promote energy savings and enhance indoor comfort. Although the long-held hue-heat hypothesis suggests that the visual features of lighting may alter human thermal responses, there currently exists no systematic review or cross-study analysis that synthesizes and characterizes light's impact along both visual and non-visual pathways during the daytime. This review highlights evidence and physiological and psychological measures examining the presence of light's thermal effects during the daytime, as obtained from the literature. This review searched articles from PubMed, Scopus, Web of Science, and other sources and screened for articles with thorough lighting information and microclimatic conditions describing experiments conducted during the daytime and using static artificial light. Eighteen articles describing 18 studies were selected based on the inclusion criteria; these studies featured different experimental and intervention designs for the indoor environment and measurements of psychological, physiological, and behavioral responses. This research specifically reviews the experimental designs and settings in terms of lighting and microclimatic characteristics and also identifies the effective and appropriate physiological and psychological measures of light's thermal effects. Much of the literature described in this review suggests that lighting exposure during the daytime is associated with thermal-related psychological and physiological responses; the analysis results across different studies showed statistically significant associations with certain psychological (e.g., thermal sensation, preferred temperature) and physiological measures (e.g., proximal skin temperature, heart rate variability). However, some cross-study results were limited by the unavailability of key measurements and reports on lighting, microclimatic conditions, and/or thermal responses and possibly high levels of heterogeneity. In general, the findings of this review will facilitate continuing advances in this area, providing more comprehensive scientific rationales and strategies for adopting smart lighting technologies in sustainable and smart buildings.

1. Introduction

Artificial lighting is indispensable in our daily lives for human vision and indoor activities, not only at night but also during the daytime. One example is commercial buildings, especially those offices that lack sufficient access to daylight through windows. Artificial lighting is also critical for energy savings purposes. According to the Commercial Buildings Energy Consumption Survey published by the US Energy Information Administration, electrical lighting energy use comprises about 17% of commercial buildings' electricity consumption in the US alone [1]. Although artificial light is mainly introduced for vision-related requirements, it is well-accepted that light's influence is not just on vision [2,3]. Various non-visual effects also exist, including influences on human health, cognition, sleepiness, emotions, alertness, work productivity, and so on [4–6]. Among these, thermal effects have long been investigated, and researchers have found that potential human thermal responses vary with changes in lighting conditions. In theory, if indoor lighting's thermal effects could be scientifically confirmed, then indoor lighting systems could be used to adjust the perceived indoor thermal environment and, in turn, affect space heating and cooling energy use. Various prior studies on energy simulations for building space heating and cooling have revealed that even minor effects on temperature perception can achieve significant energy savings over the long term [7,8], underscoring new opportunities for synergistically tuning indoor visual and thermal comfort through the optimization of lighting applications and energy efficiency. Such techniques are also highly aligned with finely tunable light-emitting diode (LED) technology and the emerging smart building paradigm. All this motivation has in the past few decades led to a number of studies investigating light's thermal effects on humans.

Kulve et al. described the potential neural pathways for light's

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Nomenclature

List of abbreviations

BL	Bright light
BF	Skin blood flow (flux)
BP	Blood pressure (mmHg)
CBT	Core body temperature (°C)
CCT	Correlated color temperature (K)
DL	Dim light
Distal SKT	Distal skin temperature (°C)
DPG	Distal proximal skin temperature gradient (°C)
EE	Energy expenditure (kcal)
EEG	Electroencephalogram
FWHM	Full width at half maximum
GSR	Galvanic skin response (microSiemens)
HR	Heart rate (beats per minute)
HRV	Heart rate variability
ipRGC	Intrinsically photosensitive retinal ganglion cells
Prox SKT	Proximal skin temperature (°C)
Mean SKT	Mean skin temperature (°C)
SKTP	Skin temperature of partial locations (°C)
SASV	Self-assessed shivering
SASW	Self-assessed sweating
SCN	Suprachiasmatic nucleus
SPD	Spectral power distribution
TE	Temperature estimation (°C)
TCV	Thermal comfort vote
TSV	Thermal sensation vote
TAV	Thermal acceptability vote
TTV	Thermal tolerance vote
TPV	Thermal preference vote

influence on thermal responses, which includes two central pathways: visual and non-visual [9]. Both are perceived through the eyes and the brain's neural systems but are processed in different ways [10,11]. On the one hand, lighting information is received by rods and cones and then translated into visual information regarding brightness, color, etc., affecting thermal responses mostly via the visual pathway, which could be characterized by psychological responses. There is a long-held but controversial belief that warm-colored light induces feelings of warmth, while cool-colored light produces the opposite. This is known as the hue-heat hypothesis, first proposed and studied by Morgensen and English in 1926 [12]. This hypothesis is based on the premise that the visual effects of a light's color (i.e., its appearance) have a direct impact on thermal sensation, a notion that can be categorized as a human being's psychological response and the visual pathway influence of light. On the other hand, lighting information is also received by another type of photoreceptor cell, ipRGC, which has been identified as important for various non-visual biological effects in terms of CBT, HR, and melatonin production [13]. According to current knowledge, the non-visual thermal effects of light can be realized through their impact on circadian rhythms via ipRGCs, which work more dominantly at night and in the early morning [14]. Previous studies have found that bright artificial light in the evenings and/or mornings can have phase-shifting effects (either delays or advances) on circadian temperature rhythms [15–17]. Relatively speaking, the mechanism for acute non-visual thermal effects from light during the daytime is not completely comprehended.

Understanding the acute non-visual thermal effects of light that directly cause physiological responses in human beings and rely on light energy will be helpful for controlling thermal comfort without influencing the light source's visual appearance.

To properly evaluate these two pathways, both psychological and physiological responses should be measured and analyzed under specific lighting exposures. Based on the above discussion, psychological responses are initiated through the visual pathway, while physiological responses tend to initially appear via the non-visual pathways [18]. However, humans have acute physiological responses to psychological stressors [19], meaning that the visual effect of the light may cause thermal physiological responses. Similarly, the physiological responses to light through non-visual pathways may also counter-impact humans' psychological responses. Thus, just as other effects by lighting [20], even though both pathways and responses are considered when evaluating thermal effects, it can be difficult to distinguish the acute visual and non-visual thermal effects of light, especially in the daytime, from the results of physiological and psychological responses. Overall, an underlying biological explanation for light's thermal effects has not yet been explicitly attained, but there has been an exponential increase in the research literature observing, measuring, and examining light's thermal effects on human beings.

Several previous review studies about non-visual effects of light or indoor environmental factor interactions include certain summary works on the light's thermal effects [21–24], while only one review work in 2015 focuses on the influence of light on thermal effects [9]. That review has attempted to comprehensively address the state-of-the-art technology in this domain, encompassing various nighttime and daytime studies and both quantitative and qualitative research [9]. So, there currently exists no systematic review or cross-study analysis that synthesizes and characterizes light's impact on thermal responses along both visual and non-visual pathways during the daytime. Due to the heterogeneity of light exposure (e.g., type of intervention, duration, light intensity, spectral power distribution), populations studied (e.g., ages, sample sizes, spatial features), and thermal response quantifications employed, conflicting findings have been reported. More importantly, without accurate and complete experimental settings (lighting information and microclimatic conditions), it is challenging to draw some conclusions across different studies. In other words, the findings of previous research have not yielded a sufficient rationale or evidence for future applications and research trajectories. Therefore, three major research questions driving this systematic literature review are as follows: 1) What does the scientific literature tell us about the acute thermal effects of light during the daytime? 2) Are there consistent or similar characteristics among those lighting conditions that confirm or disconfirm light's thermal effects? 3) What are effective and exclusive physiological and psychological indicators of the thermal effects of lighting exposure? Based on the results and answers to the above questions, this review also investigates the differences in and possible interactions among visual and non-visual pathways for acute thermal effects during the daytime. This review will provide a new platform for continued advancements in this area, as well as a rationale for adopting lighting technologies in sustainable and smart buildings.

2. Background

2.1. Light and light spectra

The white light human observes in daily life is a combination of monochromatic lights. The color appearance of the light source depends on the wavelengths and intensity of these combined monochromatic lights and the CCT. The unit of kelvin is used to characterize the color appearance of a light source. Thus, light sources have a continuous distribution of power at different wavelengths. This distribution is called the spectral power distribution of a light source. Wavelengths from 380 nm to 780 nm comprise the visible waveband. The artificial light source human uses in daily life is typically composed of this waveband. When two light sources have the same CCT, their SPDs may differ. This phenomenon is called metamerism. A group of metamerism lights is depicted in Fig. 1. When a light source contains more blue energy, it tends to have a cooler appearance and corresponds to a higher CCT.

2.2. Mechanisms of light effects

Currently, the mainstream theory for light effects is that photoreceptor cells in the eye's retina receive light and convert it into signals that can be sent to a signal receptor in the brain (as a relay center), which in turn connects to various organs as signal processors in the brain and body. With regards to the visual effects of light, photoreceptor cells are comprised of rods and cones (this has been well-known for many decades [25]). The signal receptor is the lateral geniculate nucleus, which sends information to the visual cortex [20]. The visual information determines the visual appearance of lighting (e.g., illuminance on tables, CCT of light sources) and subjective visual sensations (e.g., visual comfort, glare), that may impact psychological (e.g., cognition, alertness, thermal sensation) and physiological responses, and even behavior [26]. When perceiving visual information from lighting, rod and cone cells have different sensitivity levels for different wavelengths. These are described by spectral sensitivity curves that peak at 520 nm and 555 nm, respectively [27].

The non-visual effects of light were first identified approximately two decades ago. Much evidence has shown that the non-visual effects of light rely on the photopigment of melanopsin [28–31]. The existence of melanopsin in the retinal ganglion cells makes them intrinsically photosensitive, which are the third type of photoreceptor cell in the retina and also called intrinsically photosensitive retinal ganglion cells (ipRGCs) [6]. These ipRGC can project to many regions in the brain [8,32]. Currently, the most well-known region is SCN in the hypothalamus, which is the master circadian pacemaker that synchronizes other oscillators distributed throughout the brain and peripheral tissues, including thermo-physiological signals, along diverse pathways [33,34]. Due to the synchronization of SCNs, humans have circadian rhythms, which are oscillations of psychological and physiological responses or functions that repeat approximately every 24-h (with different deviations for different responses) along with a variety of phase-response curves [35,36]. The responses synchronize with the body's biological clock (or central circadian pacemaker) and include the sleep-wake cycle, CBT, hormone secretion (both melatonin and cortisol) [37,38], HR, BP, and so on [39,40]. Most of these can be explained by the secretion of melatonin, which is a hormone mainly produced by the pineal gland [41–44]. The pineal gland is a processor of information received from SCNs through complex pathways in the nervous system [45,46]. Furthermore, regulation of these rhythms to some extent affects alertness, activity, cognition, feeding, and so on [47,48]. As melanopsin is a photopigment in the non-visual pathway, the spectral sensitivity curve for receiving

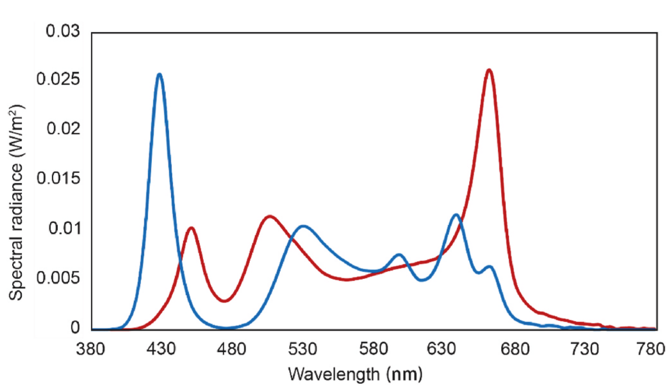

Fig. 1. Metameristic light spectra.

non-visual information from lighting peaks at about 470–480 nm [49]. In addition to spectral composition, four other factors influencing the circadian effects of light include light quantity, time of day, duration, and light history [6,50].

It has recently been determined that in addition to circadian effects, the non-visual effects of light impact human beings through acute physiological regulation [8]. The most sensitive period of the circadian effects of light is from about 2 h before regular bedtime to 1 h after regular wake-up time [51]. In addition, the non-visual effects of light that are activated by the alignment of circadian rhythms are indirect. Thus, the acute non-visual effects of light in the daytime when melatonin secretion is often negligible may be more important, if the effects exist.

It has been demonstrated that the acute non-visual effects of light may be mediated by ipRGCs [23]. However, the circuit by which light influences the acute responses mediated by ipRGCs remains unclear during the daytime. Unlike the circuit that operates through SCNs for circadian rhythm regulation, some researchers believe that the circuit for acute non-visual effects manifests in other areas of the brain and is mediated by certain subpopulations of ipRGCs [52,53]. The possibility that some types of ipRGCs project to other regions of the brain and influence acute body temperature suggests that more pathways and signs of acute thermal responses are caused by light [54].

In addition to the acute non-visual thermal effects of light, some acute daytime effects and corresponding indicators have recently been found. Research has identified the effects of light on alertness during the day, using an EEG as an indicator of alertness variations [55]. HRV was found to be an indicator of both anxiety and depression and influenced by the acute non-visual effects of light in the daytime [56]. Cognition has also been found to be non-visually influenced by short-term daytime light exposure. Positron emission tomography and functional magnetic resonance imaging have frequently been used to detect variations in regional brain activity [57].

2.3. Thermal comfort and thermoregulation

People exist in either internal or external thermal environments that form a heat exchange between the ambient environment and the human body. Judgments regarding thermal comfort are made via a cognitive process involving many inputs related to physical, physiological, psychological, and other factors [58]. According to the ANSI/ASHRAE standards, thermal comfort is defined as "that state of mind which expresses satisfaction with the thermal environment [59]." In the ANSI/ASHRAE standard, indoor human thermal comfort could be predicted by environmental and personal factors, including air temperature, mean radiant temperature, air speed, relative humidity, clothing insulation, and metabolic rate, as adopted in the well-known Fanger's Predicted Mean Vote model [59]. Human thermal comfort could also be subjectively rated by psychological responses like TCV, TSV, TPV, TAV, and TTV [59]. As for the physiological factor, during normal activities, these processes result in an average CBT of approximately 37 °C [60]. This stable CBT is essential for health and wellbeing. It has been observed that the body will feel neutral regarding thermal comfort when the CBT is maintained at this level. Human thermal interaction with the environment is directed towards maintaining this stability in a process called "thermoregulation [61]." Thermoregulation is the mechanism by which mammals maintain their body temperature. It has three phases: afferent sensing, central control, and efferent response [62]. In the afferent sensing phase, thermoreceptors that respond to cold or warm temperatures identify whether the CBT is too high or low. The information from this afferent sensing is transmitted to the hypothalamus in the brain, which is the central controller for thermoregulation. Signals are then sent to various parts of the body, including the skin, glands, muscles, organs, and circulatory system so that the CBT can be altered. Efferent responses altering the CBT include autonomic thermoregulatory responses of the human body and human behavioral responses.

There are thermoreceptors spread throughout the human body. In autonomic thermoregulatory control, the integrated CBT sensed by thermoreceptors on the skin's surface, deep in the abdominal and thoracic tissues, and in the spinal cord, hypothalamus, and other parts of the brain is sent to the hypothalamus to control thermoregulation [63]. Thermoregulatory responses depend on their thresholds, which are the corresponding triggers for CBT. If the integrated body temperature exceeds a threshold of too hot, the corresponding thermoregulatory responses, including sweating and vasodilation (i.e., dilation of blood vessels), will be initiated to suppress thermogenesis and facilitate heat loss [64]. If the integrated body temperature is less than the threshold response to cold, shivering, non-shivering (in the brown adipose tissue), thermogenesis, or vasoconstriction (i.e., constriction of blood vessels) will be initiated to generate heat or prevent heat loss [65]. By comparing the average body temperature with the threshold and triggering efferent responses, the human CBT affects a dynamic balance. It is important to note that thresholds have routine variations due to circadian rhythms and women's menses, and thus human CBT varies daily following the circadian rhythms and (in women) monthly biological cycles [62]. Other outside interferences to some extent can also alter these thresholds, such as exercise, sleep, food intake, infection, drugs, adaptations, and so on [36]. Gains in responses that characterize deviations from the triggering thresholds after autonomic thermoregulatory control also vary under different conditions [62].

However, the relationship between the thermoregulatory system and thermal comfort perception is complicated. It is generally accepted that body thermoregulation determines thermal sensation and comfort responses [66]. Vasodilation defending against hot temperatures increases BF, while vasoconstriction in response to cold reduces BF [64]. Gradients in the skin's surface temperature (from the forearm to fingertip) can be used to quantify vasoconstriction in thermoregulation [36]. As thermoregulatory control is one of the homeostatic control mechanisms influencing HRV, the latter has proven to be a predictive biomarker of thermal comfort [67,68] (e.g., HR and HRV differences, cold-defense responses, heart rate increases). Similarly, variations in the mean CBT values can be observed with an increase in metabolic rate. This has been adopted as a major parameter for determining thermal comfort [69]. Meanwhile, subjective thermal discomfort is also responsible for the initiation of behavioral thermoregulation [70], such as vasoconstriction, shivering, changing clothes, and controlling air conditioning. Unlike autonomic thermoregulatory control, the afferent input triggering these behavioral responses is skin temperature [68]. Previous studies have described the relative contributions of CBT and skin temperature to thermoregulation and thermal comfort. Skin temperature provides much less input relative to the CBT with regards to autonomic responses (i.e., vasoconstriction, metabolic heat production, and plasma catecholamine concentrations) but contributes equally to thermal comfort [66,71]. In this context, physiological responses, especially CBT and skin-related temperatures, to lighting exposure are often monitored and analyzed in literature because these temperatures have been found to contribute to subjective thermal comfort [72].

3. Review method

3.1. Search engine

The PubMed, Scopus, and Web of Science search engines were used to review research regarding light's effects on thermal responses during the day. The sources were last searched in January of 2022. The article language was limited to English. Articles were screened based on their titles and abstracts. The following keywords or phrases were adopted:

(light OR lighting OR LED OR bright OR dim OR color OR illuminance OR illumination OR visual OR non-visual OR CCT OR correlated color temperature OR spectral OR spectrum) AND (thermal comfort OR thermal sensation OR thermal perception OR thermoregulation OR thermal behavior OR dressing behavior OR core body temperature OR core temperature OR body temperature OR skin temperature OR human energy expenditure OR blood pressure OR heart rate OR blood flow OR hue-heat hypothesis).

3.2. Selection criteria and screening process

For a candidate study to be selected, five inclusion criteria had to be fulfilled:

1) Publication in a peer-reviewed journal.
2) Inclusion of both CCT for white light (or peak wavelengths for monochromatic light) and illuminance information of interventions so that thorough lighting information was available.
3) Interventions during the day (working hours, e.g., 8 AM-5PM).
4) Interventions with artificial light sources alone. In this context, dynamic light sources, wall colors, videos, and mixed light sources (both artificial light and daylight) were excluded.
5) Inclusion of key information regarding the research design (e.g., type, sample size) and measures of thermal responses.

The search and screening were tracked and concluded according to the PRISMA flow chart shown in Fig. 2 [73].

The searches of databases and other sources yielded 4,160 articles. After removing duplicates via Mendeley [74], 3,465 articles remained. These were preliminarily screened by checking titles and/or abstracts. Subsequently, the full texts of 42 articles were checked for eligibility, and 24 articles that did not fulfill the selection criteria were eliminated. This resulted in 18 articles eligible for review.

3.3. Data and key information extraction plan

The extracted information included lighting intervention designs, experimental designs, sampling, additional intervention designs, outcome measures (related to thermal responses), additional measures, and study results. Lighting intervention information included lighting type, intensity, the CCT of the light source, time of day, and exposure duration. Experimental design information reflected the design, protocol, and measure time.

4. Results

Eighteen studies were extracted from 18 selected papers: 16 containing one study, one reevaluating two studies from two previous papers, and one reporting two studies. The main characteristics in terms of lighting, research design, outcome measures, and key findings are listed in Table 1.

The study numbers varied with the year of publication and are summarized in Fig. 3. Papers fulfilling the requirements were concentrated mostly in recent years, indicating an increasing trend of reporting thorough lighting information and a greater focus on the daytime acute thermal effects of light sources.

The study characteristics, lighting intervention information, and outcome measures and results are summarized in the following sections.

4.1. Study characteristics

1) Experimental design

The experimental design is summarized in Table 1, which shows that 13 out of the 18 studies had more than one intervention variable in terms of lighting, ambient air temperature, noise, and/or melatonin intervention. Five studies did not [84,85,87,91,92]. Twelve studies had ambient air temperature interventions in addition to lighting interventions, and three reported ambient air temperature but did not involve it as an intervention [84,85,92]. Most of the designs were within-subject, except for two between-subject designs for lighting intervention [83] and two mixed-subject designs that were

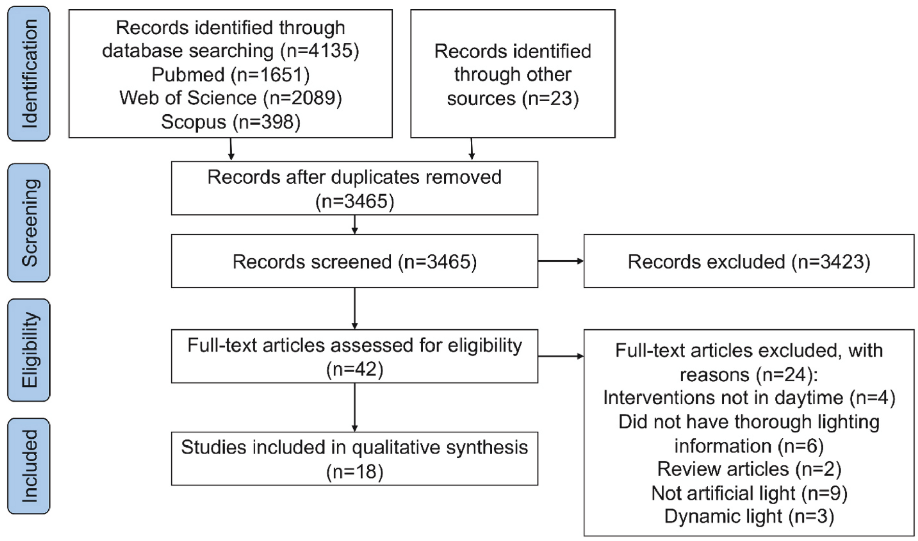

Fig. 2. PRISMA flow diagram.

within-subject for lighting intervention [86,90]. In all of the within-subject designs for lighting intervention, subjects experienced lighting interventions in one day within a specific ambient air temperature session [79–82,84–86,89–92] or in different sessions conducted on different days while maintaining the same time of day for lighting interventions; the latter design was for comparison purposes [75–78,87]. Among the studies, only one adopted a control group for comparison [86].

2) Samples

The number of participants and gender distributions are visualized in Fig. 4. Most had a small sample size of less than 50, which may have been because some designs were time-consuming and only allowed for one or two participants at a time. The large sample size seen in certain studies was mainly achieved by increasing participant numbers in one experimental group (e.g., 50 participants for each experiment). Also, four out of the total 18 studies had only one gender type, while nine had well-balanced gender distributions.

4.2. Intervention design

1) Lighting interventions

Three of the selected studies used monochromatic light with different peak wavelengths and similar illuminances for their interventions [82,85,92] while the other 15 adopted white light. Among these 15 studies, four used a fluorescent light source [79,88,89,91] while the other 11 provided white light from LED light sources. Of the 15 studies with white light interventions, nine were designed to have CCT variations with similar illuminances [76,80,81,83,84,88–90], four had illumination variations with similar CCTs [75,78,79,91], and two had both CCT and illuminance variations [86,87]. For CCT variation designs, warmer light with CCTs from about 1,800 K to 3,000 K, cooler light with CCTs around 6,000 K (except for one of almost 12,000 K [84]), and middle CCTs around 4,500 K were adopted under unchanged illuminance levels in the range of 250–500 lux; this was true except for one that was less than 100 lux. For illuminance variations in the design, bright light with illuminances of 1,000 lux, 1,200 lux, and 2,000 lux, dim light with illuminances of 150 lux, 10 lux, and 5 lux, and a middle illuminance of 500 lux (in one study) were adopted with unchanged CCT levels in the range of 4,000 K to about 6,500 K; this was true except for one study that used illuminances of 5,000 lux and 10,000 lux generated by cool light [91]. For CCT and illuminance design variations, CCTs in the range of 2,500 K to 6,000 K and 100 lux to 1,000 lux were adopted. Three studies adopted monochromatic lights, with the blue light of approximate wavelengths around 500 nm, yellow light from 600 nm to 610 nm, and red light from 623 nm. In studies [78,84], the differences in the light source were designed for comparison purposes and differed substantially from the light sources used in other studies. The lighting information for these studies is displayed and compared in Fig. 5. Different designs are indicated by different colors. There were two outliers that were not displayed in Fig. 5. Article [77] compared light sources from articles [75,76], and article [91] used 40 W cool light to generate light sources with illuminances of 5,000 lux and 10,000 lux.

The spectra of the white light were found to provide less conclusive but more detailed lighting information, including peak wavelength, which is often used to describe SPDs in radiometry, photometry, and color science [93,94]. Every SPD has one or more peak wavelengths, which can be used intuitively to understand the character of the spectrum [95]. Each spectral peak is then characterized by certain parameters such as frequency, amplitude, and spectral width. The spectra of white light provided in the articles are summarized in Fig. 6, which shows the two- and three-waveband LED lights adopted. These refer to the inclusion of two and three peak wavelengths, respectively. In general, these peak wavelength-dominated wavebands were used to form the low and high CCTs in the lighting intervention designs. In particular, among the eight LED spectra provided (see Fig. 6), five had three wavebands. These could roughly be divided into 400 nm to 500 nm, 500 nm to 600 nm, and above 600 nm [75,76,80,81,83]. One spectrum has two peak wavelengths in the 400 nm to 500 nm range and one peak wavelength in the above 500 nm range [78]. The other two spectra with two wavebands had the peaks in the 400 nm to 480 nm and above 480 nm ranges [87,90].

Finally, the exposure durations for the lighting interventions were 9 min [85], 10 min [89,92], 12 min [80], 15 min [90], 30 min [81,82,84], 35 min [79], 40 min [86], 45 min [87], 75 min [75–77], and 90 min [78,88,91].

2) Thermal interventions

As stated above, most studies designed thermal interventions. One compared four different ambient air temperature gaps to determine the potential of the light source for covering those gaps [86]. Article [83] adopted cooling and warming cycles. The others set two or three ambient air temperatures to represent higher or lower ambient air

Table 1
Study characteristics.

Study ID	Interventions-source, lighting intervention information, other intervention	Design, sample size, protocol, sampling time, how many people	Outcome measures- Responses of interest and other responses	Results of thermal responses
Kulve 2017a [75]	- LED - Lighting interventions 1) Baseline: 250 lux, 4000 K 2) I1: DL 5 lux (4.13), 4000 K (3517) 3) I2: BL 1200 lux (987), 4000 K (3776) - Eye level, view direction - In the morning - 75 min for each time block - Other intervention: Air temperature (26 °C, 29 °C, 32 °C with 29 °C as baseline)	- Randomized crossover design: 2 sessions (lighting) and 3-time blocks (air temperature, same order for two sessions within each participant, the second block is always 29 °C) in each session - In each session, baseline 8:00–8:30, block1 8:45–10:00, block2 10:15–11:30, block3 11:45–13:00, with 15 min break in between. - Five questionnaires in each block, continuous phy measurements except BP (3 times). - N = 19 F	- Measures of interest Phy: Mean SKT, CBT, HR, EE, BF, BP, Prox SKT. - Other measures: Sleep characteristics, reaction time performance.	- CBT: decreased with BL - Prox SKT: decreased with BL - DPG: increased with BL - Irrespective of air temperature. - No significant differences: EE, BF, HR, BP
Kulve 2017b [76]	- LED - Lighting interventions 1) Baseline: 5 lux, 4000 K 2) I1: 50 lux (54.4), 2700 K (2549) 3) I2: 50 lux (55.4), 5800 K (5831) - Eye level, view direction - In the morning - 75 min for each time block - Other intervention: Air temperature (26 °C, 29 °C, 32 °C with 29 °C as baseline)	- Randomized crossover design: 2 sessions (lighting) and 3-time blocks (air temperature, same order for two sessions within each participant, the second block is always 29 °C) in each session - In each session, baseline 7:45–8:30, block1 8:45–10:00, block2 10:15–11:30, block3 11:45–13:00, with 15 min break in between. - Five questionnaires in each block, continuous phy measurements except BP (3 times). - N = 16 F	- Measures of interest Phy: Mean SKT, Distal SKT, Prox SKT, DPG, CBT, EE, BF, HR, BP. Psy: TSV (7), TCV (5) - Other measures: Perception of the light, sleep characteristics, alertness task, cortisol level.	- CBT: higher in 6500 K compared to 2700 K - Prox SKT: higher in 6500 K under cool conditions - Not significant after BH corrections - No: Mean SKT, Distal SKT, DPG, BF, EE, HR, BP, hormones, TCV, TSV
Kulve 2018 [77]	A revisit and re-evaluation of the first two studies combined		- Measures of interest 1) Phy: Mean SKT, CBT, EE, SASV (2), SASW (2). 2) Psy: TCV (3), TSV (7), TPV (7). Other measures: Perceived light intensity, perceived light color, visual comfort, preferred light intensity change, preferred light color change.	- SASV: increased in5800 K compared to three other exposures during cool conditions. - No: Mean SKT, CBT, EE, TCV, TSV, TPV, SASW
Lok 2019 [78]	- LED - Lighting interventions 1) Baseline: DL 2) I1: DL 10 lux, 5800 K 3) I2: BL 2000 lux, 5800 K - Measured on the vertical plane at the level of the eye - In the afternoon - 90 min for each lighting intervention - Other intervention: Melatonin/ placebo	- 2 by 2 balanced within-subject design: 4 lighting interventions conducted in 4 days - In each day, habituation 12:00–13:00, melatonin or placebo intake at 13:00, lighting intervention baseline 13:00–14:30, lighting intervention 14:30–16:00. - Continuous phy measurements. - N = 10 5 M 5 F	- Measures of interest Phy: HR, saliva, tongue temperature as CBT, Mean SKT on the forehead, navel, sub clavicular regions, hands, and feet, DPG. - Other measures: Saliva, reaction time.	Under placebo - Hand temperature.: increased with BL - DPG: increased with BL - No: HR, CBT, other SKT. Under melatonin - CBT: increased with BL. - Prox SKT: increased with BL. - Distal SKT (average of hands and feet): decreased under BL. - DPG: decreased under BL. - No: HR, other SKT.
Yang 2019 [79]	- Fluorescent - Lighting interventions 1) I1: 150 lux (158.4), 6486 K 2) I2: 500 lux (516.5), 6486 K 3) I3: 1000 lux (997.4), 6486 K - Measured at desk level - Unknown time - 35 min for each lighting intervention. - Other intervention: Air temperature (25 °C, 30 °C, 20 °C), noise type	- Factorial within-subject design: 3 days for 3 air temperatures, 3 interventions in each day with different noise displayed. - On each day, 10 min adaptation at the start, and then three 35-min interventions, the first 20 min of which were regarded as adaptation time. - Questionnaire at the end of each intervention. - N = 60 30 M 30 F - 4 participants at a time	- Measures of interest Psy: TCV (11). - Other measures: Acoustic comfort (11), visual comfort (11), and indoor environmental comfort (11).	- TCV: Peak at 500 lux - Lighting intervention has but a weak influence on TCV.
Baniya 2018 [80]	- LED - Lighting interventions 1) I1: 500 lux (497), 2700 K (2733) 2) I2: 500 lux (506), 4000 K (4084) 3) I3: 500 lux (496), 6200 K (6208) - Measured at the center of a round table, continuous variation of CCT when changing scene in 6 min - 9–11, 12–14, or 15–17	- Within-subject design: 2 days for 2 air temperatures with 25 first, 3 interventions in each day from I1 to I3. - On each day, 12 min of each intervention for adaptation and filling in questionnaires with 6 min in between under continuously changing CCTs. - Questionnaire after about 10 min of each intervention. - N = 16 7 M 9 F	- Measures of interest Psy: TCV (4), TSV (9), continuous scale. - Other measures: Light sensation.	- TSV: At 25 °C, warmer in 2700 K than 4000 K, no differences between other pairs of CCTs - No: TCV at both air temperatures, TSV at 20 °C.

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Table 1 (*continued*)

Study ID	Interventions-source, lighting intervention information, other intervention	Design, sample size, protocol, sampling time, how many people	Outcome measures- Responses of interest and other responses	Results of thermal responses
	- 12 min for each lighting intervention - Other intervention: Air temperature (25 °C, 20 °C)			
Brambilla 2020 [81]	- LED - Lighting interventions I1: 371.3 lux, 3968 K I2: 374.5 lux, 2762 K I3: 373 lux, 6253 K - Measured at an unknown position - Unknown time - 30 min for each lighting intervention - Other intervention: Air temperature (21 °C, 24 °C, 26 °C)	- Randomized within-subject design: 3 days for 3 air temperatures, 3 lighting interventions in each day. - On each day, 5 min initial adaptation (3901 K), 30 min intervention for each CCT with 5 min rest in between. - Questionnaires at the initial and end of each intervention. - N = 45 21 M 16 F 8 unknown	- Measures of interest Psy: TSV (7), TCV (7), satisfaction with their thermal comfort (7). - Other measures: Overall satisfaction of lighting.	- TSV: 26 °C, cooler in 6253 K compared to 3968 K both initial and adapted responses, 2762 K warmer when initial, the effect disappeared after adaptation. - TCV: 21 °C, 2762 K makes more comfortable at the initial, disappeared after adaptation. - Satisfaction: 26 °C, more satisfied in 6253 K compared to 3968 K both initial and adapted. 21 °C, 2762 K makes more satisfied at the initial, disappeared after adaptation
Albers 2015 [82]	- LED - Lighting interventions I1: Blue (peaks at 495.9 nm), 232.1 lux at the ceiling I2: Yellow (608 nm), 177 lux Neutral: (520.4 nm), 290.9 lux Green: (526.2 nm), 200.3 lux Violet: (517.5 nm), 169.9 lux - Measured at an unknown position - Start at 10:00 or 14:00. - 30 min for each lighting intervention - Other intervention: Air temperature- group 1 (24.3 °C, unknown), group 2 (25.4 °C, unknown), group 3 (21.5 °C, 22.5 °C), group 4 (23.6 °C, 23.1 °C)	- Within-subject design: Same design but different air temperatures in 4 groups. In each group, 2 temperatures were experienced, and 2 lighting interventions were displayed in each temperature setting. - In each group, 1 min neutral light and irrelevant lighting (unknown time) were displayed before each air temperature experience. Two lighting interventions were displayed for 20 min with no break. - Questionnaires at the last 10 min of each intervention. - N = 199 balanced gender - 50 participants at a time (in one group)	- Measures of interest Psy: TSV (7), TCV (5), TE (°C). - Other measures: Visual appearance of light, perception of the indoor environment.	- TSV: tend to be slightly warmer in yellow light, and slightly colder in blue light. - TCV: more comfortable in yellow light. - TE: higher in yellow light
Huebner 2016 [83]	- LED - Lighting interventions I1: 550 lux, 2700 K (2892) I2: 495 lux, 6500 K (6329) - Measured horizontally on the work plane - Began at 10:30 or 15:00 - One hour for each lighting intervention - Other intervention: Air temperature- cooling cycle (continuously from 24 °C to 20 °C), warming cycle (20 °C to 24 °C)	- Between-subjects design: Each participant experience one lighting intervention and one air temperature cycle. - Each participant stayed 1 h. - Questionnaires every 10 min. - N = 32 2700 K-9M 7 F; 6500 K-9M 7 F - 2 participants at a time	- Measures of interest Psy: TSV (7), TCV (5), TPV (7), TAV (2), TTV (5).	- TSV: warmer in 2700 K for the cooling cycle; no for the warming cycle, proves the effect of time of day - TCV: more comfort in 2700 K for both cycles - TPV: prefer warmer in 6500 K during the warming cycle - TAV: higher in 2700 K for both cycles - TTV: less unbearable at 2700 K during the cooling cycle.
	- Same as above except: - Other intervention: Air temperature changed repeatedly	- Between-subjects design - N = 32 2700 K-5M 11 F; 6500 K-4M 12 F	- Measures of interest Behavior: Air temperatures to put on clothes, and what the participants put on.	- More participants put on extra clothing under 6500 K - No: Air temperatures to put on clothes
Golasi 2019 [84]	- LED - Lighting interventions I1: 500 lux (504.6), 1772 K I2: 500 lux (510.2), 4000 K I3: 500 lux (518.5), 11,530 K - Measured at desk level - Unknown time - 30 min for each lighting intervention - Other intervention: No, but the air temperature was set at 22 °C.	- One-factor within-subject design: 3 lighting interventions for each participant. - 15 min adaptation, 30 min for each lighting intervention with 10 min neutral light washout in between. - Questionnaires before and after the task. - N = 42 24 M 18 F - 2 participants at a time	- Measures of interest Psy: TSV (7), TPV (3), TAV (2), and TTV (5).	- TSV: cooler with higher CCT - TPV: prefer warmer in 11,530 K - TCV: 4000 K > 11,530 K > 1772 K - TAV:4000 K > 11,530 K > 1772 K - TTV: Small differences between cold and warm light - just provide trends, no statistical data provided
Winzen 2014 [85]	- LED - Lighting interventions Adaptation: Neutral (527.48 nm), 222.52 lux I1: Yellow 1 (603.22 nm), 134.93 lux I2: Yellow 2 (607.1 nm), 123.9 lux I3: Blue 1 (496.77 nm), 175.3 lux I4: Blue 2 (504.58 nm), 200.4 lux - Measured at an unknown position - Unknown time	- One-factor within-subject design: 4 lighting interventions for each participant. - 1-min washout and 9 min for each lighting intervention. - Questionnaires after each intervention. - N = 59 41 M 18 F - 10 participants at a time.	-Measures of interest psy: TSV (7), TCV (5), TPV. -Other measures: perception and evaluation of lighting.	- TSV: higher in yellow light - TPV: more participants preferred warmer in blue light - No: TCV.

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Table 1 (*continued*)

Study ID	Interventions-source, lighting intervention information, other intervention	Design, sample size, protocol, sampling time, how many people	Outcome measures- Responses of interest and other responses	Results of thermal responses
	- 9 min for each lighting intervention - Other intervention: No, but the air temperature was set at 22.2 °C.			
Tsushima 2020 [86]	- LED - Lighting interventions I1: 800 lux, 3000 K I2: 300 lux, 5500 K Control: 700 lux, 4500 K - Measured values did not report - Unknown time - 40 min for each lighting intervention which was displayed separately. - Other interventions: Air temperature-four groups (I1 room-27 °C, 26 °C, 25 °C, 24 °C, I2 room-27 °C)	- Mixed-subject design for with control groups: four groups of air temperature gaps with different subjects. For each temperature gap, two rooms with different lighting interventions and different temperatures were visited. Same protocol for control groups. - In each temperature gap group, participants stayed in Room 1 or 2 for 20 min. Then, the participants moved to Room 2 or 1, and stayed for 20 min. The same experiment was conducted on them twice. - Questionnaires every 5 min in the room. - N = 118 66 M 52 F: 15 for 0 °C gap, 20 for 1 °C gap, 13 for 2 °C gap, 22 for 3 °C gap, and each group has 12 for control.	- Measures of interest Psy: TSV (7).	- TSV: warmer in the warm illuminated room, and the effect more effective over time, may eliminate perception difference of 3 °C gap air temperature over time. - The control group didn't have the effect.
Kompier 2021 [87]	- LED - Lighting interventions Baseline: warm dim I1: cool bright 1012 lux, 5880 K I2: cool dim 101 lux, 5890 K I3: warm bright 1004 lux, 2676 K I4: warm dim 98 lux, 2722 K - Measured at an unknown position - 8:45, 10:45, 13:30 or 15:30 - 45 min for each lighting intervention - Other intervention: No.	- 2 by 2 within-subject design: 4 lighting interventions conducted in 4 days. - On each day, 45 min baseline and 45 min lighting intervention. - Questionnaires every 15 min, continuous phy measurements. - N = 23 10 M 13 F	- Measures of interest Psy: TSV (7), TAV (2), TCV (6). Phy: HR, HRV, GSR, Mean SKT (14 ISO defined body sites + under arm and the middle finger), SASV (10). - Other measures: Visual experience, sleepiness, task performance.	- No: Thermal comfort and thermoregulation were not significantly influenced by the lighting manipulations.
Chou 2016 [88]	- LED or fluorescent - Lighting interventions I1: 500 lux, 3000 K (3052) I2: 500 lux, 4000 K (4057) I3: 500 lux, 5000 K (5040) I4:500 lux, 6500 K (6595) I5: FL 500 lux, 6500 K (6445) - Measured at an unknown position - Unknown time - 90 min for each lighting intervention - Other intervention: Air temperature (28 °C, 30 °C)	- 2 by 5 within-subject design: 10 treatments for each participant. - In each treatment, 10 min adaptation, 30 min non-working task, and 60 min working task with 10 min rest in between. - Questionnaires five times throughout each treatment. - N = 8 M	- Measures of interest Psy: TSV (7). Phy: GSR, HR, Mean SKT. - Other measures: Visual fatigue, bright, awake, peace, overall comfort, task performance.	- GSR: in non-working conditions at 28 °C, lower in 4000 K than 3000 K; in non-working conditions at 30 °C, lower 3000 than 4000, no others - No: TSV, HR, Mean SKT.
Yang 2021 [89]	- Fluorescent - Lighting interventions I1: 300 lux, 3000 K I2: 300 lux, 4500 K I3: 300 lux, 6000 K - Measured at an unknown position - Unknown time - 10 min for each lighting intervention - Other intervention: Air temperature (26 °C, 28 °C, 30 °C)	- 3 by 3 within-subject design: 3 sessions for 3 air temperatures, 3 lighting interventions in each session. - In each session, 10 min adaptation and 10 min exposure for each lighting intervention. - Questionnaire at last 3 min of exposure. - N = 20 16 M 4 F	- Measures of interest Phy: ECG to calculate HRV Psy: TSV (7). - Other measures: Short-term memory performance.	- TSV: At 26 °C and 28 °C, negative correlations between CCT and TSV. CCT could alter TSV within a 2 °C air temperature difference. - HRV: When the TSV was neutral or slightly warmer, the HRV value was close to 1. When TSV was warm or hot, the HRV value exceeded 2. - Combined with previous research results, HRV was suggested as a physiological index to evaluate human thermal sensation.
Bellia 2021 [90]	- LED - Lighting interventions I1: 300 lux, 3000 K I2: 300 lux, 6000 K - Measured at the workplane - Unknown time - 15 min for each lighting intervention - Other intervention: Air temperature (20 °C, 25 °C)	- 2 by 2 mixed-subject design: 2 sessions for 2 air temperatures with different subjects, 2 lighting interventions in each session within-subject. - In each session, 30 min adaptation, 15 min for each lighting intervention with 15 min rest in between. - Questionnaires at the end of each intervention. - N = 128: 20°C-35 M, 35 M; 25°C-29 M, 29 F - 1 participant at a time	- Measures of interest Psy: TSV (7), TCV (4), TPV (7).	- TSV: toward colder in 6000 K. - TCV: At 25 °C, more comfortable in 6000 K. - TPV: At 25 °C, prefer warmer in 6000 K.
Badia 1991 [91]	- Fluorescent - Lighting interventions	- Randomized within-subject design: 2 lighting interventions. - 90 min for each intervention.	- Measures of interest Phy: CBT.	- No: CBT.

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Table 1 (*continued*)

Study ID	Interventions-source, lighting intervention information, other intervention	Design, sample size, protocol, sampling time, how many people	Outcome measures- Responses of interest and other responses	Results of thermal responses
	I1: 5000 lux by moving subject under 40 W cool white FL I2: 10,000 lux - Measured at an unknown place. - Start at 13:00. - 90 min for each lighting intervention - Other intervention: No.	- N = 8 M	- Other measures: Behavioral tasks, sleepiness, EEG for alertness.	
Litscher 2013 [92]	- LED - Lighting interventions L1: red (623 nm), 140.98 lux L2: blue (461.2 nm), 140.27 lux - Measured at a distance of 40 cm from the light panel - Unknown time - 10 min for each lighting intervention - Other intervention: No, but the air temperature is 28–30 °C	- One-factor within-subject design: 2 lighting interventions. - Five mins adaptation, 10 min for each lighting intervention with 10 min rest in between. - N = 7 2 M 5 F - 1 participant at a time	- Measures of interest Phy: body temperature at forehead and tip of the nose, ECG, HRV. - Other measures: Emotional state.	- Nose temperature, HR, total HRV: significant decreases were found after 10 min blue light intervention. - In association with a significant alteration of the emotional state (stress level score $P = 0.006$).

*Intervention – I; Subject number - N; Female – F; Male – M; Phy-Physiological responses; Psy-Psychological responses.
For lighting interventions, the actual measured values provided are noted in the brackets; The scale of each parameter in the questionnaire is indicated in the brackets.

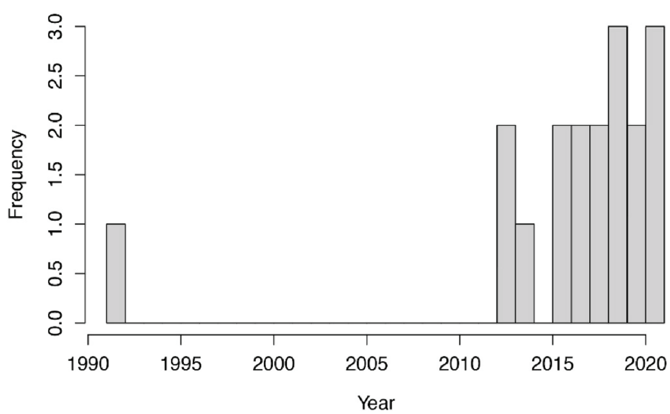

Fig. 3. Yearly distribution of papers.

temperatures, except for one with minor temperature differences, which was still regarded as an intervention [82]. The two or three levels of ambient air temperature settings in each study were different from one another. The designs of the different ambient air temperatures within each study were only for comparing effects and did not represent high or low ambient air temperatures.

4.3. Measures

The outcome measures of interest were responses related to human thermal comfort and thermoregulation, which could be divided into three categories: physiological measures, psychological measures, and behavioral events. In addition to the measures of interest, measures related to visual perception and evaluation, alertness, sleep characteristics, melatonin level, perception, and evaluation of overall indoor environment, memory, and emotion were also conducted. The details are listed in Table 1. In summary, eight articles measured psychological responses alone [79–82,84–86,90], four measured physiological responses [75,78,91,92], and five measured both psychological and physiological responses [76,77,87–89], as shown in Fig. 7. In addition, one paper reported two studies and included psychological and behavioral response documentation [83].

For measurement methods, physiological responses were typically measured continuously by devices. Psychological responses were

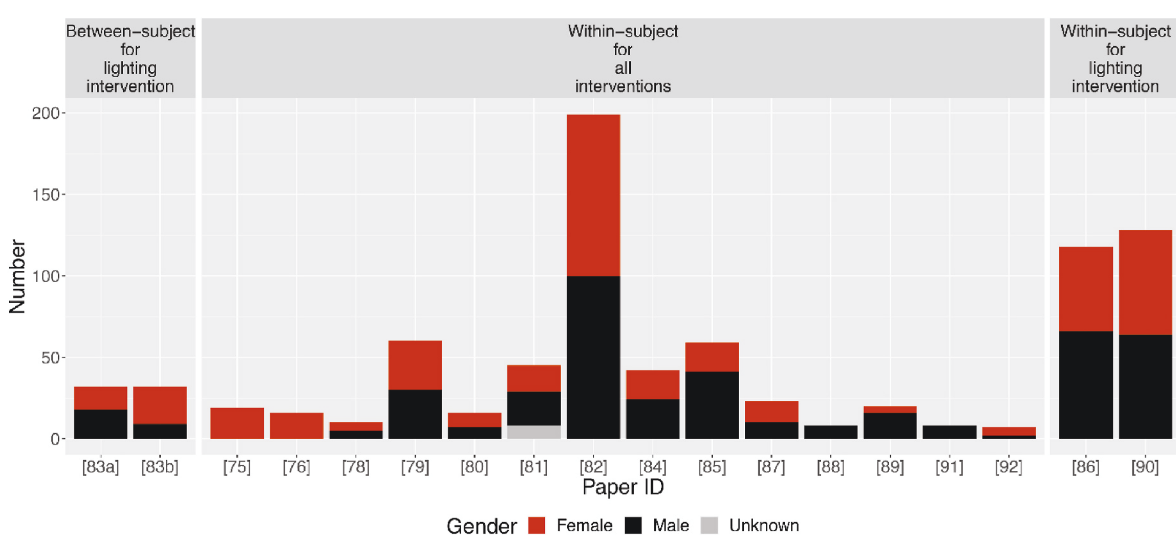

Fig. 4. Number of participants and gender distributions.

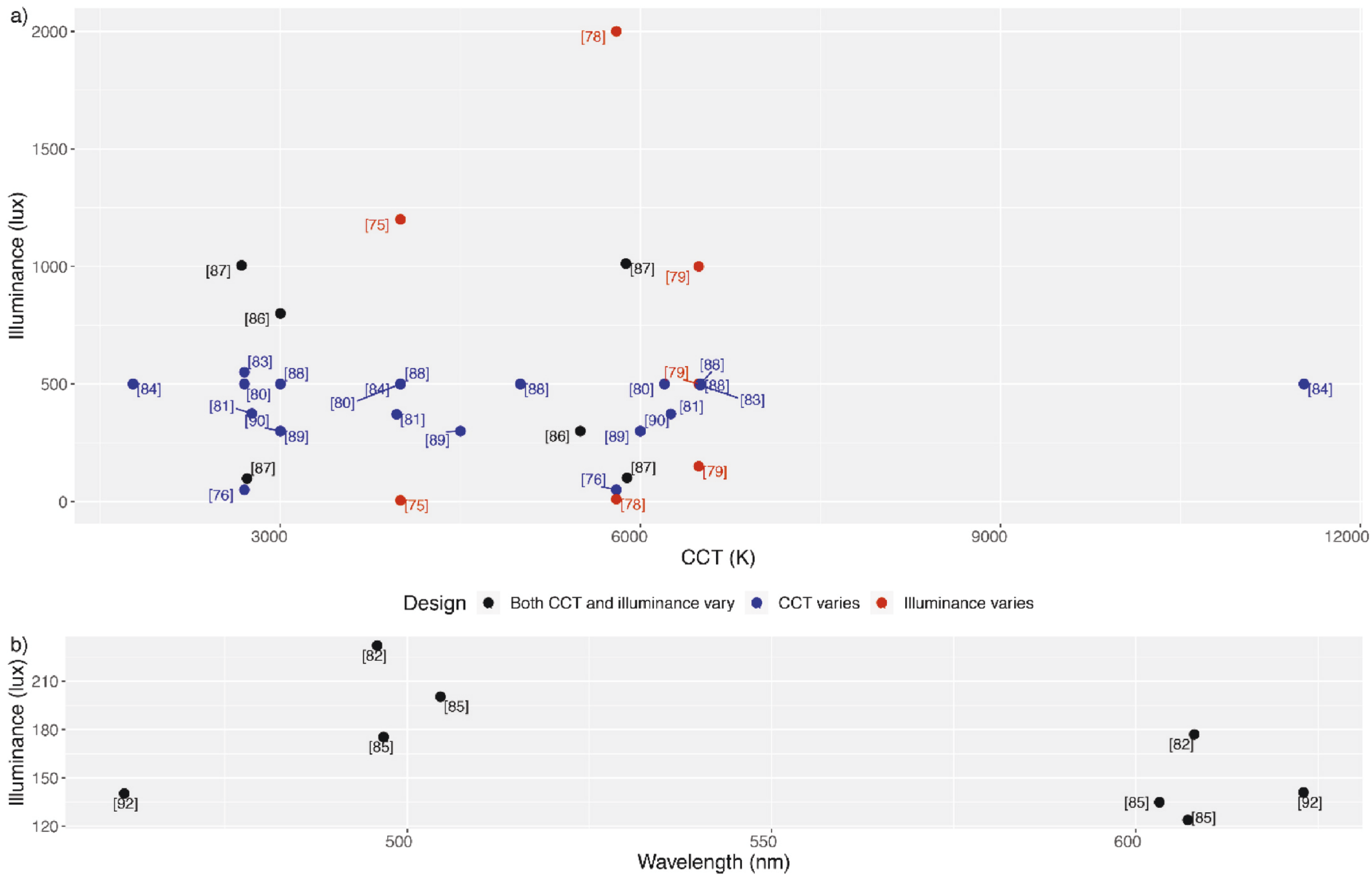

Fig. 5. Lighting information for studies with a) white light and b) monochromatic light.

measured by questionnaires within the intervention at equal intervals [75,76,83,86–88], at the end of each intervention [79,80,82,85,89,90], or initially and at the end of each intervention [81,84]. According to the results, adaptation played an important role in the effects of light sources and requires additional consideration.

4.4. Findings

1) Presence of thermal effects by lighting

To summarize the results across the 18 selected papers, it was necessary to subdivide the measures of the outcomes. Accordingly, the measures, amounts of each measure, results, and consistency of positive results are visualized in Fig. 7. The test findings are represented by color, as follows: N denotes there was no effect, Y that an effect was present, YPL that the effect existed under a partial lighting intervention, and YPTL that the effect existed only under partial ambient air temperature and the lighting intervention. Notations T and F in the red boxes will be discussed in the following section.

Although not all of the studies clearly stated null and alternate hypotheses regarding whether the lighting effects on human thermal responses (either psychological, physiological, or both) existed, the findings of all selected studies provided a landscape verifying this research question. Of the 18 studies' results, more psychological response-related articles confirmed lighting's thermal effects on humans (red boxes) relative to physiological response-related studies. Also, some results partially supporting lighting's thermal effects (YPL and YPTL) (or in other words, the thermal effects were found under certain conditions or in particular ranges) were also placed into the "Y" category. Discussion related to this decision is provided below.

In the context of psychological responses, as shown in Fig. 7, especially for TCV, TPV, and TSV measures (the most commonly used in these studies), six out of 11, four out of five, and nine out of 13 studies confirmed the presence of lighting effects, respectively. On the other side of the physiological responses, the measures and outcomes are more scattered, and the results regarding the existence of thermal effects are quite mixed. More specifically, the physiological measures used to confirm the existence of thermal effects included CBT, DPG, HRV, Prox SKT, SKTP, and SASV. Among these measures, Prox SKT and SKTP offered the most consistent findings regarding the thermal effects of the light interventions. It was consistent that the physiological measures that did not verify the existence of thermal effects under any lighting (or ambient air temperature) intervention included BF [75,76], BP [75,76], Distal SKT [76], EE [75–77], Mean SKT [76,77,87,88], and SASW [77].

2) Hypothesis testing for each measure

Additional subdivisional analyses and associated hypotheses were reviewed in studies and measures finding the presence of thermal effects from designed lighting interventions. For each measure, the causal hypothesis or preassumed relationship (if the changes in lighting caused changes in the thermal responses) was defined in this review and then listed in Table 2. Among them, the hypotheses for psychological measures were generally consistent with the hue-heat hypothesis; those with physiological measures comprised the majority observed. The results supporting the hypothesized relationship (T) and finding an inverse relationship (F) are also embedded in the red boxes in Fig. 7.

It can be seen from Fig. 7 that from the psychological perspective, most results (partially) supported the hue-heat hypothesis, while several results confirmed the inverse relationship (e.g., warmer feelings under cooler light). In particular, for TPV and TSV, all of the findings followed the hue-heat hypothesis. The results for TAV and TCV were relatively

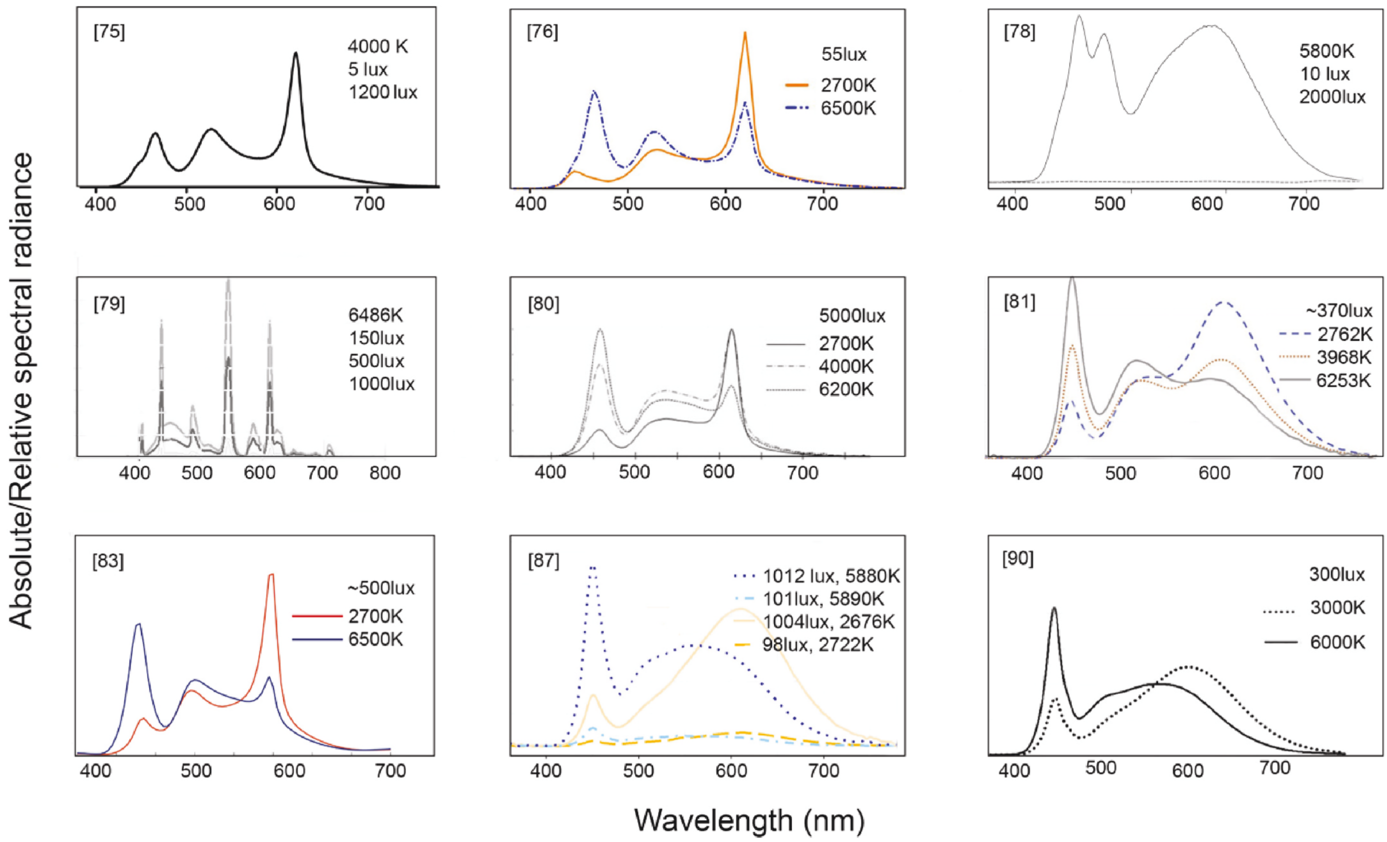

Fig. 6. Lighting spectra extracted from articles with experiments using white light. Five studies did not provide lighting spectra [84,86,88,89,91].

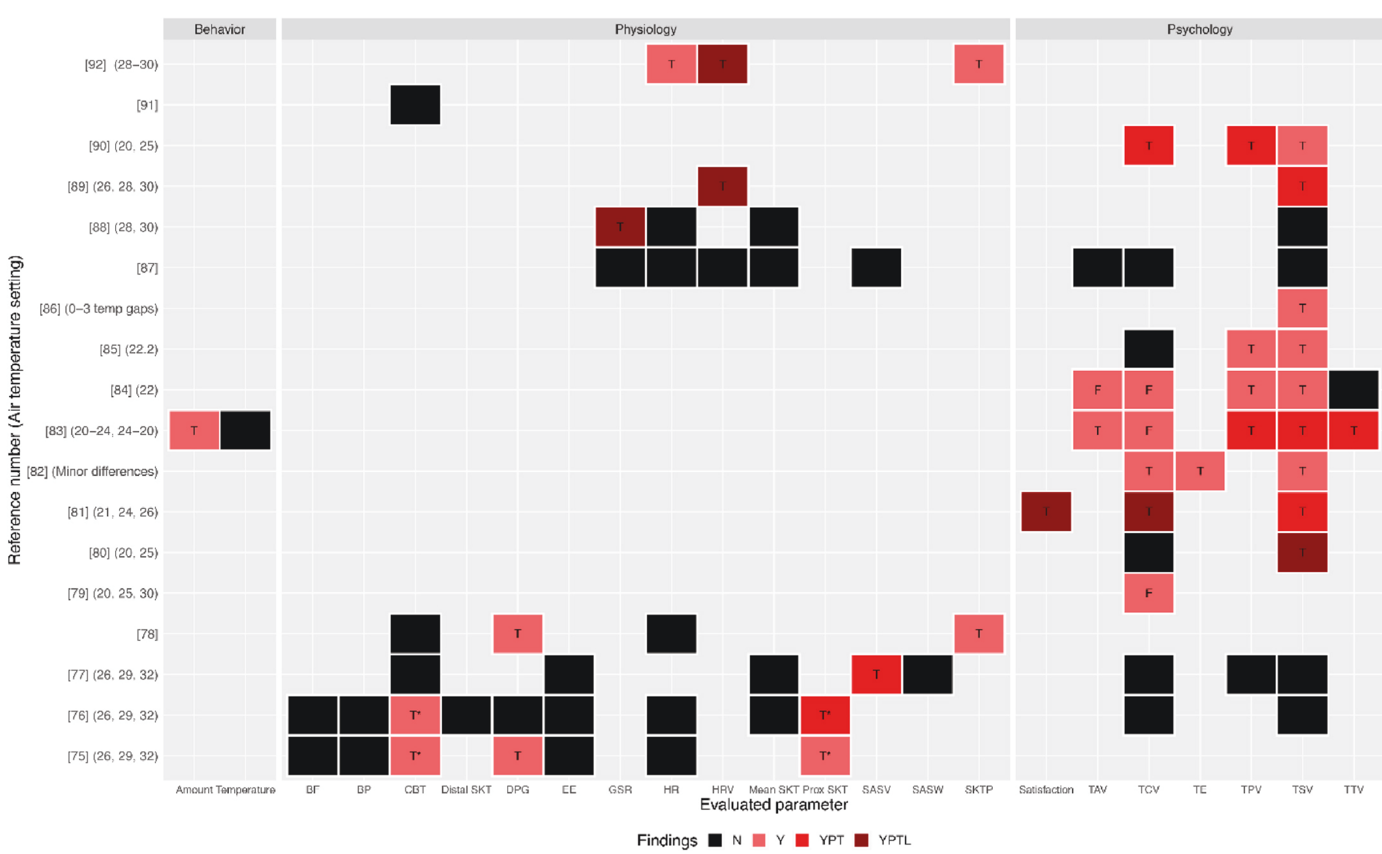

Fig. 7. Outcome measures and results. The * signs noted in the red boxes indicate different lighting designs for the same evaluated parameter.

Table 2
Hypotheses for measures with true outcomes.

Category	Measure	Hypothesis
Physiology	CBT (1)	decreased with brighter or warmer light
	DPG	increased with brighter light
	HRV	decreased with cooler light
	Prox SKT (1)	increased with bright or warmer light
	SKTP	decreased with brighter or cooler light
	GSR (1)	decreased with cooler light under lower ambient air temperature and warmer light under higher air temperature
	HR (1)	decreased with cooler light
	SASV (1)	increased with cooler light under lower ambient air temperature
Psychology	TSV	warmer under warmer light
	TCV	more comfort under bright or warmer light; for studies with ambient air temperature interventions, more comfort under cooler light and higher air temperature and warmer light under lower air temperature
	TAV	higher under warmer light
	TPV	preferred warmer than cooler light
	TTV (1)	less unbearable under warmer light in the cooling cycle
	Satisfaction (1)	more satisfied at cooler light when under higher ambient air temperature and warmer light under lower air temperature
	TE (1)	higher under warmer light
Behavior	Amount (1)	more participants put on extra clothing under cooler light

*(1) indicates only one result was reported across all studies.

mixed since half of the findings supported the hue-heat hypothesis while the other half supported the inverse relationship. The other three measures (i.e., satisfaction, TE, and TTV) were reported only once and thus could not yield summarized features across different studies. A similar issue happened with the results of behavioral responses. From the physiological perspective, the measures with more than one confirmation from the studies were more of interest. In this context, the variations in lighting showed more consistent changes (see the hypotheses in Table 2) in the DPG, HRV, and SKTP measures.

3) **Ambient air temperature distribution and lighting information with different TSV results**

In this review, TSV is the most frequent measure across all the selected studies (i.e., 13 out of the total 18). Compared to TCV (which reports the comfort scale), the TSV measure of perceived temperature indication (e.g., cold, warm, hot) provides more direct information for studying thermal responses to lighting exposure. Accordingly, the characteristics of detailed ambient air temperature and lighting information in studies that considered TCV were worth analyzing. As shown in Table 3, in the 13 studies analyzed, five fully supported the hue-heat hypothesis (denoted with a "Y"), while four studies partially supported it (denoted with "YPT" or "YPTL"). Table 3 also includes four studies that didn't confirm any presence of the thermal effects of light (denoted with an "N"). Detailed lighting information, represented by peak wavelengths and FWHM values for each dominant waveband, was obtained either from the original paper or associated SPD figures via online data extraction tools. For monochromic LED light, the typical spectral bandwidth was smaller than 50 nm [96], as listed in the table.

Generally speaking, the four studies rejecting the hue-heat hypothesis chose ambient air temperature values ranging from 26 °C to 32 °C, while the four studies confirming the hue-heat hypothesis adopted air temperature values ranging from 20 °C to 27 °C. The other four studies partially supporting the hue-heat hypothesis had relatively complicated situations, and the ambient air temperature distributions were mixed across the studies. With regards to lighting interventions, given the available information, the SPDs in all studies confirming the hue-heat hypothesis had two major wavebands: the first (453–501 nm peak wavelengths and 24–50 nm FWHM) and second (584–608 nm peak wavelengths and 50-150n m FWHM). Comparatively, the SPDs in the other studies (those partially confirming or fully disconfirming) had three major wavebands: the first (446–460 nm peak wavelengths and 27–30 nm FWHM), second (498–531 nm peak wavelengths and 69–138 nm FWHM), and third (578–621 nm peak wavelengths, and 69–138 nm FWHM, and 20–135 nm FWHM).

5. Results of other measures

Lok et al. found that during the daytime, melatonin intake alters the CBT under different lighting interventions; this result was not affected under placebo conditions [78]. Their findings suggest that the acute thermal effect of light during the daytime may still require the mediation of melatonin, which has a low level during the day. Furthermore, it has been found that visual perception [77] and emotional state [92] may also influence thermal response variations under different lighting interventions.

Table 3
Ambient air temperature and lighting characteristics for studies with TSV measures.

TSV results	Paper ID	Air Temperature (°C) supporting the hue-heat hypothesis	Air Temperature (°C) rejecting the hue-heat hypothesis	Waveband 1		Waveband 2		Waveband 3	
				Peak wavelength (nm)	FWHM (nm)	Peak wavelength (nm)	FWHM (nm)	Peak wavelength (nm)	FWHM (nm)
N	[76]	\	26, 29, 32	456	30	528	69	621	21
N	[77]	\	26, 29, 32	460	29	527	60	620	20
N	[87]	\	Unknown	451	24	591	144	\	\
N	[88]	\	28, 30	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
YPTL	[80]	25	20	457	29	531	138	616	32
YPT	[81]	26	21, 24	454	24	523	136	613	135
YPT	[83]	24–20	20–24	446	27	498	71	578	26
YPT	[89]	26, 28	30	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Y	[82]	Minor differences for 4 groups from 21 to 25	\	496	<50	608	<50		\
Y	[84]	22	\	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Y	[85]	22.2	\	501	<50	605	<50		\
Y	[86]	27, 26, 25, 24 vs. 27	\	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Y	[90]	20, 25	\	453	24	584	150	\	\

Symbol \ represents "not applicable".

6. Discussion

6.1. Evidence of psychological responses and effective psychological measures

The selected studies adopted a variety of psychological measures, most located within the thermal comfort domain. These measures provided different information about subjective thermal perceptions [97]. In the selected studies, TAV, TCV, and satisfaction measures were focused on deviation (e.g., high or low acceptability, comfort or satisfaction level) from the ideal. Thus, such measures did not incorporate perceived thermal information (e.g., cold, warm). For instance, different lighting CCTs may form "similar" acceptable/unacceptable or comfortable/uncomfortable thermal feelings. Such similar trends would simply result in no effects on thermal responses by lighting variations. Likewise, a warm or cool lighting environment might disproportionally drive feelings of acceptance and comfort in different directions, a condition that could explain several conflicting findings reported in the studies examined (see the T and F values in Fig. 7). Comparatively, findings for TPV, TSV, and TE might provide more appropriate information for demonstrating the hue-heat hypothesis, since these measures directly reflect subjective thermal feelings in terms of perceptions of cold and heat. For these three measures, across all selected papers, nine out of 13 confirmed the existence of the thermal effects of light and consistently demonstrated the hue-heat hypothesis. The other four (three studies in total) reported negative results related to thermal effects [76,77,87,88].

After careful examination of the lighting interventions, it was found that the illuminance in one study was only 50 lux [76,77], the lowest illuminance among the studies designed to explore CCT variations (see Fig. 5). Such low luminous power may not activate the psychological responses to CCT variations. Furthermore, from the human vision perspective, in a low photopic illuminance environment, color vision and visual perceptions are weakened. For instance, colors appear much more saturated under higher illuminance [98]; color discrimination performance is also dependent upon illuminance levels [99]. In other words, CCT differences in dim illuminations are substantially mitigated. Thus, future studies and experiments should consider a minimum illuminance requirement. Another study that did not find any thermal effects of light didn't report its ambient air temperature setting [87], which might have affected the results. A third study did not find a positive result regarding TSV under varying lighting conditions but observed conditional GSR variations when exposed to the lighting intervention [88]. This could be because the differences in designed SPDs of the lighting invention were too minor, but the SPD details were not provided. In summary, from the psychological perspective and in terms of associated measures, the current review results confirmed the long-held hue-heat hypothesis. This cross-study analysis also revealed that TE, TPV, and TSV were more suitable psychological indicators for studying thermal responses to varying lighting conditions.

In the studies applying psychological measures, special attention was also given to the characteristics of the microclimatic condition settings and lighting interventions.

1) Microclimatic condition settings

In cause-and-effect relationship testing, a covariate variable is often used because it is related to the outcome (or dependent variable), and may be a possible predictive or explanatory variable for outcome variations [100]. In this research context, microclimatic condition settings and changes had direct effects on subjective thermal comfort and thermal responses (e.g., preferred temperature, estimated temperature). In the studies selected in this review, the most common microclimatic parameters that were considered include ambient air temperature and relative humidity (15 out of 18 studies). Relatively, much fewer studies measured or reported air speed and mean radiant temperature during the experiments. Only three out of 18 studies measured (or reported) all microclimatic and personal variables defined in Fanger's PMV model.

Furthermore, in most studies, the ambient air temperature was considered as part of the intervention design. There were **two major connections** affecting thermal sensation outcomes. First, the initiation of ambient air temperature determined the sensitivity to thresholds for warm and cool stimuli. Assuming that the thermal effects of light exist to may provide warm or cool feelings at certain levels, such effects may be more pronounced when one resides at a boundary of the thermal comfort zone and less dramatic at the center. Also, it has been reported that ambient temperature, especially in cooler environments, affects human thermal sensitivity [101]. This may further increase collective effects on the thermal sensations reported. Another potential effect of ambient air temperature settings on outcomes is related to the well-recognized thermal transient; that is, thermal experiences have a substantial influence on human thermal sensations, such as moving from a neutral thermal environment to a mildly warm one. When experiments are designed for only short periods, this effect on the outcome may be more intense. However, most such thermal information (i.e., pre-experiment) was not available in the studies examined.

Based on the ambient air temperature information available in the articles, certain interesting features emerged. As summarized in Section 4.4-3), the ambient air temperature values in the studies that didn't confirm thermal effects were generally higher than those supporting the hue-heat hypothesis, which was about 26 °C to 32 °C vs. 20 °C to 27 °C. This suggests that light's thermal effects may be relatively more noticeable in neutral to cool environments as compared to neutral to warm environments. For the other four articles offering partial support, the ambient air temperature settings at which the hue-heat hypothesis was confirmed were relatively higher than those disconfirming the hypothesis, though the range was still between 20 °C and 28 °C, in neutral to cool environments. This may be due to SPD differences in the selected lighting. To fully confirm such phenomena in the future, the associated lighting variations across different studies must be considered in more accurate analyses and interactive experiments between the ambient temperature and visual perception designed interventions.

2) Lighting characteristics

As shown in Fig. 7, nine papers provided detailed SPDs or wavelength information for their lighting interventions. Based on the features summarized in Section 4.4-3), all studies fully confirming the hue-heat hypothesis at all designed ambient air temperature settings adopted two-waveband lighting interventions (referring to two peak wavelengths), while the studies fully or partially rejecting the hue-heat hypothesis used three-waveband lighting interventions (referring to three peak wavelengths). This feature is more obvious when comparing two particular studies ([80,90]). Both used 20 °C and 25 °C as the ambient air temperature settings and showed opposite results at 20 °C. Having a third peak wavelength may have provided more space to design multiple CCTs relative to the situation using two peak wavelengths. However, from the currently available information, this additional peak wavelength was towards the middle wavelength (~530 nm, M or green cone). Thus, this addition may have resulted in unknown effects from the light irradiation at this wavelength, possibly mitigating the thermal effects of the light or playing a more dominant role in physiology and/or psychology. Additional analyses based on differences in the radiometric qualities of the lighting designs would be helpful for clarifying this issue.

6.2. Evidence of physiological responses and effective physiological measures

In general, more mixed results were reported based on physiological rather than psychological measures. However, in all nine papers adopting physiological measures, only two rejected light's effects on all physiological measures [87,91]. So, the current finding suggests that the physiological responses to lighting variations exist, while certain physiological measures seem more effective than others for such demonstrations. Among these physiological measures, several have been widely accepted as biomarkers in the thermal comfort domain, such as CBT, Mean SKT, HRV, etc. Therefore, the effects on these measures resulting from lighting interventions were of the most interest.

1) Core body temperature

CBT is a critical indicator of thermoregulation and a fundamental parameter triggering thermoregulatory behaviors. It is also an important variable directly and/or indirectly linking variations in thermal comfort [64]. CBT was adopted by and measured in five articles. Two found the presence of lighting effects; however, the positive results in these two studies disappeared after Benjamini-Hochberg correction. One potential reason for this could have been related to the nature of CBT variations and the process for/use of this indicator. Particularly, all five studies had 90 min exposure to each lighting intervention. As CBT is a variable maintained by body thermoregulation, the mean value during this 90-min period may not reflect the true variations induced by the thermal effects of light. Since CBT is time-dependent and can be characterized by more complex variability than a simple mean value within a period of time [102], analyzing CBT by advanced mathematical/statistical techniques such as those used to assess heart-rate variability might facilitate a more comprehensive analysis of the thermal effects of light. Furthermore, some studies indicated that the existence of CBT differences did not necessarily represent the existence of variations in thermal comfort, as a threshold must be exceeded to trigger such variations [103]. Apart from the effects of physical activities, other biological factors might also contribute to CBT variations, such as food intake, emotional stress, and menstrual cycle. However, these covariate variables' control and measurement were not clearly described in these studies. Considering the mixed results and the small number of studies, it is not possible to make conclusive statements regarding the relationship between CBT and lighting exposure.

2) Skin temperature-related parameters

Among the responses deduced from skin temperature, including Mean SKT, SKTP, Prox SKT, Distal SKT, and DPG. Mean SKT was the most frequently used in the selected studies. However, none of the research confirmed the thermal effects of light through this measure. Instead, certain studies consistently showed that changes in Prox SKT, SKTP, and DPG were caused by varying the lighting exposure, suggesting that these specific skin temperature-related variables might be more suitable than the average skin temperatures of different body parts. Among these three measures, in two out of three articles exploring this variable, DPG was found to have a consistent effect and more dependably reported a thermal comfort response and quantified vasoconstriction in thermoregulation [36,104]. Thus, DPG may be a promising measure for representing thermoregulation and thermal comfort, though the relationship between DPG and CBT could not be clarified because discrepancies remained [43,46]. Additionally, the physiology of temperature sensation has advanced in recent years with the discovery that the skin has 10 times more cold sensors than warm. Also, cold sensors are more peripheral to the surface than warm sensors and are differently distributed across the body. As such, in relatively colder environments, skin temperature is more dedicated to rapid responses and also varies widely across different body parts, while in warmer environments, skin temperatures respond relatively slowly and are distributed more uniformly. In other words, the ambient air temperature in the studies might have altered the magnitude (or temporal characteristics) of any skin temperature variations, influencing the causality between light and thermal response.

3) Heart rate and heart rate variability

HR was measured in six articles, but only one of those studies confirmed the presence of the thermal effects of light. Comparatively, it was consistent that the linkage between HRV and lighting interventions was confirmed in two out of three studies [89,92]. Compared to HR, HRV focuses on the imperceptible changes between each heartbeat, providing information on both HR and its variability. This also echoes the finding that HRV is influenced by homeostatic control mechanisms that include thermoregulation [39]. HRV has been found to be a valuable predictive biomarker of thermal comfort, with up to 93.7% accuracy [67]. Accordingly, it has been suggested that HRV may be another suitable measure for investigating the thermal response to light.

Finally, fewer studies took other measures such as BP, BF, and SW, into consideration, and less evidence or mixed results were found. Various reasons and uncertainties exist. For instance, using non-invasive methods to measure BP, BF, and EE biomarkers may have resulted in issues with accuracy and uncertainty that may have offset changes attributable to lighting effects. Moreover, these parameter changes were mostly triggered when the CBT exceeded a certain threshold [105–107]. Similarly, the SASV and SASW parameters only document events when intense discomfort occurs, which may not have been even activated within the designed ambient air temperatures.

6.3. Visual and non-visual pathways

As illustrated in the introduction and background sessions, there are two pathways – visual and non-visual. Simply put, physiological and psychological responses are important for non-visual and visual pathway analysis, respectively. However, it is also well-accepted that changes in psychological and emotional states are often accompanied by physiological modifications, and interactions between human physiological and psychological responses are very common in response to the built environment [108–110]. Therefore, it is still challenging to differentiate between visual and non-visual pathways for light's thermal effects by measuring physiological and psychological responses. In this review, no studies attempted to differentiate between visual and non-visual pathways, though some potential for future research could be extracted based on the available data.

In particular, one study used 50 lux illuminance and different CCTs (2,700 K and 4,000 K) in their interventions; the results showed that no significant variations in psychological responses (either TCV and TSV) were found, but two physiological measures (CBT and Prox SKT) were found with variations caused by the lighting interventions [76]. In other words, the visual appearance of the lighting environment under different CCTs seemed similar to participants (perhaps due to the low illuminance level), which may have substantially suppressed the visual effects of light on their potential thermal responses. Thus, the physiological responses confirmed in this work reveal the potential acute non-visual effects of light on thermophysiology. This conclusion will also inform future studies investigating possible strategies for examining light's non-visual effects alone, minimizing or eliminating differences in the visual appearance of the light source (e.g., color, intensity), and only varying the radiometric power in the light spectra.

Similarly, if any experiments reported significant changes in psychological responses to lighting interventions without variations in physiological responses, conclusions could be deduced by analyzing the visual pathway alone. However, the papers in this review did not contain any such findings.

Another potential strategy for separately examining the visual and non-visual pathways of light's influence on thermal responses would be to take the time course into account. The human body takes time to adapt to transient adjustments of thermal or visual stimuli, which could be extended to the impacts of visual and non-visual pathways. All physiological and psychological responses can be documented in a time-dependent fashion, possibly providing information useful in explaining the underlying mechanism from a biological perspective. For instance, researchers have been working on time-dependent analyses of CBT, Mean SKT, and subjective thermal perception to explore how causal and interactive relationships between these physiological and psychological responses occur when people are exposed to changing environments [111–113]. One paper reported that support for the hue-heat hypothesis also indicated different psychological responses to lighting variations at different lighting exposure durations [86]. The authors found that participants expressed more intense cooler and warmer effects under cool and warm illumination over time, to a statistically significant difference [86]. Since lighting adaptation may occur instantly (or in a short period of time) and visual appearance was kept the same over time, the possible cause of this eventual psychological difference could have been certain physiological changes via a non-visual pathway. Parallel physiological measures and temporal modifications could be used to verify such assumptions, though unfortunately, the articles did not engage in such measures.

7. Conclusions

Much of the literature in this review suggests that daytime lighting exposure is associated with thermal-related psychological and physiological responses. Analysis results across the 18 papers showed statistically significant associations with certain psychological (e.g., TSV, TPV) and physiological measures (e.g., prox SKT, HRV). Thus, this review suggests that both visual and non-visual pathways exist for the influence of light on acute thermal responses during the day, though certain measures of psychological and physiological responses are relatively more effective and appropriate for examining thermal responses under particular lighting exposures. One major strength of this review is that only studies with clear experiment settings and research designs, detailed lighting information, and specific daytime situations were selected, mitigating certain levels of heterogeneity across studies and enabling comparison analyses. However, some cross-study analysis results were limited by the unavailability of key measurements and reports regarding lighting, microclimatic conditions, and/or thermal responses, as well as possibly high levels of and unknown heterogeneity in terms of thermal responses to lighting variations; thus, these results should be interpreted with caution. In particular, there are no consistent or clear measurement protocols provided by these studies for assessing the microclimatic conditions, especially regarding the mean radiant temperature and air speed. So, the result comparisons across different studies are challenging. Generalized methods to characterize microclimatic conditions should be implemented in future studies. There is also a paucity of literature on the mechanisms underlying this causal relationship between lighting and thermal response; more supportive research and evidence are required from the intersectional area of fundamental thermophysiology and subjective thermal sensations in the building environment. Additionally, differentiation between visual and non-visual pathways initially motivated this review, but the current literature does not provide sufficient information or evidence for such an examination. Some specific controls and designs of both thermal and visual conditions in experiments to potentially separate visual and non-visual pathway effects are required. Also, time-series data collection and analysis of both psychological and physiological responses via additional within-subject measurements are important methods for future exploration of this question.

A thorough understanding of the thermal effects of artificial lighting on humans will contribute not only to the enhancement of building energy conservation, but also to leveraging emergent spectrally-tunable lighting and smart heating, ventilating, and air conditioning systems for daily applications.

Author statement

Nan Wang: Literature search and screening, Systematic review, Investigation, Visualization, and Writing, **Julian Wang**: Research hypothesis, Analysis and discussion, Writing, Project administration, **Yanxiao Feng**: Writing and Investigation

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Hereby, I/insert author name/consciously assure that for the manuscript/insert title/the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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