Exploring the Interplay between Thermal and Visual Perception: A Critical Review of Studies from 1926 to 2022

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Review

Exploring the Interplay between Thermal and Visual Perception: A Critical Review of Studies from 1926 to 2022

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Abstract: Research on the links between thermal and visual perception is an ever-evolving field aimed at exploring how one modifies the other. The findings can enhance buildings' energy performance and the occupants' well-being. Based on a screening methodology on a substantial article database, this review article provides an overview of the current state of knowledge by examining studies related to the thermo-photometric perception hypothesis between 1926 and 2022. It analyzes the limitations and contributions of these studies, identifies the most recent advancements, and highlights remaining scientific hurdles. For example, we demonstrate that the "hue-heat" hypothesis appears to be verified for specific experimental conditions conducive to measuring subtle parameter variations.

Keywords: thermal; visual; perception; hue-heat; illuminance; review

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1. Introduction

Climate change and the need to reduce the environmental footprint of buildings have become urgent global issues. According to the International Energy Agency, buildings are responsible for 40% of global energy consumption and 24% of greenhouse gas emissions. Improving the energy efficiency of buildings is, therefore, crucial in the fight against climate change. Furthermore, research [1,2] has shown that indoor environmental quality and comfort are directly linked to well-being and occupants' productivity.

Nowadays, the well-being of building occupants is increasingly considered in design and building exploitation. In this context, the relationship between thermal and visual perception plays a crucial role, as it could help to improve building design strategies. However, a distinction should be made between perception and sensation. Sensation or feeling refers to detecting a stimulus in the environment, while perception refers to how we interpret that stimulus. Perception is affected by circumstances beyond the physical relationship between the body and its environment. Thus, neutrality seems to be related to sensation, while comfort is related to perception. Therefore, it is illusory to try to predict comfort from sensation.

Thermal perception results from a combination of thermal sensation and the individual's interpretation of that sensation. Thermal sensation is the physiological detection of temperature changes in the skin, leading to physiological reactions in the human body. In the case of warm conditions, the body reacts by losing heat through processes such as skin vasodilation, sweating, or decreased metabolic activity. In the face of cold, the body produces heat through shivering and limits heat loss through blood vessels' vasoconstriction. Various physiological parameters can affect thermoregulation and thermal sensation, such as acclimatization [3], physical capacities, different working postures [4], age [5], gender, weight, diet, clothing, nutrition, and medication [6]. The thermal sensation interpretation also depends on the individual's psychological parameters. These parameters may include personal comfort zones [7], level of control over external thermal regulation elements [8], expectations [9] and past experiences [10]. Social influence can also modify thermal perception, for example, with the group effect or sharing one's immediate environment. Thermal comfort was formerly defined by neutral thermal perception (or thermal neutrality). It corresponded to the absence of thermoregulatory phenomena in humans and their inability to desire a warmer or colder environment [11–13], based on the occupant's thermal sensation. The adaptive approach to thermal comfort considers comfort as a state of satisfaction and thermal well-being obtained through physiological and psychological adaptation to the ambient environment. It is possible, for example, that a person moving from a warm environment to a cooler room considers themself to be in a state of comfort because of their perception of the thermal environment. Several measurable parameters are identified in the literature linking the individual to their environment [12,14–16]. The latter also supports models for predicting perception: air temperature, mean radiant temperature, air velocity, the water vapor pressure in the air or relative humidity, activity level, thermal resistivity of clothing, and outdoor climate.

Visual and thermal perception are similar in their approach. The eye captures light to provide information about the environment to the occupant via the visual channel, but light can also have non-visual physiological effects. Visual perception depends on visual acuity, physiological mechanisms triggered by light, and the occupant's interpretation. The discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) has provided insight into how light can affect the non-visual responses of the human body [17,18]. For example, light can stimulate the secretion of melatonin [19], cortisol [20] and serotonin [21], which are involved in the regulation of body temperature. As with thermal perception, experience, and exposure habits modify the occupant's perception of the light environment. Studies have shown that views of an outdoor landscape from inside a building can improve mood, cognitive performance, and perceptions of comfort [22–24]. Thus, light plays an important role in psychological and mental well-being, as well as in human cognitive engagement [25].

Certain properties of light can influence visual perception and visual comforts, such as light intensity, the light spectrum, and color temperature of the light source [26]. Therefore, it is essential to consider these factors when designing work and living spaces to improve the health and well-being of occupants.

Thermal and visual perceptions are closely related. Physical, physiological, and psychological factors can affect thermal and visual comfort [27]. However, these two types of perception have often been studied independently, whereas humans are multi-sensory machines. Thus, research on the thermo-photometric link has become a promising area of research for human well-being and for improving the energy performance of a building, thanks to the possibilities of "sensory compensation". A key hypothesis in this area is the "hue-heat" hypothesis, which suggests that warm colors can be perceived as warmer than cool colors, which has important implications for the design and operation of buildings.

This review article provides a comprehensive overview of current knowledge on the link between thermal and visual perception by analyzing 51 papers from 1926 to 2022 that were obtained through a screening methodology based on a substantial article database. The papers were selected for their popularity and relevance to the study of the thermo-photometric link. The experiments were analyzed in terms of location, building type, thermal and light characteristics, participant demographics, measurement methods, and questionnaires. By analyzing the limitations and contributions of these studies, identifying the most recent advances, and highlighting the remaining scientific obstacles, this paper aims to provide a deeper understanding of thermo-photometric interactions and their potential to improve building performance.

This review article consists of five sections. After presenting our methodology and the associated bibliometric analysis, the second section presents the state-of-the-art on the physiological origin of interactions between thermal and visual perception. The following two sections review the papers reporting the link between light and thermal perception, classifying their results according to the relationship between light characteristics and physiological or psychological mechanisms of thermal perception. These sections also present the duality between studies supporting the existence of the thermo-photometric link and research invalidating the link. Finally, the last section critically analyzes the information gathered from the different articles and their statistical distribution.

2. Methodology and Bibliometric Analysis

As shown in Figure 1, a two-filter approach was used to build our bibliographic database. The entirety of the studies was primarily gathered from the academic database Google Scholar. This database was chosen due to its ease of use with the Publish or Perish (PoP) software [28], the quick availability of articles shortly after their publication, and the many publications available. A combination of keywords (see Figure 1) was used to search with PoP, for which the period from 1900 to 2023 was selected to ensure the inclusion of most publications, resulting in 860 articles in the first stage. Subsequently, a first selection was made using exclusive criteria related to different keywords and types of articles (review articles, simulation articles, and patents), resulting in 167 articles. The second filter selected the most relevant studies by analyzing the articles' titles, abstracts, and conclusions. This step resulted in 51 articles related to our state-of-the-art topic, which were thoroughly analyzed before being included in our study.

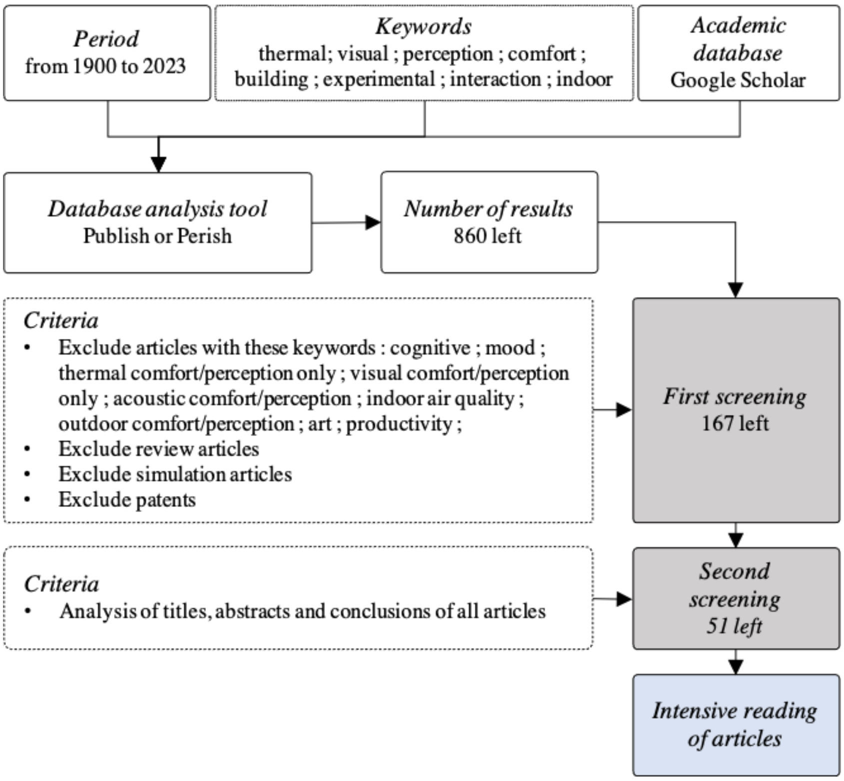

Figure 1. Method to identify relevant publications.

To ensure the relevance of this critical review, a network co-occurrence keyword analysis was conducted using the software VOSviewer [29], which used the results obtained from PoP. Figure 2 displays the clusters created with VOSviewer. As shown in the figure, three clusters could be defined: the blue-colored keywords cluster linked to thermal comfort, the cluster colored in red regrouping the keywords related to the indoor environment of the occupant, and the green one designating the physiological parameters of the occupant. The representation emphasizes the links between the three clusters, particularly those between "thermal comfort", "visual comfort", and "light" which are important keywords. These results reveal that thermal comfort studies often refer to visual comfort and light, highlighting the potential impact of light on thermal perception.

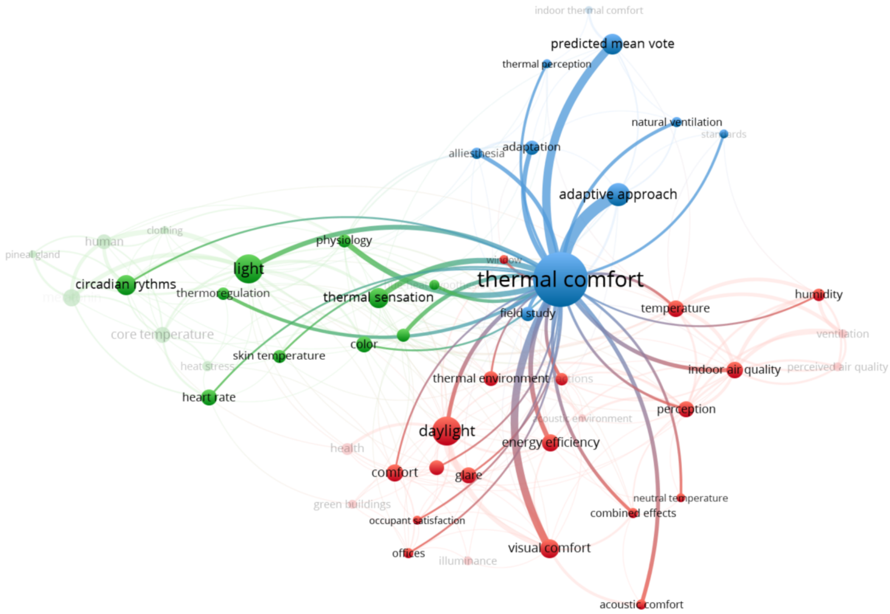

Figure 2. Keywords co-occurrence clustering with VOSviewer.

Additionally, a trend comparison analysis was performed using PoP results. Figure 3 illustrates the number of publications per year for studies related to the thermo-photometric link, thermal comfort, and visual comfort, as well as the publication ratio per year for each topic and the linear trend curve for the three topics. The interplay between thermal and visual perception was the earliest subject to be addressed and periodically published. Although there are fewer papers per year, the linear trend shows that the interest in thermo-photometric links is not decreasing but shows an increasing slope. Therefore, it is a promising research field that tends to gather interest. The publication ratio between 2017 and 2018 supports that it is a subject that does not fall behind the other two. This period displays a similar ratio for all three of them, showing that the interaction between thermal and visual is a growing field of research.

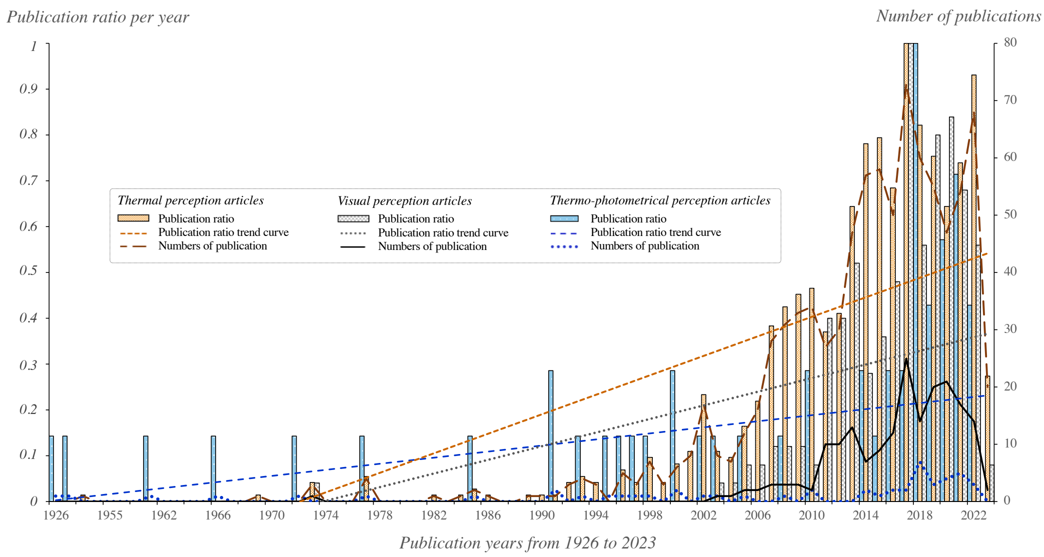

Figure 3. Temporal evolution of the publications number from 1926 to 2023.

3. Physiological Origin of Thermo-Photometric Interactions

The ipRGCs transmit the nature of the light arriving at the eye to the suprachiasmatic nucleus. This nucleus is located in the hypothalamus, a small region in the brain that plays a crucial role in the interaction between visual and thermal perception. The epithalamus is also involved in physiological mechanisms. Physiological reactions such as hormone production, changes in heart rate, and body temperature are derived from these "thermo-photometric centers".

3.1. Hypothalamus and Temperature Regulation

The hypothalamus is responsible for regulating body temperature, hunger, thirst, and other essential basic functions for survival [30]. When the body is exposed to changes in temperature, the hypothalamus receives signals from temperature receptors in the skin and other parts of the body [31]. It then sends signals to the body's thermoregulatory system to trigger appropriate responses such as sweating, shivering, or vasodilation/vasoconstriction [30]. However, these are not the only signals transmitted. The hypothalamus also receives information from the eyes through the suprachiasmatic nucleus. Studies [32–34] have shown that the hypothalamus is involved in regulating the circadian rhythm, the body's internal clock that helps to time the sleep-wake cycle. These connections have only been demonstrated under strict and controlled clinical conditions. The first analysis of these reactions was performed through animal dissection, as indicated in various studies [32,35,36]. Thus, the hypothalamus appears to be the physiological link between thermal control and visual perception, suggesting that thermo-photometric reactions are linked to the hypothalamus. For example, when the hypothalamus receives signals from the visual system indicating a warm environment, it can respond by increasing blood flow to the skin, giving the person a warm sensation. Conversely, when the hypothalamus receives signals from the visual system indicating a cold environment, it can respond by reducing blood flow to the skin, giving the person a cold sensation.

3.2. Epithalamus and Melatonin

The epithalamus is another region of the brain that is stimulated by light. Like the hypothalamus, it comprises nuclei and the pineal gland. This gland secretes melatonin when stimulated by light. This hormone affects various physiological parameters, including those related to the heart. The heart is subject to circadian rhythmicity [34] that affects blood pressure and heart rate [37–41]. Studies have shown that melatonin can have a relaxing effect on the cardiovascular system by decreasing heart rate [42] and blood pressure [43]. This effect is thought to be induced by the hormone's ability to stimulate the release of nitric oxide, a vasodilator that helps to relax blood vessels and reduce blood pressure. A change in blood flow then affects heat exchange in the body tissues. Other studies have shown that melatonin can lower body temperature [37,40,44,45]. This phenomenon is related to the decrease in the activity of the hypothalamic-pituitary-adrenal (HPA) axis. The HPA axis regulates the body's response to stress and the production of heat-producing hormones, such as cortisol. Melatonin also triggers the dilation of blood vessels in the skin [46], which allows more heat to be dissipated from the body. The drops in body temperature associated with the different phases of the wake-sleep cycle are synchronous with the phase of maximal melatonin secretion, which occurs between 2 a.m. and 5 a.m. Other studies [37,46–48] have demonstrated the link between melatonin and skin temperature. The experiments conducted had a common objective and mode of operation: they observed the thermoregulatory reactions of participants after administering melatonin orally or by injection. The areas of skin temperature measurements were at the level of the soles of the feet [37], the phalanges [48], and average values obtained at the forehead, arms, hands, back of the thighs, and trunk [49].

Although various physiological reactions have a localized origin, the fact remains that they link light to thermoregulatory mechanisms. It may seem illusory to imagine that the individual's perception is categorized and that the photometric environment cannot influence thermal perception. However, it is necessary to understand and list the results used to corroborate or refute two hypotheses on thermo-photometric interactions: the "hue-heat" hypothesis and the "illuminance-thermal markers" hypothesis.

4. "Hue-Heat" Hypothesis

The "hue-heat" hypothesis is a theory that suggests a connection between the color of an object or light source and the perceived warmth by an individual. This hypothesis states that warm colors like red, orange, and yellow, are perceived as warmer than cool colors like blue, green, and violet. This theory is based on the idea that warm colors are associated with heat and warmth, while cool colors are associated with coolness and cold. This theory has been studied in the fields of color psychology and theater [50] and has been found to have important implications for design and architecture since it suggests that the use of specific colors can affect the thermal perception of space [51–53]. The definition of the color of the primary (solar or artificial) or secondary (reflection supports: walls, objects) light source is essential information in impact analysis. In the following sections, the "hue-heat" hypothesis is explored based on the results of studies from the literature that have either supported or refuted it. Each section relies on the results and descriptions of the physiological mechanisms targeted by the authors and their findings on the psychological impact of the hypothesis.

Studies show different units to express the color of a light source (in wavelength [nm], or in correlated color temperature [K]). These units have been harmonized using Wien's law to facilitate understanding the studies.

4.1. Scientific Proof of the "Hue-Heat" Hypothesis

The existence of a "hue-heat" connection seems to be obvious to popular belief. The literature has worked on verifying these facts.

4.1.1. Colour and Heart Rate

Abbas' study [54] demonstrated that significant changes in heart rate were noticeable after 2-minute exposures to lights of different colors and varying intensities. Another study [55] confirms this result as they detected an increase in heart rate during exposure to red, considered a "stimulating" color. On the other hand, bluish atmospheres resulted in a slight decrease in heart rate, indicating that blue can be considered "soothing". Kobayashi'study [56] measured the impact of the correlated color temperature of light on heart rate. They noted that a light source at 7500 K (390 nm) led to a significant increase in diastolic tension compared to sources providing only 3000 K (970 nm) and 5000 K (580 nm). They thus deduced that high color temperatures have a more pronounced effect on vasomotor activity. Deguchi [57] raised, that Kruithof [58] probably relied on these physiological mechanisms leading to changes in subjective sensations to design his famous diagram. Two studies [55,59] were able to quantify the impact of color on heart rate. Their results show a variation in the number of heartbeats per minute after transitioning from exposure to red to blue or vice versa. Al-Ayash [55] could identify that blue, on average, reduced participants' heart rates by eight beats per minute compared to red. Wang [59] shows that transitioning from blue to red increased participants' heart rates by 15 beats per minute.

4.1.2. Color and Blood Pressure

It is found in the literature that the light source's color impacts blood pressure. Various researchers [51,60,61] report that coloration decreased blood pressure when participants moved from a white-lighting environment to a blue-tinted lighting environment and increased when participants moved from a white-lighting environment to a red lighting environment [59]. The work of Grangaard [61] highlights this relationship the most: young students moving from the usual lighting environment of their classroom to a blue-tinted environment saw their average blood pressure decrease by 9%. The study by Wu, cited in [62], sought to compare different colors of light sources. He concluded that exposure to blue light increased individuals' heart rate and systolic blood pressure while decreasing their diastolic blood pressure.

Other articles [51,59,60] corroborate the existence of this link without quantitatively evaluating it. The experimental techniques required for a quantitative evaluation need a particular method to highlight this physiological relationship.

4.1.3. Color and Body Temperature

Various studies [55,59,63–80] affirmed the link between color, the individual's thermoregulatory reactions and their thermal perception of the environment. The participants in these experiments, who were assigned office tasks, mainly seated, were subjected to light exposure times of at least 10 min. Five studies [63,69,70,77,79] present wavelength ranges to describe the colors used. The most commonly compared wavelength ranges are red (610 nm and 658 nm, that is between 4750 K and 4400 K) and blue (400 nm and 505 nm, 7250 K and 5740 K). Green at 545 $\pm$ 15 nm (5320 K) and yellow at 578 + 20 nm (5010 K) are also found in smaller proportions. Exposure to green light in the morning (for around 10 min) at an illuminance level between 1000 lux and 2500 lux caused a temporal shift in the increase of core body temperature [69,70] due to the inhibition of melatonin secretion.

4.1.4. Color and Skin Temperature

An experiment conducted by Yasukouichi [81] shows that the skin temperature was lower under a light temperature of 3000 K (965 nm) than under 5000 K (580 nm), 6000 K (480 nm), and 7500 K (390 nm), while the individuals were bathed at a rather cool ambient temperature (18 °C). This effect is probably related to the cutaneous vasoconstriction already initiated by the temperature considered as cool. Wu, in [62], confirms these results. In their experiments, the average skin temperature of the participants dropped by 0.62 °C when they were exposed to blue light rather than red light.

4.1.5. Color and Touch

The color of an object can have an impact on the perceived temperature when touched. Indeed, different colors can absorb or reflect varying amounts of light, affecting the heat generated or retained by the object. Studies [75,82] have investigated whether the blue color is cooler to the touch than red. The first study [75] examined the effect of the red or blue color of an object on tactile and thermal perception, as well as the effect of exposing the individual's hand to red or blue light on thermal estimation via touch, using the participant's hand as the stimulus and a heated plate as the evaluation tool. The second study [82] used augmented reality technology to simulate the appearance of red or blue color on steel cups, one containing hot liquid and the other containing cold liquid, to evaluate the effect of color on temperature perception. The conclusion of these studies converges towards the counter-intuitive aspect of colors, meaning that a blue object appears warmer than a red object. Dark-colored objects, such as black or dark blue, absorb more light energy, making them warmer to the touch. Conversely, light-colored objects like white or light blue, tend to reflect more thermal energy, making them cooler to the touch. This is because dark-colored objects absorb more radiant energy and convert it into thermal energy, while light-colored objects reflect more radiant energy and retain less thermal energy.

4.1.6. Color and Thermal Perception

Studies [50,83–87] sought to confirm that color could be associated with a particular temperature perception. These studies indicated that colors influenced the psychological state of the participants: red, orange, and yellow created a feeling of joy and increased motivation but were also associated with a warm thermal perception, while blue, green, and purple were soothing colors associated with a feeling of coolness. One study added that red induced better cognitive performance than green [86]. These authors set the first framework for identifying the impact of color on individuals by using the reflection of objects to estimate the effect of colors. This involved the reflectance of curtains or walls illuminated by a projector in some cases [83,86,87], while in another experiment [85], the reflection of colored paper sheets was studied. Although those studies support the "hue-heat" hypothesis, the conditions of the experiments were opaque. The means of illumination and control (such as light intensity and luminance of the light source), the thermal environment conditions, and parts of the questionnaires about evaluation, preference, or both were not reported. Additionally, demographic information, such as gender distribution, was missing from these studies. Toftum [64] indicated that at 22 °C, the transition from a "warm" hue of 2700 K (1070 nm) to a "cold" hue of 6200 K (470 nm) was equivalent to a decrease in operative temperature of 1.7 °C. Tsushima [88] reinforced this finding by indicating that it was possible to decrease air temperature by 2 °C by changing the color temperature from 3000 K (965 nm) to 5500 K (530 nm) in the summer. Fanger [63] found that participants in his experiment preferred a slightly lower ambient temperature of 0.4 °C under the red hue than the blue hue. Physiologically, this type of variation may be due to the influence of color on the hypothalamic region and, thus, on mechanisms related to thermoregulation, such as heart rate. Wu's study cited in [62] confirmed that color changes led to a modification of thermal sensation.

4.1.7. Color and General Perception of Atmosphere

Five studies [64,71,73,78,79] used the correlated color temperature to identify the occupant's preferred ambient conditions. The most commonly used colors were orange (2700 K), whitish "daylight" (4000 K, 730 nm) and bluish (6500 K, 450 nm). These values are commercially available, making acquiring suitable lamps for experiments easy. In general, the authors had identified an influence of the color temperature on the psychological reactions of the people: saleswomen under "warm" tints (close to 3000 K) felt more comfortable than in the whitish coloring of the experiment [78] for equivalent ambient air temperatures. This impression of comfort is also presented in Manav's study [73]: the orange tint at 2700 K (1070 nm) was preferred when the participant wished to relax. This demonstrates that exposure to light sources with a lower color temperature can enhance the perception of warmth, creating a sense of comfort and intimacy. In comparison, exposure to light sources with a higher color temperature can enhance the perception of coolness, creating a sense of coolness and intimacy.

4.1.8. Color and Clothing Behavior

The addition or removal of clothing layers is also influenced by the hues of the light sources, according to Huebner [79]. He stated that the higher the color temperature, the higher the level of clothing removal, and vice versa. Thus, at 6500 K (450 nm), the individual increased the number of clothes he wears and reduced them to 2700 K (1070 nm).

4.2. "Hue-Heat" Hypothesis Refutation

The "hue-heat" hypothesis has excellent potential for improving indoor building comfort. However, studies in the literature do not agree on its basis.

4.2.1. Color and Physiological Mechanisms

A few studies have corroborated the non-existence of a link between thermal perception and the coloring of light sources: [51,52,89–92]. The first reason why they did not support the "hue-heat" hypothesis is that their results did not show statistically reliable values from a physiological point of view [90,91] because the color temperature of the light sources had little impact on physiological reactions to cold (heart rate, heartbeat, finger pulsation, skin conductance). According to Baniya [91], when participants were exposed to the cold temperature of the room (20 °C) in his experiment, they already felt coolness, regardless of the color of the light source used, and they showed signs of chill. Would not this show that as soon as discomfort appears in one of the sensorialities, the occupant is "disturbed" by this discomfort and no longer considers the other feelings? This corresponds to the principle of the "one-vote veto" [27] which explains that the perception of the environment of the occupant passes by all his senses (sight, touch, hearing, smell, taste) and that if one of his sensorialities perceived a great discomfort, the global perception of the environment would be influenced.

4.2.2. Colour and Thermal Perception

Two other studies [51,89] raised the point that the "hue-heat" hypothesis was mere hearsay and had no impact on the psychological perception of the thermal environment. Berry's study [89] involved subjecting participants to a cognitively demanding task using a driving simulator on a miniature circuit. In the experiment, certain areas were illuminated but did not directly concern the participant, only part of his field of vision. Bennett's experiment [51] took a similar approach, but with one modification: participants wore glasses with filters to change the color of the light reaching their eyes. This suggests that it is important to consider the overall effect of the visual environment on the occupants' field of vision. These results could vary if an additional light source were used in the immediate environment of the participant or if the glasses covered the edge of the participant's visual field.

4.2.3. Color and Touch

Morgensen and English [93], in their study, sought to establish a correspondence between thermal temperature perceived by touch and color. The results obtained are in contradiction with popular beliefs: red, associated with heat, was one of the last colors perceived as hot, as well as royal purple, also considered as "hot". These two colors were also considered the least pleasant. The author adds that red is perceived negatively, probably because of its association with alertness and stress in popular beliefs.

5. "Illuminance-Thermal Markers" Hypothesis

Light intensity or illuminance level can significantly impact body and skin temperature. Light is a primary cue for the circadian rhythm [94] and can affect the body's internal clock and, thus, the entire circadian regulatory chain from melatonin secretion to thermoregulatory mechanisms (cortisol, vasodilation, and sensory receptors).

5.1. Scientific Evidence of The Effect of Illuminance on Thermal Markers

The following sections consider the impact of illuminance on the occupant by presenting studies that demonstrate the effects of illuminance on humans. Each part will be based on the description of physiological responses and the psychological aspect of the impact.

5.1.1. Illuminance and Core Body Temperature

Various studies [44,45,70,95–101] have demonstrated the involvement of light illumination in reducing core body temperature. Their studies focused on controlled environments in climatic chambers and mostly volunteer populations. The light levels varied between 50 and 10,000 lux. Four studies [45,70,97,101] decided to adopt at least three levels of illumination, while the others chose two conditions: dim light or bright light. Participants in these studies were either required to rest in a semi-recumbent position or perform tasks seated. Most studies had more than one hour of exposure before taking a break or transitioning to other exposure conditions.

The work of Caldwell [90] and Rohles [102] suggests that the duration of exposure to a light source has an impact on the thermal mechanisms of the human body, probably due to thermal inertia, which can slow down the evacuation of the heat produced by the body. According to Myers [97], a threshold value of 500 lux can lead to a variation in core temperature, but it is important to consider the time of exposure to this light source to understand its real impact. Studies in which light exposure occurred mainly at night [45,97,100] saw temperature variations under high illumination values of between 4500 lux and 10,000lux and generated drops in core body temperature ranging from 0.1 °C to 0.3 °C. However, one study [103] with exposure to 2500 lux identified a lower average of nearly 0.5 °C of core body temperature for one hour of exposure.

5.1.2. Illuminance and Skin Temperature

Exposure to bright light during daylight hours can alter melatonin secretion by stimulating the hypothalamus, leading to increased sympathetic nervous system activity, which is responsible for the fight-or-flight response. It may also increase blood flow to the skin, leading to an increase in skin temperature. Three studies [104–106] highlighted the impact of light levels on skin temperature. Exposure to different light levels has various effects on skin temperature. According to the study by Kim [106], exposure to low light levels leads to a more significant drop in skin temperature, particularly at hand, with a decline of 0.24 °C. However, studies by Ishimoto [104] and Kim [105] argue that exposure to high light levels results in an even more significant decrease in skin temperature. Therefore, exposure to different illuminance levels can affect skin temperature. To find the right balance, it would be necessary to standardize the approaches. Moreover, Ishimoto is the only one to have his participants take a bath for a 1-hour exposure (the other two studies carried out 30-min exposures), an approach similar to the calibration of thermocouples.

5.1.3. Illuminance and Thermal Perception

Recent studies [62,107–117] have highlighted the impact of illuminance on occupants' perception of the thermal environment. These studies covered a range of illuminance levels from 45 lux to 4000 lux. Of these, four studies [109,110,113,115] focused on natural light sources as the primary source, while the others approached the study from artificial lighting. Despite the difference in the type of light source, the finding was almost the same for all: low illumination is considered "cool" while higher illuminance induces a perception of warmth. Teramoto's work [107] indicated that the participants felt cooler under a light source of 200 lux compared to a source of 1500 lux, despite a decrease in the temperature of the room. According to Chinazzo [113], exposure to a relatively low level of illumination (130 lux) from natural sources can lead to thermal discomfort in participants, particularly in a cool environment. However, it is essential to consider the spectral composition of these sources to assess whether the dominant wavelength plays a role in this outcome.

5.1.4. Illuminance and Preferred Atmosphere

Studies by Nelson [118], Teramoto [107], Hygge [119], Higuchi [44], Gou [120], Wang [62], Garreton [121], Mohebian [108], Ricciardi [109], Chinazzo [80], Yang [122], Sun [111], Zaniboni [123], Berkouk [124], Du [112], and Jiang [125] show that participants' lighting preferences vary, but in general light levels between 200 lux and 500 lux are considered neutral and preferred over bright environments (near 1000 lux) which are more conducive to thinking and memory tasks. Du's study [112] assessed light level and air temperature preferences in small spaces, such as climatic or semi-climatic chambers with a volume of less than 40 m^3. Participants were exposed to simulated environments using a virtual reality headset and indicated a preference for moderate light levels ranging from 800 to 1500 lux, accompanied by an air temperature of 21 °C, for spaces such as average waiting rooms. It is important to note that the results of this study cannot be extrapolated to larger spaces.

5.1.5. Illuminance and Clothing Behaviour

The studies of Eun-Kim [126] and Kim [105,106] have highlighted the influence of luminous illumination on the clothing behavior of individuals. According to these studies, people tend to put on warmer clothes in dimly lit environments (between 50 and 70 lux) compared to brighter environments, even when the ambient temperature is cool (15 °C and 20 °C). This may be due to the altered temperature perception caused by the change in lighting. The authors noted that this tendency was more pronounced in participants previously exposed to bright light. This shows that past visual experience can impact a person's thermal perception.

In summary, the illuminance can significantly influence individuals' thermal well-being by modulating the activity of the sympathetic and parasympathetic nervous systems, melatonin production, metabolism, circadian rhythms, and even behavior. Bright light during the day can increase body and skin temperature, while dim light or darkness can decrease it. It is, therefore, important to consider illuminance in the design of the living environment to ensure optimal thermal comfort.

5.2. Refutation of the "Illuminance-Thermal Markers" Hypothesis

None of the studies discussed refutes the impact of illuminance on thermal perception or physiological mechanisms. The scientific community seems to agree that there is a link between the level of illuminance and thermal markers.

6. Discussions

In summary, 51 studies were selected for this critical analysis to investigate the thermal responses of occupants to light characteristics in the indoor environment. These studies, published between 1926 and 2022, were chosen to understand the aspirations, history of the thermo-photometric link topic, and advances made or to be made. Of these studies, 43% focus on the impact of color on occupant perception, comfort, or thermal appreciation, 35% on illuminance and its effect on comfort, appreciation, or thermal perception, and 22% on other aspects of the thermo-photometric link, such as the impact of the two sensorialities on physiology or general comfort. In each sub-section, the percentages were calculated by dividing the number of studies answering the considered criterion by the total number of studies. Thus, a classification work was carried out beforehand according to the various points of interest. We are now proceeding to the critical analysis of the identified studies by selecting points of interest and, particularly the distribution of studies that support/refute the link between light and thermal perception.

6.1. Analysis of the Climatic Distribution of Studies

Perception results from two mechanisms specific to humans: physiological mechanisms and psychological interpretation. Acclimatization and climatic habituation are part of the physiological aspect influencing the occupant's perception. Thermal acclimatization is an important phenomenon to consider in any experiment demonstrating thermo-photometric links' existence. Individuals can adapt to temperature changes by altering their metabolism or behavior. Thus, if the temperature conditions are not adequately controlled, or if the thermal history of the subjects is not taken into account, there may be variations in the experiment results that are not related to thermo-photometric links but rather to acclimation. It is, therefore, crucial to minimize the effect of acclimation on the experiment results, such as using control groups or the upstream selection of the subjects studied. The studies identified were therefore distributed by climate type according to Köppen's climate classification [127], shown in Figure 4.

The distributions are synthesized in Table 1. It has been identified that most of the studies (37%) have been carried out in humid temperate climates (Cf). The hypothesis of a thermo-photometric perception is verified for more than 95% of the cases. Studies conducted in cold, humid continental climates (Df) represent no less than 19% of the articles reviewed. The conclusion is similar, with nearly 80% studies corroborating the existence of a link. Studies in temperate climates with dry summers (Cs) represent 7% of our references. The proportion of tropical climates (A) reported is low (6%), while the weather conditions are marked by high relative humidity. It is interesting to note the high proportion of studies corroborating the hypothesis of a link between thermal and visual perceptions (black dots) and, in lesser quantity, those refuting it (red cross). In addition, it should be noted that the studies were essentially conducted in the northern hemisphere. This can be explained by the fact that the countries of this zone have high economic capacities and a good energy infrastructure, which leads them to prioritize optimizing the energy consumption of buildings. By studying the links between thermal and visual sensoriality in occupants, they seek to improve their quality of life in the short term and preserve resources for future generations. It is also important to note that the northern hemisphere has a high population density, reinforcing the need for efficient energy management to ensure satisfactory comfort for all. However, we note that the studies are mainly concentrated in humid temperate climates (Cf), emphasizing the need to extend the experiments to other climates. However, the difference in results allows us to conclude that there may be a strong link between acclimatization and sensitivity to thermo-photometric interactions.

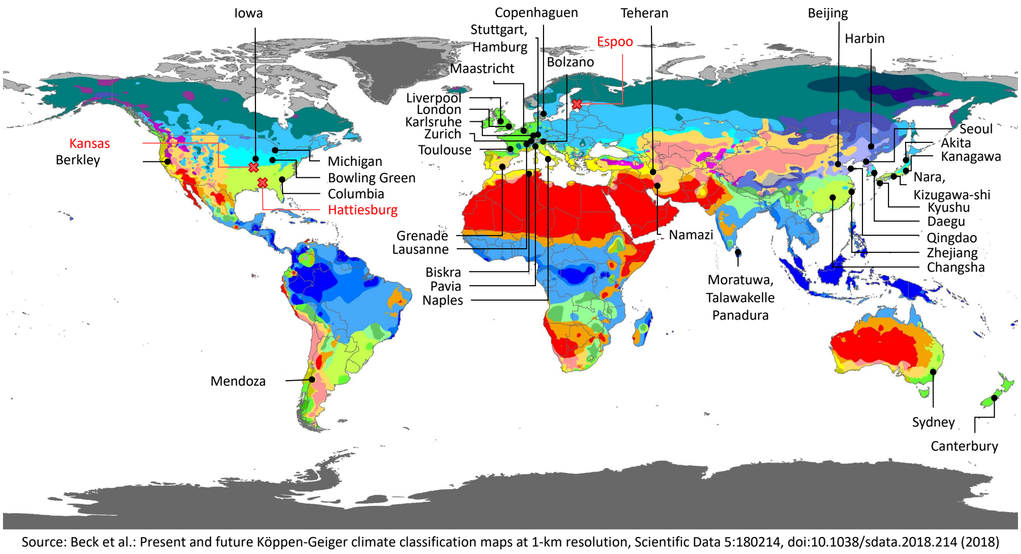

Figure 4. Location of studies on Köppen–Geiger climate classification map (1926–2022) based on the climate map produced by [128] (Red cross: refuting studies; Black dot: corroborating studies).

Table 1. Climate distribution of studies.

Köppen Climate Classification	Description	Percentage	Percentage of Studies Supporting	Percentage of Studies Refuting
A	Tropical	6%	100%	0%
B	Dry	9%	100%	0%
Cf Cs Cw	Temperate	37% 7% 0%	95% 100% 100%	5% 0% 0%
Df Ds Dw	Continental	19% - 11%	80% - 100%	20% - 0%
E	Polar	6%	100%	0%
Not specified		5%	33%	67%

6.2. Analysis of the Impact of the Experimental Platform Typology

The conditions under which the experiments were conducted are a crucial factor in understanding the observations of the relationships between the variables studied. This analysis considers four experimental conditions: climatic chambers, semi-climatic chambers, field studies, and unspecified. Climatic chambers are spaces designed to support experiments where the environmental parameters can be carefully controlled and modified according to the experiment's needs. These types of setups are usually explicitly stated in the studies. Field studies, on the other hand, involve the participation of individuals under normal living conditions, usually measured in a non-intrusive manner. Semi-climatic chambers are spaces that measure environmental parameters less precisely than climatic chambers. They are often implicitly specified in studies via the level of control and precision researchers have over the environment. The overall results are specified in Table 2.

According to this classification, 51 studies showed that 39% of the studies were conducted in climatic chambers, 37% of the experiments were conducted in semi-climatic chambers, and 13% of the studies discussed neither explicitly nor implicitly stated the conditions under which their studies were conducted. Field surveys represented no less than 11% of the studies conducted. Studies refuting the validity of the "hue-heat" effect are generally found in studies using climate chambers. However, the results are small compared to studies that corroborate a link's existence.

The climate chamber experiment seems to be the best configuration to identify the thermo-photometric link from these trends. However, the experiments performed in semi-climatic chambers also highlighted the link between visual and thermal perceptions (via color and light illuminance). This suggests that using climatic and semi-climatic chambers allows experiments to quantify the impact of light on thermal perception. These configurations permit adjustment of the environment and have the advantage of being able to simulate particular conditions which would be favorable to the thermo-photometric link but thus limit the possibility of application in real-life cases. It would then be necessary to reinforce the number of field studies, which despite their small number, have all confirmed the existence of the thermo-photometric link.

Table 2. Variation in typologies of experimental platforms.

Study Area	Percentage	Percentage of Studies Supporting	Percentage of Studies Refuting
Climatic chambers	39%	78%	22%
Semi-climatic chambers	37%	100%	0%
Field studies	11%	100%	0%
Unspecified	13%	71%	29%

6.3. Analysis of Environmental Parameters Measured

How the parameters are measured can significantly impact the conclusions of studies of thermo-photometric interactions. In most of these studies, air temperature is the most frequently measured thermal parameter (present in 81% of the studies reviewed), both during the parameter stabilization phases and throughout the experiment in some studies. However, it is curious to note that despite the importance of this parameter, it is not systematically measured. The correlated color temperature is also a key parameter in studying thermo-photometric interactions, estimated in nearly 78% of the papers reviewed. Indeed, without this data, the "hue-heat" hypothesis could not be studied. It is interesting to note that 95% of the studies measuring the existence of a link between color temperature and thermal perception corroborate this hypothesis.

However, other environmental conditions, such as relative humidity (59%), airspeed (24%), and illuminance (54%), are less frequently measured and are usually reported as threshold values, especially in the case of climatic and semi-climatic chambers. These parameters are not often measured in the field. However, many articles in the literature emphasize the importance of these variables in understanding how we perceive thermal and visual comfort.

It is interesting to note that the type of room used in the experiment determines the parameters that will be measured. In climatic and semi-climatic chambers, the thermal and visual conditions are known and imposed, with minimal variations over time, which do not require frequent measurements. On the other hand, in the case of field studies or studies with an opening allowing natural light and outside air, it is more judicious to measure the thermal and visual environmental parameters to identify their possible fluctuations and to link them to the thermo-visual perception.

Occupant-related parameters, such as metabolic level and clothing insulation, are pre-set during the experimental preparation phase. Participants are placed in preconditioning situations and are asked to rest for a period of time before participating in the experiment and to wear clothing with known thermal resistivity. Measuring metabolic levels could increase the accuracy of existing thermal comfort prediction models, as this variable is unique to each individual.

All of these elements are described in Table 3.

6.4. Analysis of the Influence of the Light Source Typology

Analyzing the typology of the light source used in the studies, described in Table 4, it appeared that more than 72% of them were carried out with artificial lighting, mainly fluorescent lamps. Artificial lighting can be stable over time and adjustable according to the experiment's needs. Furthermore, it does not limit the tests to a single day. Fluorescent lamps have long been favored because of their technological advances, but more and more studies use LEDs. The combination of artificial and natural light sources (opening to the outside) represents 15% of the studies. On the other hand, studies using only natural lighting represent only 9% of the articles listed. This source is less used because it is very variable in the level of illuminance and in its electromagnetic spectrum (according to the type of day: cloudy or sunny).

Table 3. Repartition of measured environmental parameters.

Parameters	Percentage of All Studies	Percentage of Studies Supporting	Percentage of Studies Refuting
Thermal			
Air temperature	81%	91%	9%
Radiant temperature	6%	94%	6%
Relative humidity	59%	100%	0%
Airspeed	24%	100%	0%
Unspecified	17%	89%	11%
Visual			
Correlated color temperature	78%	95%	5%
Illuminance	54%	86%	14%
Unspecified	13%	86%	14%

Overall, the artificial light source seems to add cases where the thermo-photometric perception is not verified. The overall positive effect of access to daylight is no longer to be proven and is in line with the logic of energy frugality. In this way, experiments in daylighting on the "hue-heat" effect should be privileged because the results systematically corroborate the existence of a thermo-photometric link and have been little studied.

Table 4. Influence of the type of light source.

Light Source Type	Percentage	Percentage of Studies Supporting	Percentage of Studies Refuting
Artificial	72%	89%	11%
Daylight	9%	100%	0%
Daylight + Artificial	15%	90%	10%
Unspecified	4%	67%	33%

6.5. Analysis of Study Groups

By analyzing the different characteristics of the group, we can give reflections about the effect of gender, age, or group size on verifying the existence of thermo-photometric perception (see Table 5). Craenondock [16] recommends a minimum sample size of 20–25 people for comfort experiments. This seems to corroborate the conclusions that can be drawn from the analysis of the identified studies. As many as 59% of the studies included at least 20 participants and provided 87% confirmation of the existence of sensory interaction. The increase in the number of individuals tested seems to give an advantage to validating the presence of a thermo-photometric link. Indeed, the gap widens when the number of individuals increases. Sufficiently large samples allow representative results, but the difficulty of obtaining parity limits studies on gender differences. Indeed, the effect of gender on thermo-photometric perception is still poorly understood, as studies often lack male/female parity and adequate sample size. The effect of gender on the "hue-heat" hypothesis and thermo-photometric perception is an evolving research topic. Some studies suggest that women may have different heat perceptions than men due to hormonal and physiological differences. However, other studies show that gender does not significantly affect thermo-photometric perception. Psychological interpretation and female representations of color may also be responsible for these differences. Even so, the results of the experiments consistently support the thermo-photometric perception hypothesis when most subjects are female. Future studies with balanced samples of men and women and adequate sample sizes are needed to understand better the effect of gender on sensory perception of environments. In addition, we note that among the studies identified, the groups of individuals tested were generally highly male-dominated (48%), for a confirmation of the multisensory link at 88%.

Age may also have an impact on thermo-photometric perception. Visual perception and light sensitivity may decrease with age, affecting the perception of perceived temperature in a given environment. For example, older individuals may be more sensitive to bright light and unable to distinguish shades of color, which may influence their perception of perceived temperature. In addition, medical conditions such as cataracts, heart disease, dehydration, and diabetes can also affect thermo-photometric perception with age. It is, therefore, necessary to ascertain the health conditions of the test subjects. The variability in age (14-76 years) shows that some works cover the elderly and other young adolescents. Few studies have examined thermo-photometric perception in people over 50 (4%). The vast majority of articles have reported on younger subjects, whose results confirm the existence of thermo-photometric perception to the tune of 90%.

Table 5. Characteristics of the study populations.

Population Characteristics	Percentage	Percentage of Studies Supporting	Percentage of Studies Refuting
Large group (>20 people)	59%	87%	13%
Small group (<20 people)	41%	94%	6%
Elderly group (average age >50 years)	4%	100%	0%
Young group (average age <50 years)	91%	90%	10%
Unspecified Age	5%	88%	12%
Predominantly female group	30%	100%	0%
Predominantly male group	48%	88%	12%
Equal gender group	19%	89%	11%
Unspecified gender	3%	67%	33%

6.6. Posture and Activity Analysis

The studies reviewed showed variations in participants' postures and activities (see Table 6). The tasks performed included distractions or activities involving thinking or logic. In general, 72% of the studies reviewed had participants assume a seated posture to perform "light office" tasks, including writing/reading on paper and other interactions that did not require significant postural changes. 13% of the studies placed their participants in supine or semi-recumbent postures, with the activity of resting with eyes open during light exposure phases. All these studies corroborate the existence of a link between the two sensorialities.

Finally, only 6% of the referenced studies chose a standing posture with a higher metabolic activity than the other experiments. The metabolic level can impact thermal comfort, as it determines the internal heat production of the body. A high metabolic level means an increase in internal heat production, which can make the environment warmer for the body and lead to a feeling of less thermal comfort. Therefore, the change in the lighting environment affected the thermal perception of the environment.

The participants' choice of activities and postures provides a framework for the results obtained. It is plausible that extremes in posture and activity impact the light environment's effect on thermal perception. Research results seem to support this hypothesis, as studies that refute the existence of a link between light environment and thermal perception are generally associated with seated postures with light activities. This may be because the metabolic level is relatively low under sitting posture with light activity, reducing internal body heat production. As a result, thermal perception is less sensitive to the influence of the light environment.

Table 6. Influence of posture and activity.

Posture and Activity	Percentage	Percentage of Studies Supporting	Percentage of Studies Refuting
Posture: sitting Activity: light	72%	87%	13%
Posture : standing Activity: high (cycling)	6%	100%	0%
Posture: lying down or semi-lying Activity: resting	13%	100%	0%
Unspecified	9%	75%	25%

6.7. Analysis of the Methods of Questioning Thermal and Visual Perception

Questionnaires are used to transform subjective information into quantifiable data that can be translated into statistical data. However, how the questions are asked can influence the participant's response and bias the values obtained. Questionnaires usually use a weighted scale with several points that allow participants to qualify their feelings, comfort, preferences, or other subjective ideas. Another modality used is the analog scale, which consists of a horizontal bar with two opposing adjectives at the ends and a midpoint. The participant must then place an indicator along this bar to indicate which adjective or word best represents their state concerning the question asked. Guidelines on subjective surveys are provided by the standard ISO 10551 [129] in which general information on the format of questionnaires, vocabularies to be applied and examples are presented. Thus, the standard indicates three aspects to be covered in the surveys about indoor environmental quality: perception, evaluation, and preference.

The ASHRAE scale is an excellent example of a scale used to measure thermal comfort [130]. This scale is composed of 7 points, centered on a neutral feeling, which qualifies the thermal atmosphere from "very cold" to "very hot". ASHRAE has popularized this 7-point scale, which is widely used in many studies to measure feeling, preference, acceptability, and other aspects related to the thermal, visual, general ambiance, and even some cognitive aspects. Some studies have attempted to promote a 13-point scale, but the results have been similar to those obtained with the 7-point scale [107,109]. Therefore, it is recommended that the 7-point assessment be preferred for thermo-photometric link experiments. The studies reviewed used questionnaires to assess participants' perceptions (see Table 7). These questionnaires were designed to identify the relationship between thermal and visual perceptions. Approximately 41% of the questionnaires focused solely on thermal assessment, while 30% assessed both sensory aspects simultaneously. About 26% of the studies measured only thermoregulatory physiological responses to visual stimuli or considered the occupant's overall assessment of the environment resulting from the relationship between visual and thermal perception. Very few studies (3%) have chosen to assess only visual perception. These trends indicate that thermal perception is considered more important than visual perception. However, overall occupant comfort is dependent on both sensory aspects. Most studies assessing thermal and visual aspects have shown that the lighting environment affects participants' thermal perception. Therefore, questionnaires should address both aspects of comfort simultaneously.

Table 7. Survey and questionnaire influences.

Sensory Evaluation	Percentage	Percentage of Studies Supporting	Percentage of Studies Refuting
Thermal Assessment only	41%	86%	14%
Visual Assessment only	3%	100%	0%
Thermal and Visual Assessment	30%	94%	6%
Others	26%	93%	7%

6.8. Using Thermo-Photometric Perception for Building Energy Savings

In a cold climate, each celsius degree increase in air temperature in an uninsulated dwelling increases by at least 10% in energy consumption and at least 7% if the dwelling is adequately insulated, according to ADEME [131]. However, these figures can vary depending on other factors and reach up to 14-15%. Similarly, in hot climates, each one-celsius degree drop in air temperature increases about 5% in energy consumption, proportional to the efficiency of consumer air conditioners. In order to reduce the energy consumption of buildings, it is important to find ways to act on the perceived temperature inside. Sensory compensation is an interesting method to achieve this. Although few studies have quantified the correlation between thermal and photometric parameters of an environment and energy consumption, some have provided key figures. For example, Toftum's study [64] shows that a reduction in heating setpoint temperature, coupled with lighting usage ranging from 4500 K (645 nm) to 2700 K (1080 nm), can result in a reduction of approximately 8% in a building's total annual energy consumption, under ideal conditions, without regard to daylight or other factors. These results highlight the importance of LED lighting color temperature on building energy consumption.

Current studies are more about assessing the indirect link between thermo-photometry and energy savings rather than offering actual correlation figures. This can be explained simply by the lighting environment affecting an individual's "thermal tolerance," which can ultimately lead to energy savings. In other words, by creating a comfortable environment, energy consumption can be reduced by adjusting the temperature to a slightly different level while maintaining thermal comfort. Work supports this conclusion by calling this new lighting design strategy a commercially viable solution for reducing building energy consumption [67,132].

More research is needed to test the energy-saving potential of sensory compensation, as even small savings could significantly impact nonresidential buildings that generate a large portion of carbon emissions due to temperature control in a narrow range [79]. Recent advances in LED lighting make the practical implementation of such systems commercially feasible. In the future, designers may consider new processes for regulating ambiance using home automation to meet individuals' conscious and unconscious needs. However, this will require the development of new equipment capable of learning the habits and needs of individuals. For example, new types of lighting could be able to modulate their intensity according to the natural circadian rhythm of humans and their thermal routines while optimizing their home's energy consumption.

7. Conclusions and Perspectives

The human body is a complex multisensory machine capable of processing sensory information from the environment. Our senses work together to provide a nuanced understanding of the world, which is crucial for survival and well-being. These senses also play a role in our perception of the indoor environment of a building. As hedonic beings, it is crucial to identify simple solutions that can meet our comfort needs while reducing the energy footprint of a building. In this regard, studying sensory interactions can be an opportunity if one projects a sensory compensation strategy. Indeed, modifying the lighting environment is less energy-intensive than modifying the thermal environment. So, it is interesting to consider whether research on thermo-photometric interactions is justified and whether it can offer promising solutions for indoor comfort aiming at energy frugality. This article presents a comprehensive review of studies that have sought to prove or disprove the existence of a link between thermal perception and visual perception.

7.1. Findings and Conclusions

This review of the current state of research has enabled the identification of these various findings:

- Climate and the thermal history of individuals influence the relationships between thermal and visual perceptions. The variability in results suggests the potential presence of a strong correlation between acclimation and sensitivity to thermo-photometric interactions. However, there is a lack of research in many climates.

- The climatic chamber experiment does not confirm or reject the hypothesis of a link between sensorialities, but it enables control of environmental factors, which can affect the analysis. Semi-climatic and field studies support the thermal-photometric link. However, psychological factors significantly impact thermal comfort in a climatic chamber, and the closed environment can create a sense of confinement due to the lack of connectivity with the outside world.
- Different light sources can also impact. Artificial lighting studies offer stable and repeatable measurements, while daylight studies are validated but less common. The view of the environment from daylight studies can improve psychological well-being and performance, while blind rooms may lead to the isolation that impacts the occupant's overall perception. However, the link between light ambiance and thermal perception is confirmed in most cases, regardless of the light source used.
- The group characteristics in studies of thermo-photometric interactions lack diversity, particularly by age and gender. Groups larger than 20 people allow for statistical validation of these interactions, which are confirmed in groups of average age under 50. However, studies on middle-aged people over 50 are scarce, and gender balance in studies is often lacking. Despite fewer studies on female groups, the impact of the light environment on thermal perception is consistently confirmed.
- Activity and posture during the experiment can affect the interactions between the sensorialities. The effect of the light environment on thermal perception is enhanced by low or high metabolic levels and various postures (lying or standing).
- It is recommended to use questionnaires that assess thermal and visual perception with consistent rating scales, such as the ASHRAE 7-point scale, to obtain accurate results. The questionnaires also need to consider the guidelines provided by ISO 10551.

To conclude, experiments in semi-climatic chambers and real buildings, exposed to different types of climate and daylight, systematically verified the thermo-photometric interactions. However, the studies involved a small group of mostly female subjects over 50 with low or high metabolic activity in lying or standing postures.

7.2. Scientific Hurdles

The research theme aiming at studying multisensoriality to improve the design of buildings is relatively recent but promising. Indeed, sensory compensation could be a simple, effective, and inexpensive solution to reduce the energy consumption of a building. However, several scientific barriers still need to be addressed to create a scientific consensus.

- Thermal perception is complex and depends on many factors, including air and surface temperatures, humidity, and airspeed. Understanding how these factors interact to influence thermal perception is challenging.
- There is not much research on the theory of "illuminance-thermal markers," making it difficult to understand how lighting affects thermal perception. This lack of research is evident in the number of studies that refute this hypothesis.
- Few tools are available to measure thermo-photometric perception in a linked manner, making it difficult to obtain reliable and comparable data between studies.
- Simulating real building occupancy conditions in the laboratory is challenging, which limits the applicability of thermo-photometric perception research results to real buildings.
- Further study of the correlation between sensory compensation and energy savings could interest architectural designers, who might then consider this simple and innovative solution.

More research is needed to understand the influences of physiological, psychological, and environmental factors on the confirmed interaction between thermal and visual perception. The inconsistent results in the literature may be attributed to the control of the varying lighting conditions, uniformity, and stationarity of microclimatic parameters. This makes investigating the interaction between thermal and visual perception more challenging for scientists. Therefore, experimental studies are essential to quantify the impact of light and thermal environments on comfort and perception, which can lead to the development of a mathematical model. This model will improve the design of buildings and living spaces, enhancing human well-being and efficiency.

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