Building and Environment 269 (2025) 112479

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Experimental and modeling approach for estimating the psychological adaptation and perceived thermal comfort of occupants in indoor spaces

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ARTICLE INFO

Keywords:
Perceived thermal comfort
Psychological adaptation
Thermal comfort evaluation
Adaptive factor
Physiological evaluation
Thermal perception

ABSTRACT

This study proposes a methodology for examining the relationship between environmental thermal conditions and occupant's perceived thermal comfort evaluation. Therefore, their psychological adaptation was examined to quantify and incorporate it in thermal comfort evaluations. To achieve the closure of the model's system of equations, experiments are carried out in which subjects are exposed to various thermal conditions in an enclosed space that simulates an office indoor environment; thermal measurements and perceived data are collected. Thus, the study aims to evaluate the adaptive factor that causes the difference between the physiological evaluation and the subjects' actual thermal perception. This adaptive factor is linked to the physical stimuli experienced owing to the thermal environment and the cognitive information within the occupant's memory systems; thus, the closure equation is derived from the outdoor air temperature and indoor operative temperature.

1. Introduction

The changing global climate, combined with global warming, is becoming a significant factor influencing occupants' thermal comfort [1,2]. Climate change can affect human thermal behaviors [3], human psychological information, and thermal perception [4]. Therefore, it is necessary to consider thermal, behavioral, and psychological variations in thermal comfort evaluations.

Thermal comfort is defined by ASHRAE as *"that condition of mind that expresses satisfaction with the thermal environment, assessed by subjective evaluation"* [5]. This definition specifies human satisfaction as the primary criterion for delivering thermal comfort to occupants. However, human satisfaction is subject to many conditions relating to the human environment, which first encapsulates the physical thermal conditions that affect the space surrounding the human body. Moreover, it includes human body systems, such as metabolism, physiology, anthropometry, and anatomy, as well as the conditions of the mind, which are nonphysical processes in human cognitive and mental systems. These belong to different scientific domains and may be difficult to synchronize into a single evaluation. However, to precisely evaluate thermal comfort, it is necessary to investigate and enumerate the complex relationships that exist between physical and psychological processes.

Brager et al. [6] explained that occupant satisfaction was not just an outcome of the physical environment but a complex perception built out of the intersection between objective stimuli as well as cognitive and emotional processes. Therefore, achieving satisfaction involved aligning the current thermal environmental conditions with individual thermal expectations [7–9]. This implies that satisfaction is determined by both the thermal environment and cognitive information in the occupants' memory. According to Nikolopolou et al. [10], human perception and response to physical stimuli were not only based solely on the magnitude of thermal conditions but also on the information available for a particular situation. Therefore, perceived comfort evaluation requires the magnitude of stimuli, human sensational responses, and the influence of innate information on the occupant's cognition.

In this study, a methodology that evaluates these physical and psychological factors with the objective of delineating the relationship between thermal stimuli and the psychological adaptive component of occupants' perceived comfort is proposed.

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https://doi.org/10.1016/j.buildenv.2024.112479
Received 22 March 2024; Received in revised form 13 November 2024; Accepted 18 December 2024
Available online 19 December 2024

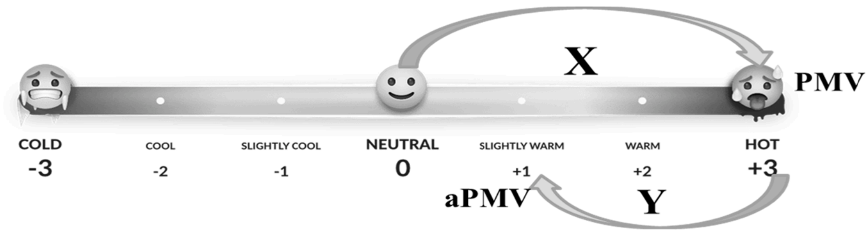

Fig. 1. Illustration of the feedback between the physiological (X) and adaptive (Y) components of thermal comfort.

2. Concept of thermal adaptation

In the context of thermal comfort, adaptation involves the processes through which people improve the fit between environmental conditions and occupants' requirements [11]. Therefore, the fundamental principle of the adaptive approach states that, *"if any change occurs such as to produce discomfort, people react in ways that tend to restore their comfort"* [12]. Following this fundamental principle, adaptive comfort factors can be classified into two categories: (1) physical adaptation, involving the adjustments individuals make to themselves (reactive adaptation) or to their environment (interactive adaptation) [11,13], and (2) psychological adaptation, which involves altered perception and reaction to sensory information based on past thermal experiences and expectations [8,14]. Various psychological processes, such as expectations, experiences, perceived control, environmental stimulation, and other factors, play a significant role in adaptive comfort [4,15–17]. To incorporate these adaptive factors into thermal comfort evaluation, some models have been developed using mathematical methods and correlations. These include models based on the correlation between the outdoor air temperature and indoor operative temperatures [18–20], the extended PMV model by Fanger and Toftum [21], known as the PMV*e*, etc. The PMV*e* includes an expectancy factor '*e*,' which depends on the prevalence of air-conditioned buildings in warm climate regions. Another adaptive comfort model is the adaptive predicted mean vote (aPMV) model proposed by Yao et al. [22]. It is a black-box model that considered the adaptive behaviors of occupants by linking Fanger's PMV evaluation to the occupants' actual mean vote (AMV). Most of these models focused on evaluating and predicting occupants' thermal perceptions, such that the influences of behavioral and psychological adaptation were integrated collectively and inseparably from other components of thermal comfort. Therefore, to evaluate adaptive comfort accurately, it is necessary to distinctly evaluate the magnitude of psychological or behavioral adaptation and comprehend the parameters influencing it. Thus, the aPMV model was adapted and enhanced to evaluate the psychological adaptation of occupants because it considers the reactions between the physiological and adaptive components of thermal comfort.

2.1. Components of aPMV model

Yao et al. [22] theoretically stated that Fanger's PMV model expressed the relationship between the physiological processes and responses of the human body and the physical thermal conditions of the person's environment. Consequently, it omitted the adaptive and psychological factors that influences occupant's thermal perception [23,24]. However, psychologically adaptive self-regulation plays a significant role in determining human thermal sensations [25,26]. Therefore, Yao postulated that, *"similar to the steady state theory, physiological processes exist within the 'black box,' but psychological and behavioral processes provide an 'adaptive (contrary)' feedback"* [27]. This implies that the physiological component (X) in the 'black box' (G) responded proportionately to the thermal load influencing the physical thermal stimuli (δ), while the adaptive component (Y) in the 'black box' acted adaptively, contrary to the value of the physiological response when evaluated on the thermal sensational scale (TSS), as shown in Fig. 1.

Thus, Yao et al. [22] proposed the following mathematical expression to define these relationships:

$$aPMV = X - Y \quad [-] \tag{1}$$

where the physiological component is expressed as follows:

$$X = G \times \delta = PMV \quad [-] \tag{2}$$

and the adaptive component introduced the psychological coefficient K_δ:

$$Y = G \times K_\delta \times aPMV \quad [-]. \tag{3}$$

Yao et al. [22] then defined the adaptive factor η as follows:

$$\eta = \frac{K_\delta}{\delta} \ [-] \tag{4}$$

where δ denotes the physical thermal stimuli.

Combining Eqs. (1), (2), (3) and (4) provides Yao the following equation:

$$aPMV = \frac{PMV}{1 + \eta \times PMV} \ [-]. \tag{5}$$

Eq. (5) considers the physiological component (X) and adaptive component (Y), which leads to a single thermal comfort evaluation, *aPMV*. Subsequently, we proposed enhancing this modeling approach by considering thermal radiation in thermal stimuli. We also proposed some modifications to the approach of Yao et al. [22] which filled a gap in the relationship between PMV and *aPMV* evaluations. These modifications consequently enhanced the evaluation of the psychological coefficient (K_δ) of the occupants.

2.2. Proposed modification of the aPMV model

First, according to the Yao et al. model, the physical thermal stimuli δ is expressed as follows:

$$\delta = T_a - T_a^n \ [^\circ C] \tag{6}$$

where T_a denotes the air temperature, and T_a^n denotes the neutral air temperature. To consider the radiant exchange that occurs between occupants and their environment in an indoor space [28,29], we suggested and considered the following thermal stimuli:

$$\delta = T_{op} - T_{op}^n \ [^\circ C] \tag{7}$$

where T_{op} denotes the operative temperature and T_{op}^n denotes the neutral operative temperature

$$T_{op} = \frac{T_{mrt} h_r + T_a h_c}{h_r + h_c} \ [^\circ C] \tag{8}$$

where h_c and h_r denote the convective and radiant heat transfer coefficients of air and internal surfaces (walls, ceiling, and floor), respectively. They characterized the heat exchange between the indoor environment and occupants. Therefore, the mean radiant temperature

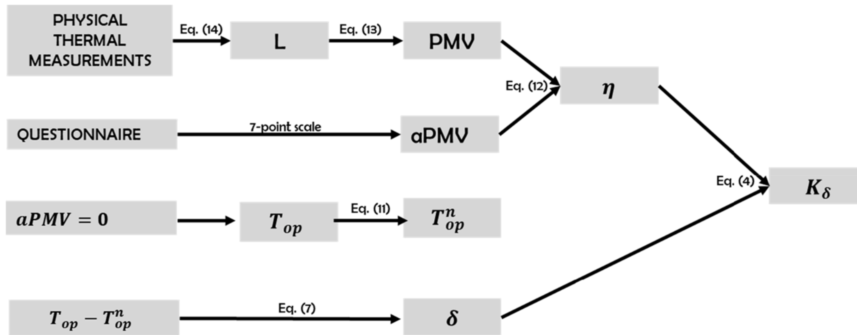

Fig. 2. Chart of the combined experimental-modeling protocol, up to obtaining the psychological coefficient K_δ.

T_{mrt} for a seated person in an indoor space with a cuboid shape and six surfaces, up (u), down (d), right (r), left (l), front (f), and back (b), can be estimated *using* their plane radiant temperature as follows [5]:

$$T_{mrt} = \frac{0.18[T_u + T_d] + 0.22[T_r + T_l] + 0.30[T_f + T_b]}{2[0.18 + 0.22 + 0.30]} \ [^\circ C] \tag{9}$$

The radiant heat transfer coefficient can be calculated using Eq. (10):

$$h_r = 4\varepsilon\sigma F_{eff}\left(273.2 + \frac{T_{cl} + T_{mrt}}{2}\right)^3 \ [W.m^{-2}K^{-1}] \tag{10}$$

where F_{eff} represents the effective area factor, T_{cl} represents the clothing temperature, and h_c is estimated to be 3.1 $W.m^{-2}K^{-1}$ for an indoor space with air velocity less than 0.2 $m.s^{-1}$ [5].

Therefore, in Eq. (11), the neutral operative temperature T_{op}^n is the operative temperature when the subject neither feels hot nor cold, nor has any impulse to adjust himself/herself or the environmental thermal conditions. Thus, the operative temperature occurred when the aPMV value was zero.

$$aPMV = 0 \Leftrightarrow T_{op} = T_{op}^n \ [^\circ C] \tag{11}$$

Second, Yao et al.'s Eq. (5) showed that $PMV = 0$, is equivalent to $aPMV = 0$ ($PMV=0 \Leftrightarrow aPMV=0$). However, this expression fails to efficiently assess the adaptive behavior of subjects when $PMV = 0$, because the resulting *aPMV* value from the equation is always zero. Therefore, we choose to replaced Eq. (5) with the following:

$$aPMV = PMV - \eta \qquad [-]. \tag{12}$$

This aligns with Yao's [27] assertion that physiological evaluations and adaptive factor react inversely, as shown in Fig. 1, and it is consistent with the foundational principle of adaptive comfort proposed by Nicol et al. [12]. Yao postulated that *"similar to the steady state theory, physiological processes exist within the 'black box,' but psychological and behavioral processes provide an 'adaptive (contrary)' feedback"* [27]. As illustrated in Fig. 1, the PMV represent the physiological process while the adaptive factor η represents the psychological and behavioral adaptive processes [22]. Hence the difference between the PMV and the adaptive factor η will result into the thermal perception of the occupant aPMV. Also, Nicol et al. [12] postulated that *"if any change occurs such as to produce discomfort, people react in ways that tend to restore their comfort"* [12]. Therefore, we can conclude that the psychological and behavioral reaction (adaptation) to occupant's discomfort can be evaluated as the adaptive factor η.

In addition, to evaluate the physical components of Eq. (12), we considered Fanger's *PMV* equation [30–32]:

$$PMV = \left(0.303e^{-0.036\,\varphi} + 0.028\right) \times (\varphi - L) \ [-] \tag{13}$$

where φ represents the subject's metabolic rate, dependent on their activity level [5], and L represents the total heat loss from the subject's body, which comprises:

- convective heat losses from the clothing surface φ_{cl}^{Conv} [33], to align with the operative temperature stimuli (Eq. (7)),
- radiant heat losses owing to long-wave radiant exchanges φ_{cl}^{rad} [34],
- heat losses from the skin surface by sweating φ_{sk}^{Sw} and vapor diffusion φ_{sk}^{Diff} [31],
- respiratory heat losses by convection φ_{res}^{Conv} [35] and evaporation φ_{res}^{evap} [36].

$$L = \varphi_{cl}^{Conv} + \varphi_{cl}^{rad} + \varphi_{sk}^{Sw} + \varphi_{sk}^{Diff} + \varphi_{res}^{Conv} + \varphi_{res}^{evap} \ [W.m^{-2}]. \tag{14}$$

3. Proposed yao-based modeling-experimentation methodology

3.1. Proposed modeling protocol

Eqs. (12), (13), and (14), along with Eqs. (7) and (4), form a system of five equations. However, solving this adaptive thermal comfort problem requires determining six unknown variables: *aPMV, PMV, L*, T_{op}^n, δ, and K_δ. Thus, a sixth or closure equation is required. This closure equation establishes a relationship between the psychological coefficient K_δ and thermal loads of the subjects. It is obtained by experimental processes described subsequently; this combined experimental modeling protocol involved simultaneous *PMV* and *aPMV* evaluations versus the thermal loads of the subjects.

Fig. 2 shows the operations of the relationships that formulate the psychological coefficient K_δ as a function of some significant thermal factors (6th closure equation).

The physical measurements collected from the experimental rooms and the subjects' clothing were used to calculate the heat loss L and, consequently, the PMV values using Eqs. (14) and (13). The results of the questionnaire (see Appendix B) collected from the subjects were then used to derive the thermal sensational votes (TSV) values; the TSV evaluates the thermal perception of the subjects on a 7-point scale between "hot" and "cold," and according to ASHRAE 55 and ISO 7730 standards [37,36], a value from −3 to +3 is then substituted as the experimental aPMV value in the adaptive thermal comfort modeling approach. Thus, according to Eq. (12), the adaptive factor η values were obtained; subsequently, the operative temperature T_{op} values were evaluated and the neutral temperature T_{op}^n values were determined in accordance with the definition provided in Eq. (11), then enabling the calculation of thermal stimuli δ *using* Eq. (7). Finally, the values of the psychological coefficient K_δ were calculated using Eq. (4).

3.2. Experimental setup

The experiments aimed to establish a controlled indoor environment with precise and measurable surface characteristics, allowing for the accurate modification and measurement of thermal factors and temperatures. This setup facilitated the simultaneous collection of

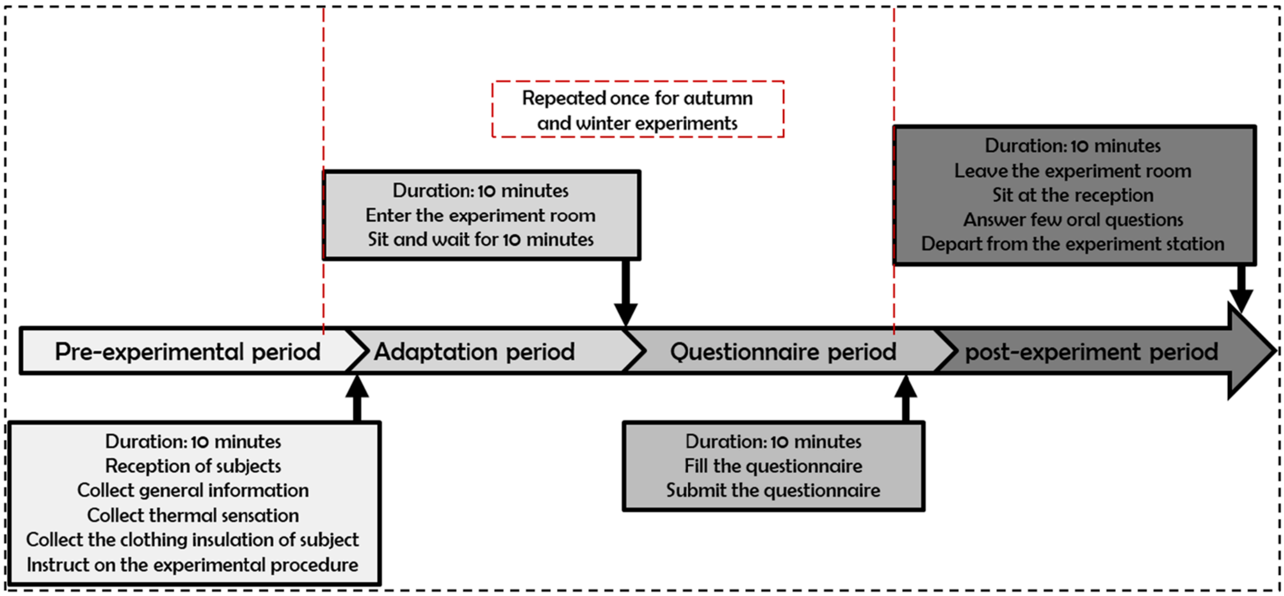

Fig. 3. Experimentations protocol: Timeline diagram.

information on both the thermal flux reception and thermal perception of the subjects within the enclosure.

Three experimental periods were used: summer (05/07/2022 to 08/07/2022), autumn (20/10/2022 to 26/10/2022), and winter (30/01/2023 to 03/02/2023). These experiments were conducted in two types of rooms (see Appendix A). The winter experiments were conducted in a naturally ventilated room with no insolation, while the autumn and summer experiments were conducted in a dedicated experimental room (an experimental cell with a rectangular floor area of approximately 2.5 × 4 m). These two experimental rooms were located at the Institute of Mechanics and Engineering (I2M), a CNRS laboratory in Bordeaux, France.

The walls of the dedicated experimental room were made of a uniform and conductive surface material (a metallic plate with high emissivity at ambient temperature) to ensure efficient radiant emission. The ceiling was constructed with a gypsum board and the floor had a terrazzo floor finish. To accurately account for the radiant load, direct solar radiation (shortwave radiation) was deliberately prevented from entering the dedicated experimental room. The surface temperatures within the dedicated experimental room were adjusted by external heating and cooling of the enclosure. To imitate real office conditions in the experiment room during the summer and autumn experiments, such as experiencing solar gains from a wall, one of its metallic external walls was either cooled (20–10 °C range) or heated (20–40 °C range), through a heating and cooling buffer zone (see Fig. A1 in Appendix A). No imitation was necessary to achieve the cold conditions required for winter experiments conducted in a naturally ventilated experimental room (see Fig. A2 in Appendix A).

PT100 surface temperature sensors were strategically placed on the interior surfaces of the walls, floor, and ceiling, as well as on the subject's clothing. A nearby meteorology acquisition station collected the air temperature, relative humidity, air velocity, and black globe temperature (see details of instrumentation in Appendix A).

Therefore, the participants completed a questionnaire designed to gather data on their TSV, enabling the evaluation of aPMV. The questionnaire was completed online and included other questions that could obtain qualitative outcomes of the subjects' physical and psychological adaptive behaviors [38]. The questions covered preferred perceptions, comfort levels, thermal tolerance, acceptability, and satisfaction (Appendix B). The objective was to calibrate the subjects' psychological characteristics, particularly through the psychological coefficient K_δ, a key component of the proposed adaptive thermal comfort model.

3.3. Schedule of the experiments

Participants in the experiments included staff members from various offices and laboratories in Bordeaux, aged between 20 and 65 (over 80 % falling between 20 and 32 years old), representing different nationalities, with approximately 70 % of French origin. In the 'winter' season, there were 17 males and 12 females; in 'autumn' 18 males and six females, and in 'summer' 15 males and 14 females. Clothing insulation only varied slightly among the subjects because we previously proposed a uniform dress code that would make them more sensitive to indoor radiant and convective thermal conditions. Therefore, most of the subjects' clothing was estimated to be in the range of 0.45 ±0.05 clo, and the subjects' clothing (radiant) emissivity was estimated to be in the range of 0.95±0.05.

The outdoor air temperatures varied between 23 °C and 35 °C in 'summer,' 15 °C and 22 °C in 'autumn,' and 0 °C and 14 °C in 'winter,' throughout the experiments. Each experiment involved four stages for each participant: pre-experimental, adaptation, questionnaire, and post-experimental (see Fig. 3).

During the **pre-experimental period**, personal information was collected from the participants, including their name, age, weight, and current thermal sensation. Data collection was conducted outside the experimental room in the reception room (see Fig. A1 in Appendix A) and lasted for approximately 10 min.

During the **adaptation stage**, the participants entered the experiment room, were seated, and waited for approximately 10 min. This allowed the subjects to acclimate to the thermal conditions within the enclosure. Following the adaptation stage, the **questionnaire stage** involved the subjects paying attention to the sensations induced by their environment. The subjects then answered the questions, expressing their perceptions and thoughts regarding their thermal situation and comfort. Typically, the questionnaire took approximately 10 min to complete. In the 'autumn' and 'winter' experiments, the participants underwent adaptation and questionnaire periods twice for each experiment. This additional experimental process was adopted after the summer experiments to increase the period of perception of the subjects and to enable more subjects to deploy their adaptability. Certainly, according to Goto et al. [39] and David [40], the metabolism of the human body usually requires approximately 10–15 min to descend, rest, or become uniform

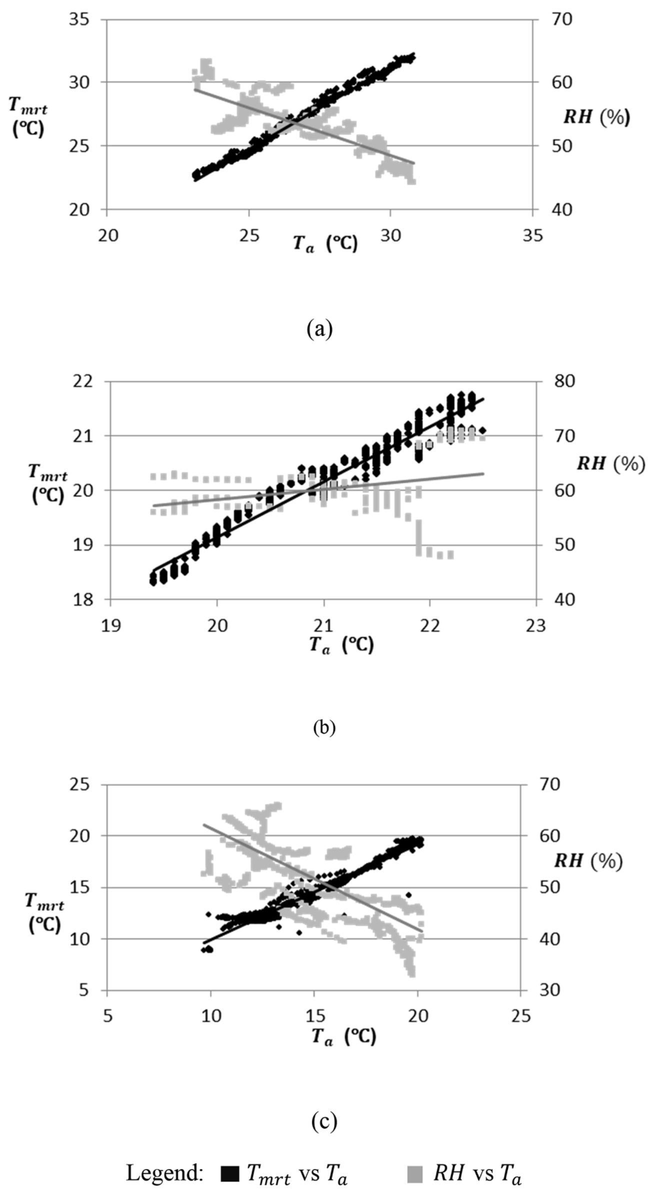

Fig. 4. Mean radiant temperature T_{mrt} and air relative humidity RH versus air temperature T_a in the experiment rooms, during the (a) summer, (b) autumn, and (c) winter experiments (raw data and linear regressions).

at its respective activity level. Therefore, in light of the experiences gained during the experiments conducted in summer, we thought that it might be suitable to increase the perception period (adaptation and questionnaire period) to allow the subject's perception to become stable; thus, enabling accurate evaluations.

The **final period** involved a brief discussion with the participants regarding their experiences in the experimental room.

Thus, physical and perceptive data were collected concurrently during the experiment.

4. Analysis of results

Fig. 4 summarizes the behavior of the thermal conditions experienced by the subjects within the experimental space. The air temperature varied proportionately with the mean radiant temperature, whereas it varied inversely with the relative humidity. Hence, the subjects' adaptive behaviors and perceptions were analyzed in subsequent sections.

4.1. Evaluation of adaptive factor η

Based on Eq. (12), the signs of the adaptive factor η are directly linked to the adaptive or contra-adaptive behaviors of the subjects. Fig. 5 shows these adaptive and contra-adaptive behaviors based on PMV and aPMV values, and the corresponding sign of the adaptive factor (η); in this figure, the illustrative PMV values were assumed to be $+2$ and -2 while the illustrative TSV were represented by the aPMV values on the TSS. Therefore, an adaptive behavior implies that the value of aPMV is closer to 'TSV=0′ than the value of PMV; therefore, a contra-adaptive behavior implies that the value of aPMV is farther from 'TSV=0′ than the value of PMV.

During the autumn and winter experiments PMV values were mostly negative; thus, the adaptive factor was less than zero ($\eta < 0$) for the subjects that manifested adaptive behavior, and greater than zero ($\eta > 0$) for the subjects that manifested contra-adaptive behavior; conversely, during the summer experiments PMV values were mostly positive, and thus, the adaptive factor was greater than zero ($\eta > 0$) for the subjects that manifested adaptive behavior and less than zero ($\eta < 0$) for the subjects that manifested contra-adaptive behavior.

Notably, during the experiments, the subjects were not aware that their adaptive capacity was being evaluated. Therefore, some of them consciously or subconsciously chose not to deploy their adaptive abilities (even if they had some) depending on their mental state and the magnitude of the thermal stimuli experienced.

Fig. 6 shows the values of the adaptive factors for each experiment under the summer, autumn, and winter conditions.

Fig. 6 clearly shows the distinction between adaptive and contra-adaptive experiments, highlighting the fact that more subjects engaged in their adaptive capacities during winter than during autumn and summer. This observation suggests that the subjects in our panel possessed a greater adaptive ability to achieve winter comfort than summer comfort, whether consciously or subconsciously.

For the purpose of this study, we chose to analyze only the experiments in which the subjects manifested adaptive behavior. The sequence for evaluating the adaptive experimental results was as follows:

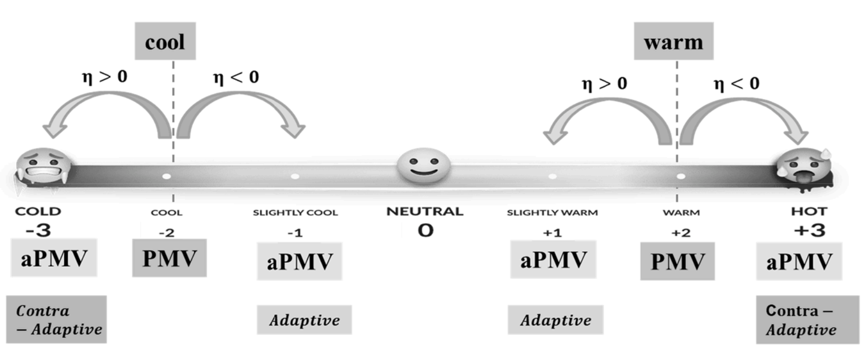

Fig. 5. Illustration of the subject's adaptive or contra-adaptive behavior, resulting to either a positive or negative sign of the adaptive factor (η).

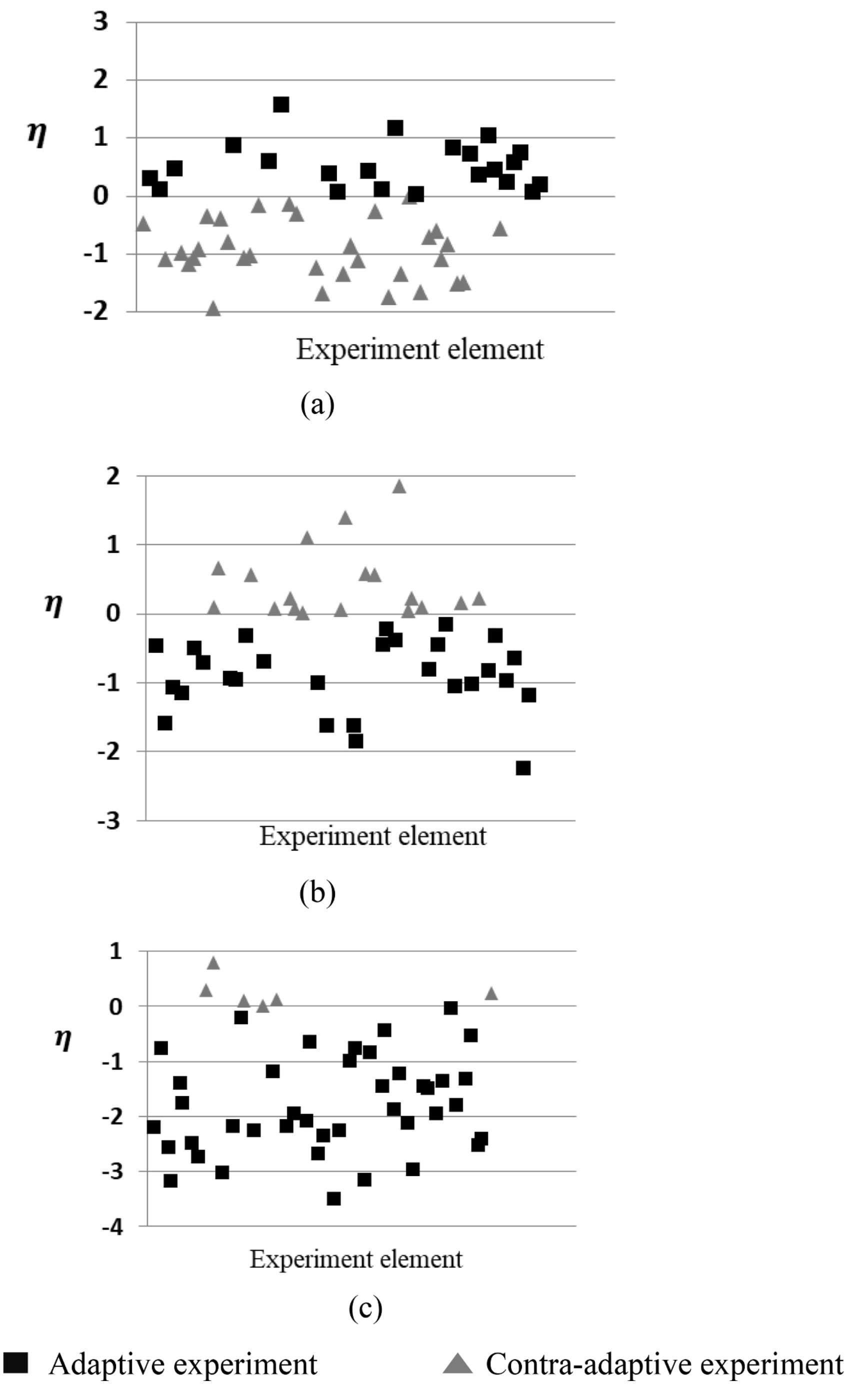

Fig. 6. Values of adaptive factor η during the (a) summer, (b) autumn, and (c) winter experiments.

1. The indoor operative temperature T_{op} was calculated from physical measurements (8),
2. The neutral temperatures T_{op}^{n} were determined through definition and regression (11),
3. The values of the physical thermal stimuli δ were calculated (7),
4. The values of the psychological coefficient K_{δ} were calculated (4),
5. The variables of psychological coefficient as related to indoor and thermal conditions were evaluated.

4.2. Determination of neutral operative temperature

Fig. 7 shows the relationship between *aPMV* votes and the indoor operative temperature values for the experiments conducted in summer, autumn, and winter.

The neutral temperature values for summer, autumn, and winter were determined using the following protocol:

- The mean value of the operative temperature $\overline{T_{op}}$ was calculated for each iso-value of the aPMV.
- The regression of these mean values (linear in this case) was aligned,
- This (linear) regression was interpolated to the x-axis, reaching a neutral operative temperature value, which was defined as the value of the operative temperature when aPMV $= 0$.

As shown in Fig. 7, the neutral temperature values for summer, autumn, and winter were $T_{op}^{n} = 25^{\circ}C$, $T_{op}^{n} = 21^{\circ}C$, $T_{op}^{n} = 18\,^{\circ}C$,

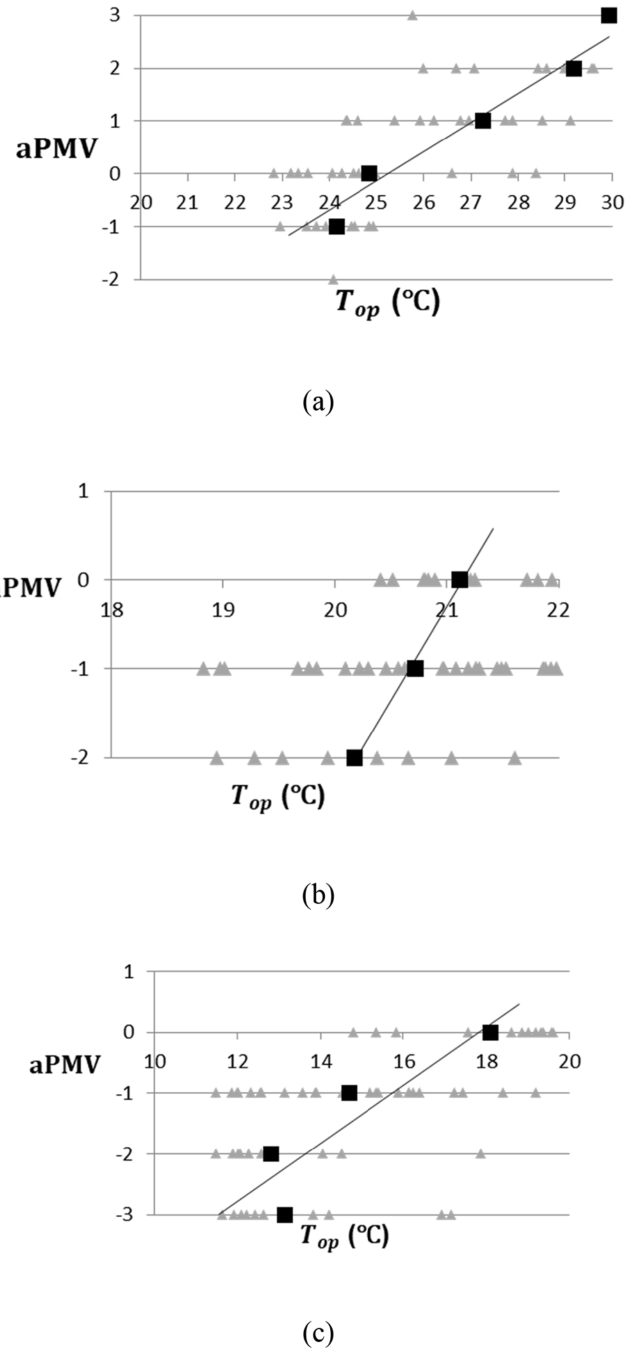

Fig. 7. Adaptive predictive mean vote aPMV versus indoor operative temperature T_{op} during the (a) summer, (b) autumn, and (c) winter experiments. ▲: Raw data, ■ : Mean value of operative temperature ($\overline{T_{op}}$) for each iso-aPMV value (linear regressions).

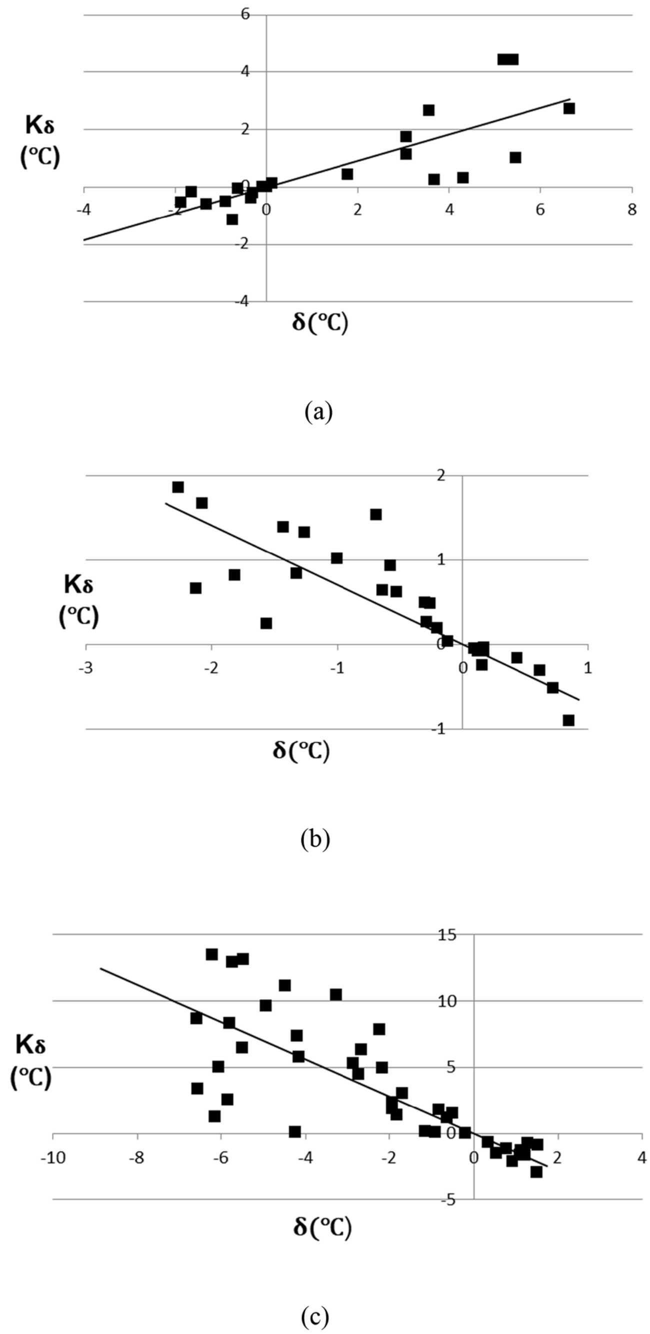

Fig. 8. Psychological coefficient K_δ versus thermal stimuli δ during the (a) summer, (b) autumn, and (c) winter experiments (linear regressions).

Table 1
Psychological coefficient $\boldsymbol{K_\delta}$ versus thermal stimuli: regression equation and adaptive factor $\boldsymbol{\eta}$ value.

Season	Regression equation	Adaptive factor	Equation number
Summer	$K_\delta = 0.5{\cdot}\delta$ [°C]	$\eta = 0.5$	(15)
Autumn	$K_\delta = -0.7{\cdot}\delta$ [°C]	$\eta = -0.7$	(16)
Winter	$K_\delta = -1.4{\cdot}\delta$ [°C]	$\eta = -1.4$	(17)

respectively.

4.3. Psychological coefficient evaluation

The psychological coefficient K_δ values were calculated using Eq. (4). Subsequently, a regression graph of the psychological coefficient K_δ versus the physical thermal stimuli δ was plotted to determine the function for the adaptive factor η (Table 1). This process was conducted during summer, autumn, and winter, as shown in Fig. 8.

Thus, the adaptive factors derived through experimental procedures for summer, autumn, and winter seasons were +0.5, −0.7, and −1.4, respectively. This process yielded only average values across the three seasons (summer, autumn, and winter). To broaden these results, we proposed a method for assessing these adaptive factors by evaluating

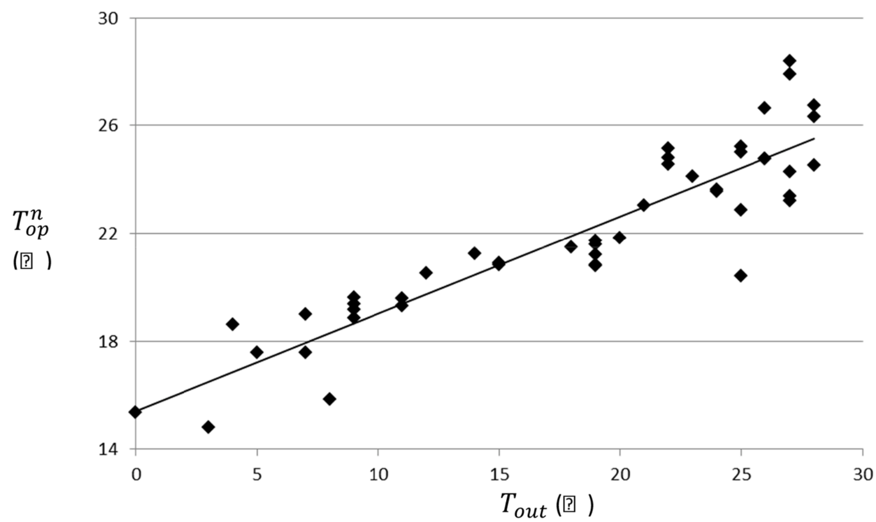

Fig. 9. Neutral temperature T_{op}^{n} versus outdoor air temperature T_{out}: raw values and linear regression.

quantifiable thermal factors without conducting experiments. We therefore investigated the relationship between key determinants of the adaptive factor (psychological coefficient K_δ and physical thermal stimuli δ) and various physical thermal parameters.

4.4. Relationship between adaptive factor and physical thermal parameters

According to Eq. (4), the determinants of the adaptive factor are the psychological coefficient K_δ and the physical thermal stimuli δ, where δ is a function of the neutral temperature T_{op}^{n} and the operative temperature T_{op} (see Eq. (7)). Therefore, we explored the link between the adaptive factor and both indoor (where the occupant's perceived comfort was estimated) and outdoor (where the occupant was in the recent past) temperatures. The following analysis has been developed for the three sets of experimental data corresponding to the three "seasons:"

1. Exploration of the relationship between the neutral temperature T_{op}^{n} and outdoor air temperature T_{out}, encompasses all three seasons collectively [19,41,42]. This exploration led to establishing the relationship between the physical thermal stimuli δ of the subjects and both the outdoor air temperature T_{out} and indoor operative temperature T_{op}.

$$T_{op}^{n} = 0.36 \times T_{out} + 15.4 \quad [^\circ\mathrm{C}] \tag{18}$$

2. Exploration of the relationship between the psychological coefficient K_δ and indoor operative temperature T_{op} for each of the three "seasons" (see Fig. 10 and Table 2).

The regression line in Fig. 9 illustrates the relationship between the neutral temperature T_{op}^{n} and outdoor air temperature T_{out}, along with its regression Eq. (18). This graph represents the outdoor air temperature for the summer, autumn, and winter "seasons" in Bordeaux and the corresponding neutral temperature of the subjects. The value of the gradient of Eq. (18), namely 0.36, is similar to that of the ASHRAE adaptive equation (0.31), which has the thermal acceptability limits of $+2.5^\circ C$ and $-2.2^\circ C$ [5]. However, the difference between the regressions implies that the population in Bordeaux has a higher adaptive threshold than the population in the expansive data evaluated by ASHRAE.

Therefore, this regression equation can be applied to the adaptive factor (Eq. (4)) as follows:

$$\eta = \left(\frac{K_\delta}{T_{op} - 0.36T_{out} - 15.4}\right) [-] \tag{19}$$

Combining the relationships mentioned above into Eq. (4) allows us to express the psychological adaptive factors of the subjects by solely using physical thermal parameters, such as indoor operative temperature T_{op} and outdoor air temperature T_{out}.

Therefore, by substituting equations (20), (21) and (22) into Eq. (19), the adaptive factor for all three thermal conditions can be expressed as listed in Table 3.

Moreover, it is more functional to define the closure equation of this model based on the derivatives of equations (23), (24) and (25), rather than equations (15), (16) and (17) which are composed of the average adaptive factor for each season. Therefore, the average adaptive factors in each equation were replaced with equations (23), (24) and (25). Thus, the closure equation for each season is defined in equations (26), (27) and (28).

Based on the equations derived in Tables 3 and 4, the adaptive magnitude was characterized by the value of the adaptive factor η (see Eq. (12)), and the psychological part relative to the physical stimuli (see Eq. (4)) was characterized by the psychological coefficient K_δ. These adaptive and psychological parameters can be determined when the outdoor thermal conditions (characterized by the outdoor air temperature T_{out}) and indoor thermal conditions (characterized by the indoor operative temperature T_{op}) are known.

Moreover, the equations (in Table 4) linking the psychological coefficient K_δ to indoor operative temperature T_{op} and the outdoor air temperature T_{out} (developed in the temperate oceanic climate of the Bordeaux geographical region), when combined with Eqs. (12), (13, 14, 4), and (7), formed a closed system of six equations with six unknown variables (*aPMV, PMV*, η, L, K_δ, T_{op}^{n}).

This system of six equations makes it possible to autonomously determine the physical components (L *and PMV*) and the perceived and adaptive components (T_{op}^{n} , *aPMV*, η *and* K_δ) of thermal comfort, once (i) the operative temperature T_{op} in the indoor space where the subject is, and (ii) the outdoor air temperature T_{out} where the subject was before coming into the indoor space, have been measured.

5. Conclusions and perspectives

In this study, we considered the relevant parameters influencing the thermal comfort of occupants in the geographical region of Bordeaux to comprehensively evaluate their adaptive capacities. Therefore, the air

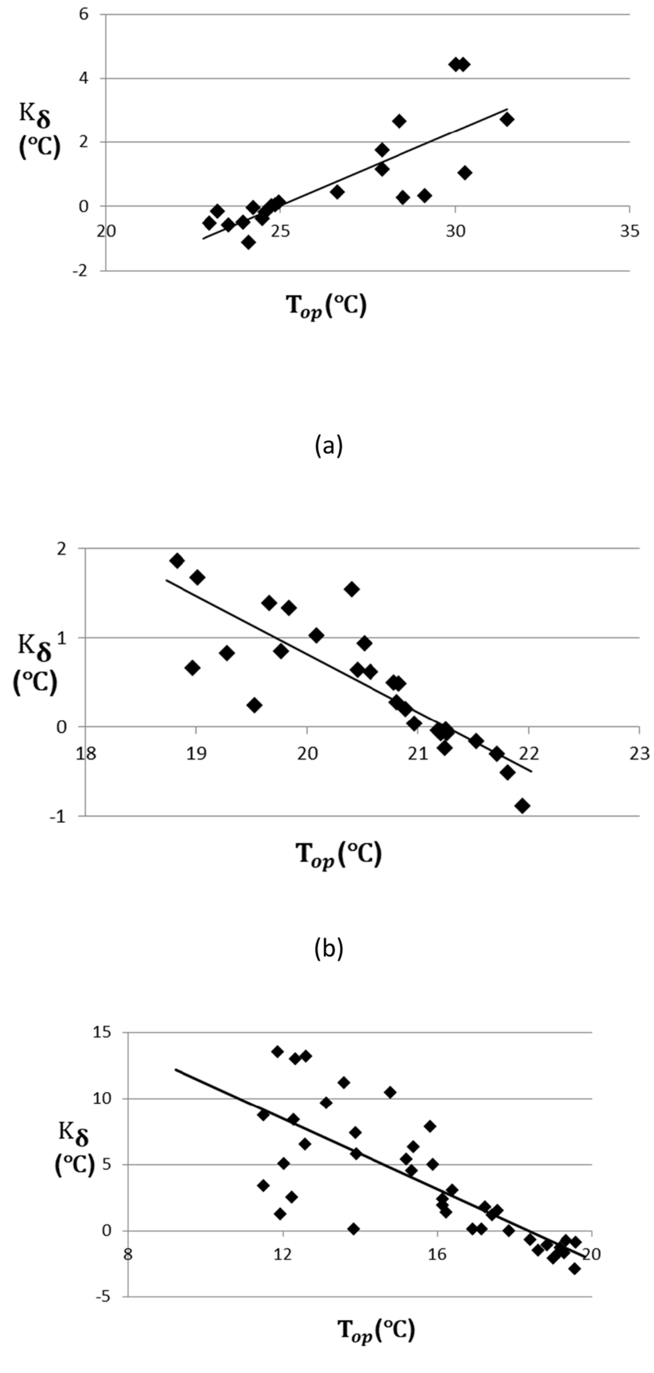

Fig. 10. Psychological coefficient K_δ versus indoor operative temperatures T_{op} during the (a) summer, (b) autumn, and (c) winter experimentations (linear regressions).

Table 2
Psychological coefficient K_δ versus indoor operative temperature T_{op}: regression equation.

Season	Regression equation	Equation number
Summer	$K_\delta = 0.5{\cdot}T_{op} - 11.6$ [°C]	(20)
Autumn	$K_\delta = -0.7{\cdot}T_{op} + 13.8$ [°C]	(21)
Winter	$K_\delta = -1.3{\cdot}T_{op} + 24.3$ [°C]	(22)

Table 3
Adaptive factor η versus indoor operative temperature T_{op} and outdoor air temperature T_{out}.

Season	closure equation	Outdoor temperature range	Equation number
Summer	$\eta = \dfrac{0.5Top - 11.6}{T_{op} - 0.36T_{out} - 15.4}$ [−]	23°C ≤ T_{out} ≤ 30°C	(23)
Autumn	$\eta = \dfrac{13.8 - 0.7T_{op}}{T_{op} - 0.36T_{out} - 15.4}$ [−]	15°C ≤ T_{out} ≤ 22°C	(24)
Winter	$\eta = \dfrac{24.3 - 1.3T_{op}}{T_{op} - 0.36T_{out} - 15.4}$ [−]	0°C ≤ T_{out} ≤ 14°C	(25)

Table 4
Closure equation: Psychological coefficient versus indoor operative temperature T_{op} and outdoor air temperature T_{out}.

Season	Closure equation	Outdoor temperature range	Numbering
Summer	$K_\delta = \dfrac{0.5Top - 11.6}{T_{op} - 0.36T_{out} - 15.4}\delta$ [°C]	23°C ≤ T_{out} ≤ 30°C	(26)
Autumn	$K_\delta = \dfrac{13.8 - 0.7T_{op}}{T_{op} - 0.36T_{out} - 15.4}\delta$ [°C]	15°C ≤ T_{out} ≤ 22°C	(27)
Winter	$K_\delta = \dfrac{24.3 - 1.3T_{op}}{T_{op} - 0.36T_{out} - 15.4}\delta$ [°C]	0°C ≤ T_{out} ≤ 14°C	(28)

and radiant parameters were systematically evaluated, which revealed the significance of the indoor operative temperature in the evaluation of the thermal stimuli and thermal adaptation of the occupants.

Three neutral temperatures and the corresponding adaptive factors for the climate seasons were determined. These adaptive factors were psychophysical quantities influenced by physical parameters in the occupants' environment and psychological parameters in the occupants' memories (particularly outdoor memory).

Furthermore, the relationship between these psychophysical quantities (adaptive factors) and some environmental thermal parameters was investigated. Therefore, it can be concluded that the main physical thermal parameters influencing the subjects' psychological adaptation are the indoor operative temperature T_{op} and outdoor air temperature T_{out}. This implies that, in addition to the influence of the indoor thermal load on the subject's body, the outdoor thermal conditions induced psychological 'resistance' or 'adaptive information' in the human cognition, which influenced the magnitude of the adaptive factor of the subjects, and consequently, their thermal perception. In the psychological realm, the recall of the outdoor thermal conditions (which formulate the seasons) is ignited by some cognitive codes in the subjects' long-term memory called "schema."

These schemas are cognitive structures that represent the organized knowledge regarding a particular stimulus as well as rules that direct its information processing: Weick [43] defined schema as an abridged, generalized, corrigible organization of experiences that served as an initial frame of reference for action and perception; it therefore served as the tools that people used to extract the maximal useful "information" from an environment using the least amount of effort [44,45]. The concept of a schema implies that information regarding stimuli has been categorized or organized in the human cognitive (long-term) memory, and the result of this organization is a discernible pattern that may be used as a basis for future judgments, decisions, inferences, or predictions [46,47]. Thus, these schema patterns influenced the magnitude of the occupants' adaptive factors in each season.

Consequently, we proposed a self-sufficient model that enabled us to determine the physical, adaptive, and perceived components (T^{n}_{op} , η, K_{δ}) of thermal comfort, when the indoor and outdoor thermal parameters (T_{op}, T_{out}) were known. Therefore, this model can be applied to thermodynamic simulations for the thermal design of buildings where the psychological and adaptive capacities of the occupants are considered. This will aid engineers and professionals in designing that correspond to the actual thermal requirements of occupants, which may eventually minimize energy waste and maximize energy savings in buildings.

Notably, the results of this model experimentation methodology have some limitations linked to the specificities of the geographical location, climate variation, culture, and lifestyle in the Bordeaux region. It will be interesting to explore other regions and continents to characterize the thermal and psychological parameters in these regions. Furthermore, the present study explored only the office environment, building type, and office population; it would be interesting to explore residential buildings and occupants because an occupant's perception may vary owing to place factors. Moreover, the differences between the perceptions of the male and female genders were assumed to be negligible, and according to Lan et al. [48], males and females exhibit similar neutral temperatures, and their thermal sensation votes (TSV) near neutral thermal conditions are similar; note that an increase in the population size of these subjects could allow for these differential evaluations [49]. In addition, in the present study, the population with an age group between 20 and 50 years is considered to be adults, which is different from the children and elderly populations; therefore, this adult population is assumed to have a similar threshold of perception, so that the differences in the perception threshold within this age group are assumed to be negligible [9]. Finally, this study was limited to only psychological adaptation, because the subjects were not allowed to execute any behavioral adaptation during the experiments; therefore, further studies can create experimental procedures that permit the behavioral patterns of the subjects to be observed.

CRediT authorship contribution statement

Tosin Omoya: Writing – original draft, Software, Methodology, Funding acquisition, Data curation, Conceptualization. **Denis Bruneau:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Thomas Recht:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Aline Barlet:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Acknowledgments

The authors would like to thank the Petroleum Technology Development Fund (PTDF), Nigeria and the Ministry of Culture, France, for providing financial support for this research.

Appendix A. Summer, autumn, and winter experimental stations

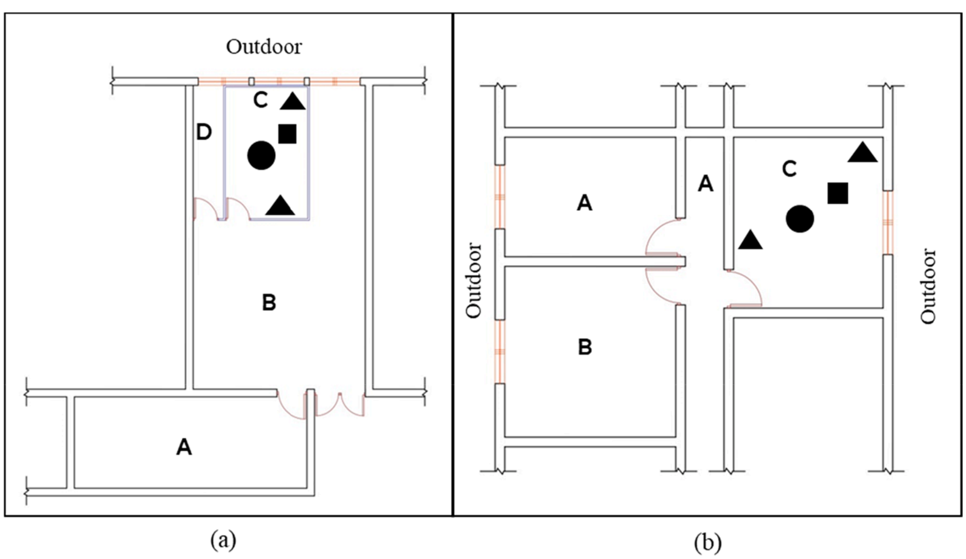

Fig. A1. Layout of spaces in the (a) summer and autumn experiment station, (b) winter experiment station. A: utility room; B: reception room; C: experiment (indoor) room; D: heating and cooling buffer zone. ▲: walls-ceiling-floor and clothing surface temperature sensors; ■: air temperature, air relative humidity, air velocity, and black globe temperature sensors; ●: position of the subject/participant.

Each of the two experiment stations shown in Fig. A1 had a utility room A (where useful materials for the experiments and subject/participant personal belongings were stored), reception room B (where the subject/participant was received), and experimental room C (where the experiments were conducted). The summer and autumn experimental stations also have a heating and cooling buffer zone D (which is used to modify the radiant heat emanating into the experiment room through the partition wall between buffer zones D and C). Fig. A1 also indicates the position of the subject and sensors in the experimental room; subjects were seated centrally within the space (see photos in Fig. A2) and the microclimate sensors (and its data logger HD32.3TC from Delta Ohm company, see Table A1) were placed 900 mm from the subjects and 700 mm above ground level to collect the measurements of the air temperature, air velocity, air relative humidity, and black globe temperature, ambient to the body of the subject. This is based on the ASHREA Standard 55 [50], which recommends that air temperature, air velocity and radiant temperature sensors be located at seated height (0.6–1.1 m) or standing height (1.1–1.7 m). Also, researches in environmental psychology and ergonomics have suggested that temperatures and airflow speed have a pronounced effect on occupants' perception of comfort when measured within 0.5 to 2 m from their location [5,36].

Furthermore, the Type-T thermocouples (PT100) were used to measure the surface temperatures of the walls, ceiling, floor, and clothing of the subjects (through a data logger GL840 from Graphtec). Therefore, the accuracy of these thermocouples was ensured through a relative correction method; this was performed by immersing the thermocouples in a thermostatic bath LAUDA RE415 (temperature stability: ±0.01°C, temperature accuracy: ±0.2°C). The thermocouple temperature values were measured and recorded simultaneously with several bath set-temperatures (10 °C, 20 °C, 30 °C, and 40 °C). The thermocouple temperature measurements were corrected using a temperature-dependent function that closely matched the thermostatic bath temperature. Based on this relative calibration method, the relative accuracy obtained for these thermocouples was ±0.02 °C, and the absolute value accuracy was the same as the thermostatic bath.

Table A1
Characteristics of HD32.3TC probes/sensors used for the experiments.

HD32.3TC of DELTA OHM						
Probes	parameter	Dimension	Temp. range	Resolution	Accuracy	Temp. drift
HP3217.2R	Air temperature	150 mm long; 14 mm diameter	−40 to 100 °C	0.1 °C	1/3 DIN	0.003 %/ °C
HP3217.2R	Relative humidity	150 mm long; 14 mm diameter	0 % to 100 %	0.1 %	±1.5 %.	0.003 %/ °C
TP3276.2	Globe thermometer	170 mm long; 50 mm diameter	−30 to 120 °C	0.1 %	1/3 DIN	0.003 %/ °C
AP3203.2	Air Speed	230 mm long; 8 mm diameter	0.02–5 m/s / 0–80 °C	0.1 %	± 0.05 %	0.06 %/ °C

(a) (b)

Fig. A2. Subjects in the (a) summer and autumn experiment room, (b) winter experiment room.

Appendix B. Content of the questionnaire filled out by the subjects

1. *How do you feel currently?*
   Options: Cold, cool, slightly cool, neutral, slightly warm, warm, and hot
2. *How would you like the room temperature to be?*
   Options: Cold, much cooler, slightly cooler as it is now slightly warmer, much warmer, and hot.
3. *According to you, what is the factor that most influences your comfort in the room where you currently are?*
   Options: The air temperature, air velocity, relative humidity, temperature of the wall, and I do not know specifically.
4. *If the room temperature is not totally comfortable, what would you like to do to be more comfortable?*
5. *Based on the temperature you feel now, what does it remind you of?* (It can be the past, place, event, something you read, or any other information).
6. *If the current temperature was the temperature of your room, how long could you stay there?*
   Options: I cannot stay there, 1 h, 2 h, 3 h, or more than 3 h
7. *If this room was your bedroom, what would you like the temperature to be like, compared to your current thermal sensation?*
   Options: Cold, much cooler, slightly cooler, as it is now, slightly warmer, much warmer, and hot.
8. *If this room was your bedroom and room temperature was not totally comfortable, what would you like to do to be more comfortable?*
9. *In general, what temperature level do you prefer to have in your room most of the time?*
   Options: Cold, cool, slightly cool, neutral, slightly warm, warm, and hot.
10. *If the current temperature was the temperature of your office, how long could you stay there?*
    Options: I cannot stay there, 1 h, 2 h, 3 h, or more than 3 h
11. *If this room was your office, what would you like the temperature to be like, compared to your current thermal sensation?*
    Options: Cold, much cooler, slightly cooler, as it is now, slightly warmer, much warmer, and hot.
12. *If this room was your office and the room temperature was not totally comfortable, what would you like to do to be more comfortable?*

13. *In general, what temperature level do you prefer to have in your office most of the time?*
    Options: Cold, cool, slightly cool, neutral, slightly warm, warm, and hot.

Data availability

Data will be made available on request.

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