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Deriving thermal sensitivity across educational stages: Evidence-based definition of Griffiths' coefficient

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ABSTRACT

Thermal sensitivity directly impacts occupants' comfort by influencing neutral temperatures and comfort models. The Griffiths method, commonly used to derive thermal sensitivity, often assumes a constant value of 0.5°C^{-1} for calculating occupants' neutral temperatures. However, it is important to note that thermal sensitivity can vary depending on factors such as building type, climatic conditions, operation mode (i.e., natural ventilation, mechanical ventilation, or mixed mode), and occupants' age. This study aims to define whether age-dependent differences in thermal sensitivity exist in schools, achieved through the formulation of specific Griffiths coefficients for each educational stage. A field study was conducted in naturally ventilated classrooms within the same climate zone, collecting 1548 subjective responses and objective measurements from students across different educational stages. The results demonstrate that the thermal sensitivity in schools is lower than the commonly assumed values, especially in primary schools (0.085°C^{-1}), and it increases with students' age. This variation is reflected in the corresponding neutral temperatures, which also increase with age. Using a constant Griffiths coefficient can lead to significant estimation errors in neutral temperature, potentially up to 1 °C, impacting both comfort and energy consumption. This study emphasizes that there are different thermal comfort expectations related to students' age. To improve the reliability of adaptive thermal comfort models and ensure accurate neutral temperatures estimations, it is essential for future research to consider the students' age when evaluating the thermal sensitivity.

1. Introduction

Thermal comfort plays a crucial role in students' health [1] and productivity [2]. Despite the significance of ensuring comfortable learning environments, specific guidelines tailored to schools are often not available [3]. Indeed, schools are often treated similarly to other building types, overlooking the diverse thermal perceptions of students across different age groups [4]. Consequently, students' thermal preferences frequently fall outside the comfort ranges provided by existing standards that were conceived for adults [5,6]. Indeed, in schools, the interplay of adaptive capacities strongly influences thermal perception [7–9]. Previous studies have highlighted that in school buildings the influential factors on thermal sensation include the educational stage (e.g. from kindergartens to universities), climate zone (e.g. based on Koppen-Geiger zones [10]), and operation mode (e.g. naturally ventilated, air-conditioned, or

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mixed-mode) [11]. Moreover, even within the same climate zone, calculated neutral temperatures can present consistent variations [12]. Significantly, the adaptive capacities and neutral temperatures show considerable variability based on the educational stage, with an increase in neutral temperature corresponding to the age of the students [13].

One of the aspects that define occupant comfort is thermal sensitivity, which describes how sensitive occupants are to temperature variations in buildings. The sensitivity quantifies the rate at which occupants perceive temperature changes (°C^{-1}), directly influencing their neutral temperature and impacting the development of thermal comfort models [14]. Generally, the thermal sensitivity is calculated by doing a regression analysis between the indoor operative temperature and the Thermal Sensation Vote (TSV) [15,16]. The TSV represents occupants' perception of thermal sensation on a 7-point scale, ranging from −3 (cold) to +3 (hot). For example, this approach has also been used to establish the adaptive relationship in the ASHRAE 55 standard [17]. However, in some cases, the use of regressions may not be advisable due to potential errors in the predictive variables or variations in the regression slope related to subjects' adaptation (e.g., changes in clothing, air movement, etc.) [18]. In such cases, when dealing with limited temperature ranges or a small number of votes, the method proposed by Griffiths [19] is recommended.

The Griffiths method, employed in the development of the adaptive thermal comfort model in the European standard EN 16798-1 [20] and in other studies [21–23], allows for the derivation of comfort temperature using the indoor temperature and TSV of occupants, along with the assumed value of thermal sensitivity (i.e., the Griffiths coefficient). Initially considering air, mean radiant, and operative temperatures, recent research predominantly prioritizes operative temperature [16,24]. This approach offers the advantage of deriving comfort temperature without requiring a consistent amount of data, as it relies on a constant thermal sensitivity of occupants.

In the past, different values of Griffiths coefficients, assumed as constants, were proposed based on field studies. Fanger suggested a value of 0.33°C^{-1} [25], Humphreys et al. proposed 0.469°C^{-1} [26], and de Dear recommended 0.489°C^{-1} [27]. The constant value of 0.50°C^{-1} has often been adopted to estimate comfort temperatures in various building types such as offices [28,29], residences [30], or educational buildings [13,22,31]. However, recent studies have demonstrated that the Griffiths coefficient is not a constant, but a variable [16,24]. Considering an extensive Australian field study database, Rupp et al. [24] found that thermal sensitivities varied across different building types (offices, schools, and residential buildings), operation modes (air conditioning, natural ventilation, and mixed mode), and climates (tropical, subtropical, temperate marine, and hot arid). They also observed that the thermal sensitivity in office buildings, collected from the ASHRAE Database II, varied depending on the building's operation mode [16]. Furthermore, Ryu et al. [18] conducted a study showing a thermal sensitivity of 0.356°C^{-1} in residential buildings. Additionally, Teli and Gauthier [32] reported a range of thermal sensitivity in schools in the UK and Sweden, ranging from 0.240°C^{-1} to 0.400°C^{-1}. These findings highlight the variability of thermal sensitivity and challenge the concept of a constant Griffiths coefficient.

In the context of schools, it is important to acknowledge that thermal perception can vary depending on the age of students, even within the same climate zone and operation mode [4,5]. Therefore, using fixed values of Griffiths' coefficient as constants to calculate neutral temperatures in schools may lead to inaccuracies, as it does not account for the different thermal sensitivities across various educational stages. Furthermore, there is limited literature available on deriving the Griffiths coefficient specifically for schools, and its variation across different educational stages under the same climate and operation conditions has yet to be analysed.

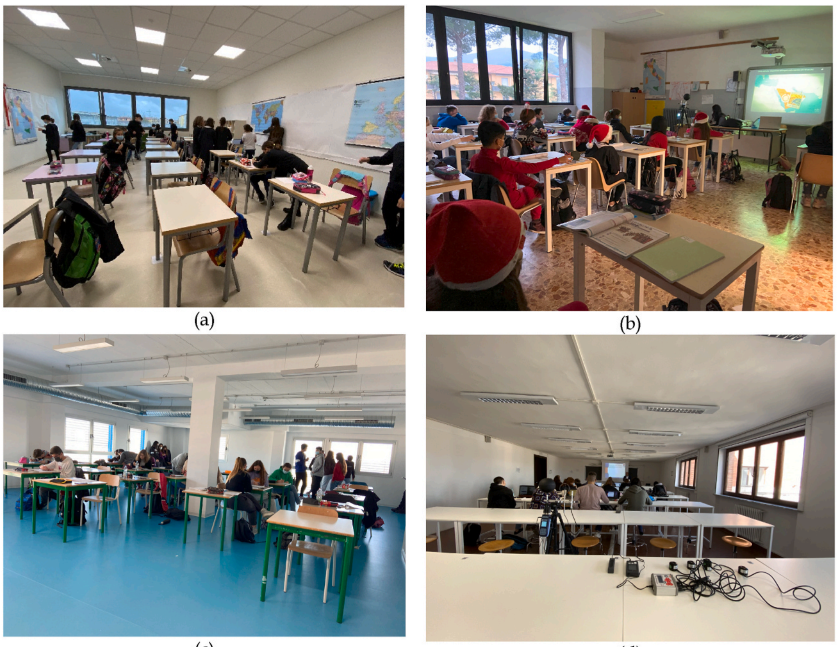
(a) (b)
(c) (d)

Fig. 1. Example of surveyed classrooms for each educational stage: primary (a), middle (b), high school (c), and university (d).

This paper seeks to assess whether there are age-dependent differences in thermal sensitivity within schools by quantifying specific Griffiths' coefficients, moving beyond a constant value. To this aim, 1548 responses from students at different educational stages, but with the same operation mode and climate, will be analysed to determine specific thermal sensitivities for each stage.

2. Methods

2.1. Selection of the case studies

Schools were selected across four different educational stages: primary (ages 6–10), middle (ages 11–13), high schools (ages 14–19), and universities (ages 19 and above). The characteristics of the selected schools are representative of the typical Italian building stock, with details provided in Appendix A. For the analysis, 24 classrooms were chosen: 5 classrooms in three primary schools, 8 classrooms in two middle schools, 2 classrooms in one high school, 9 classrooms in five university buildings. Fig. 1 displays an example of surveyed classrooms for each educational stage. This allowed a quasi-random selection of the respondents, required in thermal comfort studies [26].

Students from primary to high schools are assigned designated classrooms, while university students change classrooms approximately every 2–3 h, reflecting a typical 5-h school day. Engaged mainly in sedentary activities, students spend much of their time seated at desks and have no uniform requirements. Heating systems, doors, and windows are under the control of both teachers and students.

To assess potential variations in thermal sensitivity across educational stages, classrooms in the Pisa province were chosen, considering the impact of climate on occupant acclimatization [5,12]. The selected schools are located within a maximum distance of 20 km from each other; therefore, the climatic conditions can be considered the same (Fig. 2). Pisa is within the "Csa" group according to Köppen-Geiger [10] and categorized as "Climate D" in the Italian classification system. The region experiences a Mediterranean climate, characterized by a heating period with 1694-degree days. Fig. 3 shows the monthly variation of outdoor temperatures and relative humidity during the investigation year.

All classrooms were naturally ventilated, as occupants in centrally controlled air-conditioned buildings typically exhibit increased sensitivity to temperature fluctuations [26,33]. Classrooms with samples evenly distributed between males and females were chosen, considering that women generally may present greater sensitivity to temperature changes than men [26].

2.2. Field campaign

For the field campaign, the following steps were performed:

- ***Data Collection:*** Objective and subjective measurements were concurrently gathered through transverse surveys (one vote per student). The survey period was Winter 2021 during the heating season (from November 1st to March 15th in Pisa). A single season can be reasonably chosen for deriving thermal sensitivity due to the requirement for short measurement periods. Statistical analyses on large databases have shown no notable differences in thermal sensitivity at higher indoor temperatures [26], hence the choice of a single season doesn't affect the results. Moreover, opting for a single season reduces variations in clothing insulation and, consequently, in occupants' adaptation [26].
- ***Dataset Creation:*** A dataset was created, where each row represented data from a single interview. Specifically, rows contained subjective responses linked to the environmental parameters at the respective location and time.
- ***Batch Separation:*** Due to the typical constraints encountered in field studies, where analysing data from a single day often proves impractical for obtaining a significant amount of data, measurements were divided into shorter duration batches. Using the date

Fig. 2. Location of the buildings used as a case study. Legend: primary schools (blue), middle schools (red), high schools (yellow), and universities (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

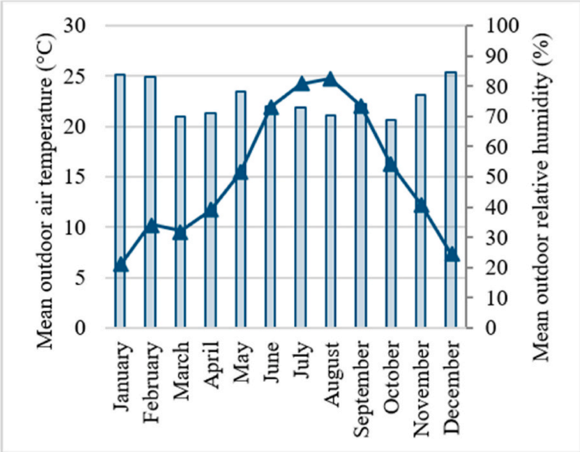

Fig. 3. Monthly variations of outdoor air temperature (triangles) and relative humidity (rectangles) in Pisa throughout the year of investigation.

associated with each record, daily batches were selected to minimize the impact of clothing changes, as suggested by Humphreys et al. [26]. This selection helps the acquisition of a quasi-random sample, a typical approach in thermal comfort studies.

Overall, 1548 occupants' responses were associated with environmental parameters.

2.2.1. Objective measurements

During the monitoring period, indoor and outdoor environmental parameters were collected. Indoor parameters, including air (T_a) and globe temperatures (T_g), relative humidity (RH), and air velocity (V_a), were measured alongside outdoor parameters: outdoor temperature (T_{out}) and relative humidity (RH_{out}). These measurements were conducted using a microclimate datalogger (Fig. 4) compliant with ISO 7726 standard [34], with specifications outlined in Table 1 [35]. Sampling occurred at 1-min intervals to capture environmental parameter fluctuations.

Microclimate dataloggers were strategically positioned in the classroom, within 1 m of each student's location and at a height of 1.1 m from the ground to evaluate sitting positions. Positioning multiple dataloggers allowed to assess potential thermal environment variations, providing an accurate evaluation of the actual conditions experienced. Dataloggers were placed at least 1.5 m away from external walls and doors. Furthermore, the instruments were shielded from direct solar radiation, regularly cleaned, and calibrated.

2.2.2. Subjective measurements

A transverse survey was carried out simultaneously with objective measurements. To facilitate acclimatization to the environment [36], surveys were conducted at least 60 min after the students entered the classroom. A transverse survey, with one feedback per day per occupant, ensures independent responses, crucial for deriving thermal sensitivity and mitigates the anchoring effect on subsequent votes, reducing potential bias in thermal sensitivity estimates [26].

The questionnaire consisted of three sections, and the questions complied with the ISO 28802 standard [37]. Further details on the questionnaire can be found in Appendix B.

In the first section, students were asked to provide information such as age, gender, height, weight, and their location within the classroom. Students' classroom locations were used to correlate their responses with specific environmental parameters monitored by a datalogger positioned within a distance less than 1 m. The second section focused on assessing each student's clothing insulation, following the guidelines outlined in ISO 9920 [38]. The third part was dedicated to evaluating the thermal environment. In particular,

a) b)

Fig. 4. Microclimate datalogger installed in university (a) ad primary school (b).

Table 1
Technical specifications of the microclimate datalogger *DeltaOhm HD 32.3* [35].

Probe	Accuracy	Resolution	Measuring range
Globe thermometer temperature *(TP3275 probe)*	1/3 DIN	0.1 °C	−10.0 ÷ 100.0 °C
Hot wire anemometer *(AP3203 probe)*	± 0.2 m/s	0.01 m/s	0.1 ÷ 5 m/s
Relative humidity and air temperature *(HP3217R probe)*	± 1.5 ÷ 2 % RH	0.1 % RH	0 ÷ 100% RH
	1/3 DIN	0.1 °C	−40.0 ÷ 100.0 °C

the Thermal Sensation Vote (TSV) was selected for the analysis of the thermal sensitivity of the students. The TSV expresses the thermal sensation of the occupants on a 7 points scale (from [−3] "cold" to [+3] "hot").

In accordance with previous studies [13,39], the questionnaire for primary school students was provided with pictures, as shown in Appendix B.

2.3. Data processing

Firstly, the mean radiant temperature (MRT) was calculated following the ISO 7726 standard [34] as follows:

$$MRT = \left[\left(T_g + 273\right)^4 + \frac{0.25 \bullet 10^8}{\varepsilon_g} \bullet \left(\frac{|T_g - T_a|}{D}\right)^{\frac{1}{4}} \bullet \left(T_g - T_a\right)\right]^{1/4} - 273 \tag{1}$$

where T_g is the globe temperature, ε_g is the globe emissivity, T_a is the indoor air temperature, and D is the globe diameter.

Secondly, the operative temperature (T_{op}) was calculated based on the air and mean radiant temperatures, as outlined in the ISO 7726 standard [34].

Thirdly, the running mean outdoor temperature (T_{rm}) was determined by calculating the weighted mean of the outdoor temperatures from the preceding seven days, following the EN 16798-1 standard [20]:

$$T_{rm} = (1 - \alpha) \bullet \left(T_{od-1} + \alpha \bullet T_{od-2} + \alpha^2 \bullet T_{od-3} + \alpha^3 \bullet T_{od-4} + \alpha^4 \bullet T_{od-5} + \alpha^5 \bullet T_{od-5} + \alpha^6 \bullet T_{od-7}\right) \tag{2}$$

where α was 0.8 according to Ref. [20], T_{od-1}, T_{od-2}, etc., represent the daily mean outdoor temperature for the day before the measurement and the previous days.

The clothing insulation was determined based on the information gathered from the students' questionnaires, which included details about the garments they were wearing. The thermal insulation for each garment was determined from the ISO 9920 standard [38]. The total clothing insulation was calculated according to the ISO 7730 standard [36]:

$$I_{cl} = 0.83 \bullet \sum_i I_{cl,i} + 0.161 \tag{3}$$

where Icl is the total clothing insulation (clo), and Icl,i is the clothing insulation of the single garment (clo).

2.4. Determination of thermal sensitivity

To estimate the thermal sensitivity, the Griffiths method was used [19]. The method is based on the day survey [15], which involves assessing the occupant's thermal sensitivity by comparing indoor temperature measurements with thermal sensation votes over a single day in a building. This approach was used as, during a one-day survey, there are limited or no opportunities for adaptive actions.

Firstly, the difference between the indoor operative temperature (T_{op}) and the mean operative temperature for each day-survey (mT_{op}) was calculated as follows:

$$dT_{op} = T_{op} - mT_{op} \tag{4}$$

Secondly, the difference between the TSV of each occupant and the mean Thermal Sensation Vote (mTSV) for each day survey was calculated:

$$dTSV = TSV - mTSV \tag{5}$$

Thirdly, a linear regression between the dT_{op} and the dTSV was fitted for all day-surveys to derive the regression coefficient b.

Finally, the resulting regression coefficient was adjusted for possible errors in the predictor variable, as suggested by Ref. [15], as follows:

$$b_{adj} = \frac{b \bullet \sigma^2_{dTop}}{\sigma^2_{dTop} - \sigma^2_{err}} \tag{6}$$

where:

b_{adj} is the adjusted regression coefficient, which represents occupants' sensitivity (Griffiths' coefficient) (°C^{-1})
b is the regression coefficient
σ^2_{dTop} is the variance of dT_{op} (°C^2)

σ^2_{err} is the error variance dT_{op} (°C^2), which was assumed equal to 0.158 °C^2 [26]

The error variance σ^2_{err} addresses limitations of measurement instruments, accounting for both accuracy and challenges in probe placement. With the impracticality of placing instruments at each student's position, the chosen 0.158°C^2 error variance assesses high-quality thermometers within 1 m of the desired location [33], aligning with the objective measurement specifications carried out. The adjusted regression coefficient represents the thermal sensitivity to indoor temperature changes. For example, a b_{adj} equal to 0.5°C^{-1} [26] implies that a temperature change equal to 2 °C results in one unit change on the 7-points TSV.

Since evidence suggests that the thermal sensitivity is a function of the students' age [4,13], different thermal sensitivities were calculated for each educational stage.

2.5. Determination of neutral temperatures

To derive neutral temperatures, the Griffiths method was used. Following Humphreys et al.'s [26] methodology for deriving the Griffiths coefficient, the data were not binned. From the adjusted regression coefficient, it is possible to calculate the neutral temperature for each response (T_N) using the Griffiths method as follows:

$$T_N = T_{op} - \frac{TSV}{b_{adj}} \tag{7}$$

Based on the outcomes of the analysis performed in Section 2.4, the different b_{adj} were used for assessing neutral temperatures at various educational stages.

The correlation between indoor and outdoor environments was examined by plotting the neutral temperatures against the running mean outdoor temperatures. This allowed the comparison between the adaptive capacities of the students at different educational stages and the adaptive relationship defined by EN 19798-1 [20]:

$$T_N = 0.33 \bullet T_{rm} + 18.8 \tag{8}$$

All data analysis and calculations were performed with Python scripts developed by the authors.

3. Results

3.1. Analysis of the monitored data

The analysis of the data was performed separately for each educational stage. Table 2 presents the mean values and standard deviations of environmental parameters observed during field studies across various educational stages. Fig. 5 shows the distribution of operative and running mean outdoor temperatures across various educational stages.

Both indoor and outdoor conditions appear uniformly distributed across the stages, with T_{rm} ranging from 4 to 20 °C and T_{op} ranging from 14 to 27 °C. The mean relative humidity fell within the approximately 50% range, with variations of less than 5% among stages. Air velocity remained nearly zero in all instances, consistently below 0.1 m/s. Indoor temperatures showed minimal differences, generally less than 0.5 °C, except for university classrooms, which exhibit slightly increased temperatures. Considering the external conditions, both the temperatures (both T_{out} and T_{rm}) remained similar across all educational stages, ranging from 10.9 °C to 14.2 °C, and the same applies to the outdoor relative humidity, with average values ranging between 64% and 70%.

Analysing the subjective measurements (Table 3), a balanced distribution of the sample by gender is evident, comprising 766 males and 689 females, except for high schools, where classrooms were mainly composed by females. Student ages spanned from 9 to 23 years. The mean clothing insulation remained consistent across all educational stages. Regarding Thermal Sensation Votes (TSV), these predominantly hovered around thermal neutrality, slightly leaning towards sensations of cold, aligning with the winter season.

3.2. Deriving thermal sensitivity through Griffiths' coefficient

The thermal sensitivity was derived from the adjusted Griffiths' coefficient at each educational stage using the operative temperature (Table 4). The calculation was performed under the assumption that during a day survey, people have limited possibilities to adapt to temperature fluctuations inside a building [15].

The lowest thermal sensitivity was found for primary schools (b_{adj} = 0.085), followed by high (b_{adj} = 0.216), middle (b_{adj} = 0.314) schools, and universities (b_{adj} = 0.320) and the differences among them were statistically significant. This indicates that thermal sensitivity varies according to students' age and that primary school children are much less sensitive to temperature changes compared to older students, especially in universities.

Table 2
Descriptive statistics (Mean ± Standard Deviation) for the objective measurements.

	Outdoor parameters			Indoor parameters					
	T_{out} (°C)	T_{rm} (°C)	RH_{out} (%)	T_a (°C)	T_g (°C)	RH (%)	V_a (m/s)	MRT (°C)	T_{op} (°C)
Primary school	13.1 ± 2.4	11.6 ± 3.0	65 ± 7	21.9 ± 2.8	22.2 ± 3.1	48 ± 6	0.00 ± 0.00	22.2 ± 3.6	22.0 ± 3.1
Middle school	14.2 ± 3.1	10.9 ± 4.1	64 ± 6	21.8 ± 1.4	22.0 ± 1.6	49 ± 9	0.01 ± 0.02	22.0 ± 1.4	22.1 ± 1.8
High school	13.1 ± 3.8	12.4 ± 3.6	69 ± 10	21.6 ± 1.8	21.4 ± 1.5	52 ± 13	0.00 ± 0.00	21.4 ± 1.8	21.5 ± 1.8
University	13.8 ± 2.8	13.1 ± 3.6	70 ± 6	23.1 ± 2.0	23.2 ± 2.2	52 ± 12	0.03 ± 0.05	23.2 ± 2.0	23.2 ± 2.0

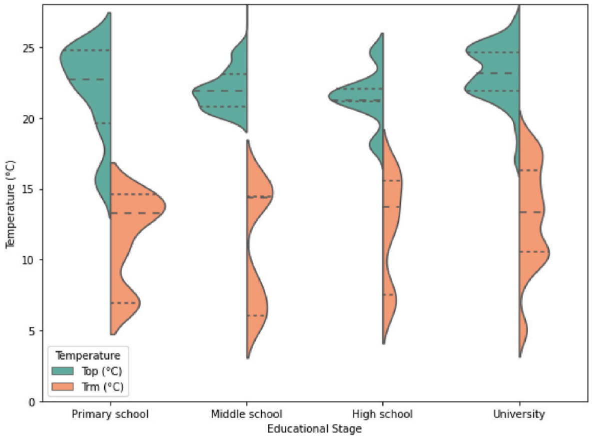

Fig. 5. Violin plot of indoor operative (green) and running mean outdoor (orange) temperatures at different educational stages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Descriptive statistics (Mean ± Standard Deviation) for the subjective measurements. N represents the number of votes (students).

	Age (years)	Gender		I_{cl} (clo)	TSV
		Males	Females		
Primary school (N=149)	9 ± 1	72	77	0.9 ± 0.1	−0.34 ± 1.22
Middle school (N=342)	12 ± 2	195	147	0.8 ± 0.1	0.07 ± 1.19
High school (N=149)	16 ± 7	35	114	0.8 ± 0.1	−0.36 ± 1.05
University (N=815)	23 ± 5	464	351	0.9 ± 0.1	−0.06 ± 0.94

Table 4
Thermal sensitivity (adjusted Griffiths' coefficient) estimated for primary, middle, high schools, and universities.

Reference	dT_{op}		Regression coefficient (b)		b_{adj} (°C^{-1})
	σ^2_{dTop} (°C^2)	σ^2_{err} (°C^2)	Value	p-value	
Primary school	8.687	0.158	0.083	< 0.05	0.085
Middle school	2.566	0.158	0.183	< 0.05	0.314
High school	3.207	0.158	0.205	< 0.05	0.216
University	0.362	0.158	0.180	< 0.05	0.320

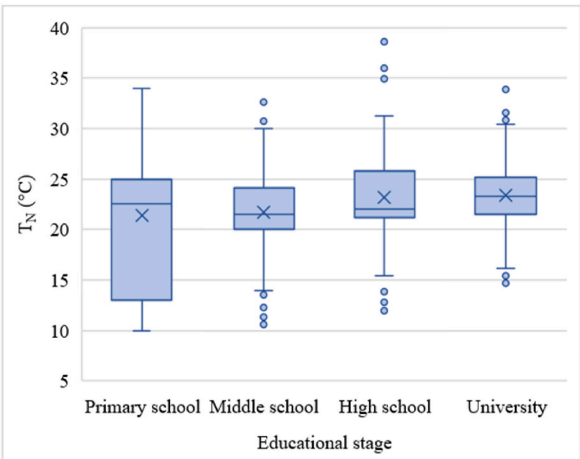

Fig. 6. Boxplot of neutral temperatures estimated using the different Griffiths coefficients for each educational stage.

3.3. Calculation of the neutral temperatures

The neutral temperatures for each respondent were calculated using the respective Griffiths coefficients derived for each educational stage. Fig. 6 shows the distribution of neutral temperatures at each educational stage. Neutral temperatures were spread across a broader range for primary schools, which diminished for higher-level schools. The mean neutral temperature, calculated for each educational stage, tended to increase with the students' age.

The presence of low values in the Griffiths coefficient amplified the extremities of TSV records resulting, in some cases, in the generation of implausible neutral room temperature values, as also highlighted in Ref. [16]. Hence, in primary schools, there are instances where very unlikely comfort temperatures below 15 °C are predicted. However, this issue diminished with higher Griffiths constants.

Using the Griffiths method, neutral temperatures can be calculated for both individuals and groups [26]. Neutral temperatures for each educational stage can be derived from the responses of all students, as shown in Table 5. It resulted that the neutral temperature increases with the educational stage, starting from 20.8 °C for primary school, 21.7 °C for middle schools, 23.1 °C for high schools, and 23.4 °C for universities. The difference in mean TSV between middle and high schools (0.07 and −0.36 respectively) leads to higher neutral temperatures for high schools, despite their lower thermal sensitivity.

By calculating the neutral temperatures through a weighted regression analysis, the following T_N were obtained: 20.6, 21.7, 23.1, and 23.6 °C, respectively for primary, middle, high schools, and universities. Therefore, there are no significant differences in the neutral temperatures depending on the method used.

The difference among the neutral temperatures at different educational stages was statistically significant (p-value<0.01) and practically relevant. Regarding T_N, negligible differences were observed in practice only between high schools and universities, with a variation of less than 0.5 °C. However, when comparing other scenarios, the difference in neutral temperature reached up to 2.6 °C.

Additionally, neutral temperatures were calculated using the Griffiths coefficients proposed by Fanger [25], and Humphreys et al. and de Dear [26,27] (Table 5). Using Griffiths coefficients from the literature, neutral temperatures still increase with the educational stage, indicating age-related variations in thermal perception. The differences between neutral temperatures calculated using Griffiths' coefficients from this study and those derived from coefficients found in the literature were statistically significant (p-value<0.01), except for middle and primary schools, where the standard deviation was notably high.

From a practical perspective, T_N values calculated with Fanger's Griffiths constant match those of middle schools and universities. However, there was a consistent overestimation of approximately 1 °C when using literature-based Griffiths coefficients for primary schools. Moreover, neutral temperatures for high schools are underestimated by approximately 0.5 °C–0.8 °C.

3.4. Relation between neutral temperature and running mean outdoor temperature

Fig. 7 reports the neutral temperatures in the adaptive graph given by EN 16798-1 [20], considering the lower limit of T_{rm} at 10 °C by, as suggested the standard. The standard includes the division into three comfort categories, expressed as [20]:

$$T_N = 0.33 \bullet T_{rm} + 18.8 + 2 \quad T_N = 0.33 \bullet T_{rm} + 18.8 - 3 \quad \text{Category I} \tag{9}$$

$$T_N = 0.33 \bullet T_{rm} + 18.8 + 3 \quad T_N = 0.33 \bullet T_{rm} + 18.8 - 4 \quad \text{Category II} \tag{10}$$

$$T_N = 0.33 \bullet T_{rm} + 18.8 + 4 \quad T_N = 0.33 \bullet T_{rm} + 18.8 - 5 \quad \text{Category III} \tag{11}$$

In primary schools, neutral temperatures often fell outside the defined comfort ranges, with children feeling comfortable at lower temperatures. In middle schools, neutral temperatures tended to be towards the lower end of the comfort ranges. In high schools and universities, neutral temperatures generally remained within the defined comfort ranges.

At all educational stages, neutral temperatures tended to be evenly distributed in the adaptive comfort bands, both at the upper and lower end. Overall, students often felt thermally neutral within a broader range of operative temperatures than those predicted by the standard, as neutral temperatures were observed not only outside the most restrictive comfort range (Category I) but sometimes even beyond Category III. However, T_N lower than 15 °C or higher than 30 °C related to low Griffiths coefficients may be implausible.

4. Discussion

4.1. Variations in the Griffiths coefficient as a function of the educational stage

This study aimed to analyse thermal sensitivity variations across different educational stages, considering age-related factors. The Griffiths' method was used to mitigate the issue of linear regression yielding inaccurate values as TSV moves away from the neutrality [40]. The investigation included randomly selected naturally ventilated classrooms situated within the same climatic zone. Clothing

Table 5
Neutral temperatures and their standard deviation calculated according to different values of Griffiths' coefficients for primary, middle, high schools, and university.

Reference	Griffiths' coefficient	Primary school	Middle school	High school	University
T_N (°C)	Variable	20.8 ± 7.6	21.7 ± 3.6	23.1 ± 4.5	23.4 ± 2.9
Fanger [25]	0.33	21.7 ± 4.0	21.7 ± 3.4	22.6 ± 3.0	23.4 ± 2.8
Humphreys et al. and de Dear [26]	0.50	21.8 ± 3.4	21.9 ± 2.3	22.3 ± 2.2	23.3 ± 2.2

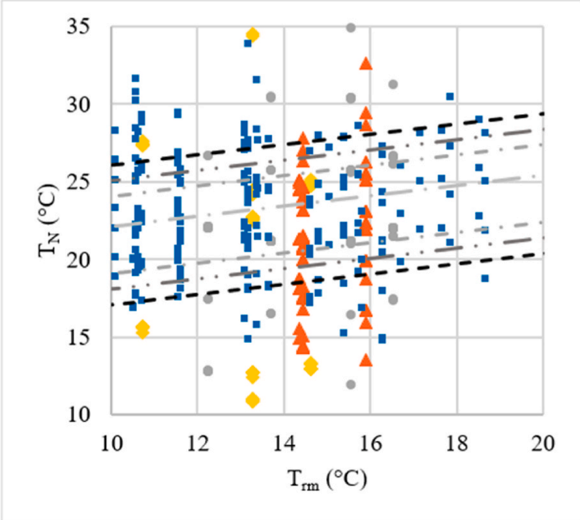

Fig. 7. Comparison between the neutral temperatures obtained using the Griffiths equation and the adaptive relationship obtained from EN 16798-1 [20] for primary (yellow diamonds), middle (red triangles), high schools (grey circles), and universities (blue squares). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

insulation, uniform during Winter 2021, minimized adaptation due to clothing changes and helped derive thermal sensitivity (Table 3). Despite variations in indoor parameters, the mean indoor operative temperature remained within 21.5–23.2 °C, with no significant impact on thermal sensitivity [26]. Gender distribution was equal to account for potential sex-based differences, notably in high schools where females were more numerous. In high schools, neutral temperatures were evaluated by gender, with no statistically significant differences compared to inter-individual differences.

Thermal sensitivity increased with educational stage, with primary schools showing the lowest sensitivity ($b_{adj} = 0.085$), consistent with prior research indicating children's reduced sensitivity to temperature changes [5,11]. The regression slope for primary school students is notably low, suggesting a temperature shift of up to 12 °C to influence one TSV, aligning with previous findings [29]. Early studies demonstrate the reduced sensitivity of young scholars, with research on 7–9-year-old children revealing lower sensitivity compared to adults [41]. Recent studies further support these findings, indicating a lower comfort equation slope for children compared to adults [42], and consistent adaptability to indoor temperature fluctuations [43]. Moreover, temperature shifts of up to 10 °C have been observed in naturally ventilated primary schools [44]. However, reliance on Griffiths' coefficient for deriving neutral temperatures may lead to unreliable outcomes [24].

Conversely, sensitivity is similar across higher educational stages, comparable to values obtained by Fanger (0.33°C^{-1}) [25] and observed in Chinese university dormitory buildings [45]. However, it is significantly lower than values from the SCATs project (0.469°C^{-1}) [46] and ASHRAE RP884 databases (0.489°C^{-1}) [27]. In high schools, the b_{adj} coefficient slightly decreased ($b_{adj} = 0.216$), resulting in lower thermal sensitivity. The lower b_{adj} of high schools compared to middle schools may be influenced by various factors. Indeed, the classification into primary (6–10 years), middle (11–13 years), high schools (14–19 years), and universities (19+ years) was based on the Italian school system. During the transition from middle to high school, individuals undergo significant physiological, social, psychological, and behavioural changes, encompassing the three phases of adolescence (early: 11–13 years, middle: 14–17 years, and late: 17–19 years) [47]. While childhood and adulthood are clearly defined age ranges, this period involves substantial developmental changes, potentially affecting thermal sensitivity. To address this complexity, b_{adj} was recalculated for the entire adolescent phase by combining data from middle and high schools. This yielded a thermal sensitivity value of 0.283°C^{-1}, representing an intermediate value between childhood and adulthood.

The variation of Griffiths' coefficient across educational stages underscores the influence of factors like building types, climates, operation modes, and age on thermal sensitivity, emphasizing the need to not treat it as a constant. In contrast, Rupp et al. [24] reported higher Griffiths coefficients (0.431°C^{-1} for primary schools and 0.126°C^{-1} for high schools), indicating greater thermal sensitivity among younger students. Further research is needed to understand parameters influencing thermal sensitivity in schools, including age-related differences, unaddressed in existing standards.

4.2. Influence of Griffiths' coefficient in determining the neutral temperatures

Griffiths' method is valuable for deriving neutral temperatures, especially when data limitations or minimal environmental variations prevent regression methods [33]. Despite historically treating Griffiths' coefficient as a constant [16], thermal sensitivity has evolved, with regression gradients ranging from 0.24°C^{-1} to 0.40°C^{-1} [48]. However, these varying sensitivities haven't consistently led to notably different neutral temperatures. For example, in Qatar offices [49], different b_{adj} values resulted in negligible T_N differences. Similarly, Japanese offices [50] showed comparable mean comfort temperatures with different coefficients. Recent studies [16,24] question the widespread adoption of Griffiths' constant (0.50°C^{-1}) in thermal comfort literature, given its variability across building types and operation modes, which was also found in the present study as a function of occupants' age.

In the present study, the different thermal sensitivity also results in diverse predictions of neutral temperatures. The trend of increasing T_N with educational stage was confirmed in this study: 20.8 °C for primary schools, 21.7 °C for middle schools, 23.1 °C for high schools, and 23.4 °C for universities.

Naturally ventilated primary schools typically provide lower comfort temperatures for children compared to adults and those predicted by PMV and adaptive models [51,52]. The scenario in secondary schools varies, with some studies showing similar neutral temperatures to primary schools [53], while others report consistently higher temperatures [13]. This highlights the complexities in deriving neutral temperatures during adolescence [47] and results in variable comfort ranges [4,5]. Universities have been also extensively studied. In some cases, neutral temperatures were derived using the regression method [54,55], revealing variations across seasons [54] and climates [55] within the same country. Employing Griffiths' method also yields wide ranges of comfort temperatures. Using three standard Griffiths coefficients (0.25, 0.33, and 0.50) produced no difference in neutral temperatures, with a range of 21.6–23.8 °C [56]. Similarly, using these coefficients for regression-estimated temperatures yielded comparable results, but with wider neutral temperature ranges (21.8–29.6 °C) [57].

The broad ranges of neutral temperatures underscore students' high adaptability to various climates, seasons, cultural factors, and operation modes throughout education. Identifying a universal neutral temperature is challenging, suggesting the concept of "comfort clouds" rather than precise point conditions [58,59]. However, one consistent finding across studies is that neutral temperatures tend to increase with students' age [4,5].

However, even with constant Griffiths values [25–27], the trend of increasing neutral temperatures with educational stage remained consistent. This confirms younger students' preference for lower temperatures, consistent with their reduced sensitivity to temperature changes and higher sensitivity to higher temperatures compared to adults [4,13]. Relying on constant Griffiths values can significantly impact estimated neutral temperatures, potentially leading to overestimations of up to 1 °C, with implications for thermal comfort and energy consumption. Analysing students' thermal sensitivity separately across educational stages is crucial, emphasizing the need for standards to account for these disparities to enhance comfort conditions and reduce energy consumption effectively.

4.3. Limitations

This study reveals thermal sensitivity differences across educational stages and their implications for estimated neutral temperatures in schools. However, further research is needed to address the study's limitations.

First, to evaluate the potential impact of sample size on neutral temperatures, smaller samples were randomly chosen for larger categories (i.e. university). Despite the reduction in sample size, the difference between neutral temperatures among different educational stages remained statistically significant. The results seem promising, but future studies should validate these findings through larger sample sizes.

Secondly, the monitoring campaign focused on naturally ventilated schools during winter within the same climate zone. While research suggests that thermal sensitivity is independent of type of climate control, occupants' exposure temperatures, and clothing insulation, caution should be exercised when applying Griffiths' coefficients to derive neutral temperatures. Future studies are necessary to validate this trend in diverse settings and assess possible gender differences in thermal perception in schools.

Lastly, it should be noted that low Griffiths coefficients, such as those observed for primary schools, may lead to unrealistic neutral temperatures for extreme TSV. While these coefficients are useful for understanding the varying thermal sensitivity among different educational stages and deriving neutral temperatures for a group of individuals it is necessary to carefully assess the validity of the results.

5. Conclusions

This paper aimed to address the diverse thermal perception at different educational stages by deriving distinct thermal sensitivities using the Griffiths coefficient for students of various ages. Although the Griffiths coefficient is commonly employed to derive neutral temperatures in environments, assuming it as a constant implies a uniform thermal sensitivity across all school stages.

Through a comprehensive field study including objective and subjective measurements in schools of different educational stages, it was possible to define the age-related thermal sensitivity differences, driving age-specific thermal sensitivities for students. In particular, the findings highlight that:

- Primary school students showed the lowest thermal sensitivity (b_{adj} = 0.085°C^{-1}), while the highest thermal sensitivity was observed among university students (b_{adj} = 0.320°C^{-1}), confirming that adults are much more sensitive to temperature changes compared to children.
- The thermal sensitivity found for university students (0.320°C^{-1}) is similar to that proposed by Fanger (0.33°C^{-1}).
- The Griffiths coefficient should be carefully used to derive the neutral temperature for each individual, as it can result in implausible values for very low thermal sensitivities.
- The derived coefficients indicate an increase in neutral temperatures with the educational stage. Specifically, the neutral temperatures for primary, middle, high schools and universities resulted 20.8 °C, 21.7 °C, 23.1 °C, and 23.4 °C, respectively.
- Considering the adaptive relationship, students often experienced thermal neutrality within a broader temperature range compared to the comfort range defined by standards.

Future studies should further explore the differences in thermal sensitivity among different educational stages to ensure healthy environments, also considering factors like climate, operation modes, seasons, etc.

CRediT authorship contribution statement

Giulia Lamberti: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giulia Torriani:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Fabio Fantozzi:** Writing – review & editing, Supervision, Conceptualization, Methodology. **Francesco Babich:** Writing – review & editing, Supervision, Methodology, 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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2024.109081.

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