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Thermal comfort and indoor air quality in schools: analysis of students' perception and impact of perceived control on satisfaction

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INTRODUCTION

OVERVIEW

- Addressing **thermal comfort** and **indoor air quality (IAQ)** in school buildings is particularly challenging.
- Current thermal comfort standards [1, 2] , determine the design values for indoor operative temperatures based on the **Predicted Mean Vote (PMV) – Predicted Percentage of Dissatisfied (PPD)** model.
- This model is based on the heat exchange between the human body and the environment and does not consider the hypothesis that people can **adapt to their surroundings for achieving comfort**.
- Furthermore, **different perceptions at diverse educational stages** are not considered. At different educational stages, students exhibit different **metabolic rates**, perform **different activities**, and have **different adaptive capacities**.
- Guaranteeing **perceived control** in school buildings seems challenging but relevant as it is a form of **psychological adaptation**: occupants with more means of control think they have more chances to adapt to their surroundings and therefore are less likely to complain of discomfort than those with a lower level of perceived control.

[1] ISO 7730, "Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria", 2006.
[2] ASHRAE, "Standard 55 - Thermal environmental conditions for human occupancy", 2020.

INTRODUCTION

LITERATURE REVIEW

Database: Scopus

TITLE-ABS-KEY (("thermal comfort" OR "indoor air quality") AND ("school*" OR "educational building*" OR "class" OR "classroom*"))

RESEARCH GAP

- Investigation of **all the educational stages** simultaneously and in the **same area**;

→ *This strongly limits the possibility to distinguish between the effects of the educational stage and climate or cultural habits*

- Combined effect of **IAQ and thermal comfort** in schools;
- Impact of **perceived control** on indoor comfort in schools.

OBJECTIVE OF THE WORK

1 Developing a better understanding of students' perception of the **thermal environment** at different **educational stages**.

1.1 Evaluating whether the predictive performance of the **PMV-PPD model** varies with the educational stage.

2 Investigating any possible correlation between the **perceived control** and the students' **thermal comfort** and **perception of IAQ**.

METHODS

SCHOOL BUILDINGS

Located within a 14 km distance from Pisa (Italy)

	School	Year	Heating system	Ventilation system	Classes	N° respondents
Primary schools	P1	1970	Central radiator system	Natural ventilation	ID1	111
	P2	2018	Split air system	Mechanical ventilation	ID2, ID3	224
	P3	1970	Central radiator system	Natural ventilation	ID4, ID5	136
Middle schools	M1	1970	Central radiator system	Natural ventilation	ID6, ID7, ID8, ID9	209
	M2	2020	Central radiator system	Mechanical ventilation	ID10, ID11, ID12, ID13	221
High schools	H1	2018	Central radiator system	Mixed Mode	ID14, ID15	157
University	U1	1936	Central radiator system	Natural ventilation	ID16, ID17, ID18	169
	U2	1970	Central radiator system	Natural ventilation	ID19, ID20	168
	U3	1970	Central radiator system	Natural ventilation	ID21	30
	U4	2015	Central air system	Natural ventilation	ID22	30
	U5	2015	Central air system	Natural ventilation	ID23	93

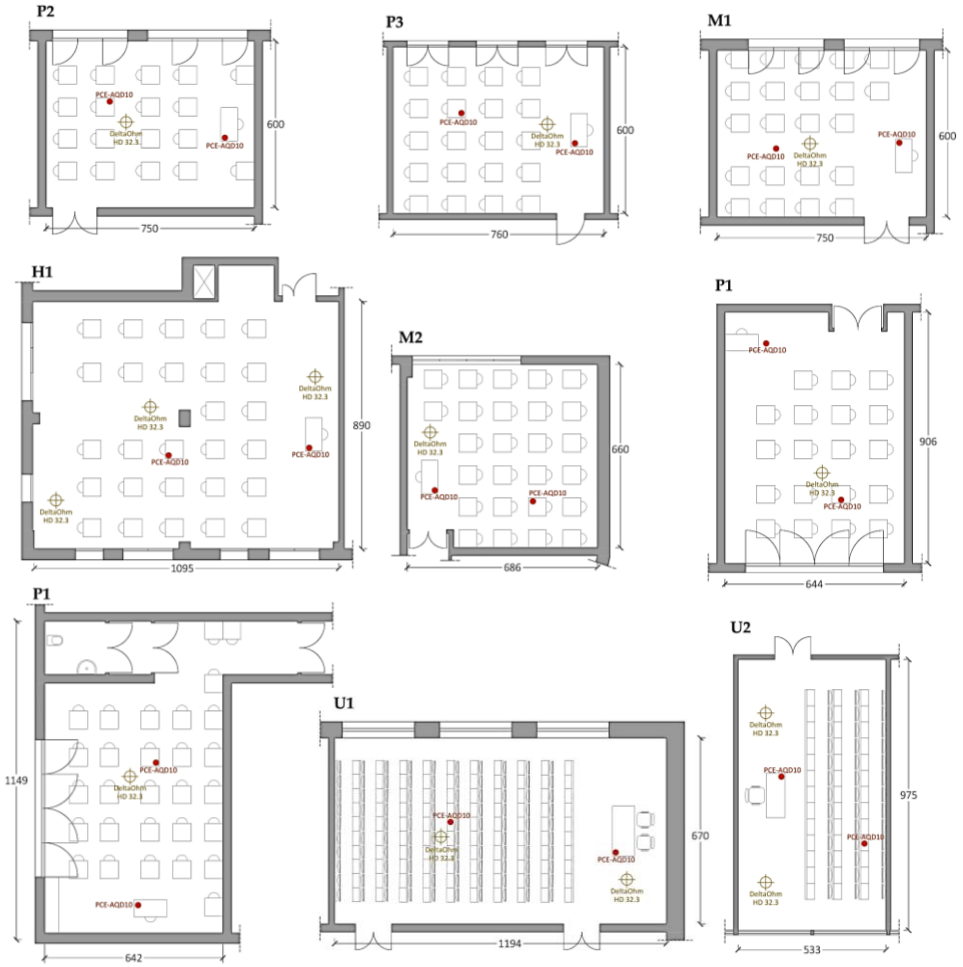




METHODS

ENVIRONMENTAL MEASUREMENTS

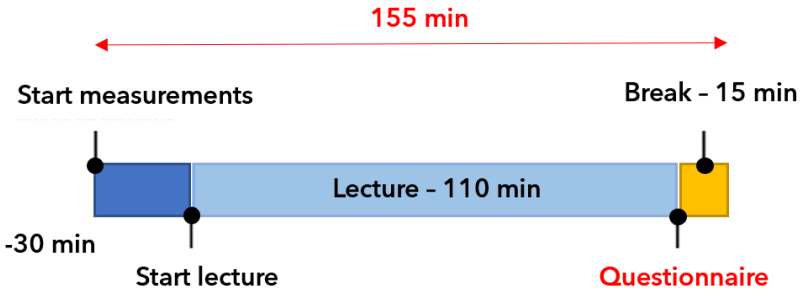
Physical quantity	Instrument	Range	Accuracy
Indoor air temperature	HP3217R temperature and humidity probe	−40 to 100 °C	± 1/3 DIN
Outdoor air temperature	PCE-HT110 probe	0 to 50 °C	± 0.8 °C
Globe-thermometer temperature	Globe-thermometer TP3275	−30 to 120 °C	± 2 °C
Relative humidity	HP3217R temperature and humidity probe	0%-100%	± 1.5%
	PCE-HT110 probe	10%-90%	± 1%
Air velocity	AP3203 hot-wire anemometer	0.02 to 5 m/s	± (0.05 + 5% of the measure) m/s



METHODS

QUESTIONNAIRE — **1548 responses** collected.

- The questions complied with the ASHRAE 55 and ISO 28802 standards [2,3].
- **First section**: age, gender, height, weight, and location occupied in the classroom.
- **Second section**: clothing insulation based on ISO 9920 [4].
- **Third section**: thermal environment on a 7-point scale - Thermal sensation vote (TSV), Thermal preference vote (TPV), Thermal acceptability vote (TAV).
- **Fourth section**: perceived control (PC) on a 7-point scale - *"How do you evaluate your control of comfort parameters at this moment?"*
- **Fifth section**: air quality perception on a 7-point scale.



[2] ASHRAE, "Standard 55 - Thermal environmental conditions for human occupancy", 2020.
[3] ISO 28802, "Ergonomics of the physical environment - Assessment of environments by means of an environment survey involving physical measurements of the environment and subjective responses of people", 2012.
[4] ISO 9920, "Ergonomics of the thermal environment. Estimation of thermal insulation and water vapour resistance of a clothing ensemble", 2009.

METHODS

DATA PROCESSING

- The **indoor operative temperature** (T_{op}) and **mean radiant temperature** (MRT) were calculated according to the ISO 7726 standard [5].
- **Clothing insulation** (Icl) and **PMV-PPD indices** were calculated according to the ISO 7730 standard [1].
- The students' **metabolic rate** (Met) was initially estimated to be 1.2 met, based on the ISO 8996 standard [6]. Subsequently, the value was corrected by considering the different body surfaces of each student.
- The **running mean outdoor temperature** (T_{rm}) was calculated from the seven days before the measurements based on EN 16798-1 [7].
- The values of the **environmental parameters** were **combined** with the **subjective responses**.
- The questionnaire sample was divided into **two groups based on the perceived control vote**: students with perceived control (PC>0) and students without perceived control (PC<0).

[1] ISO 7730, "Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria", 2006
[5] ISO 7726, "Ergonomics of the thermal environment - Instrument for measuring physical quantities", 2001.
[6] ISO 8996, "Ergonomics of the thermal environment - Determination of metabolic rate", 2005.
[7] EN 16798-1, "Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics", 2019.

RESULTS AND DISCUSSION

EVIDENCE OF ADAPTATION – CLOTHING INSULATION

1. Calculation of the clothing insulation I_{cl} (clo) [1]

$$I_{cl} = 0.835 \cdot \Sigma_i I_{cl,i} + 0.161$$

2. Binning method (T_{op} = 0.5 °C)

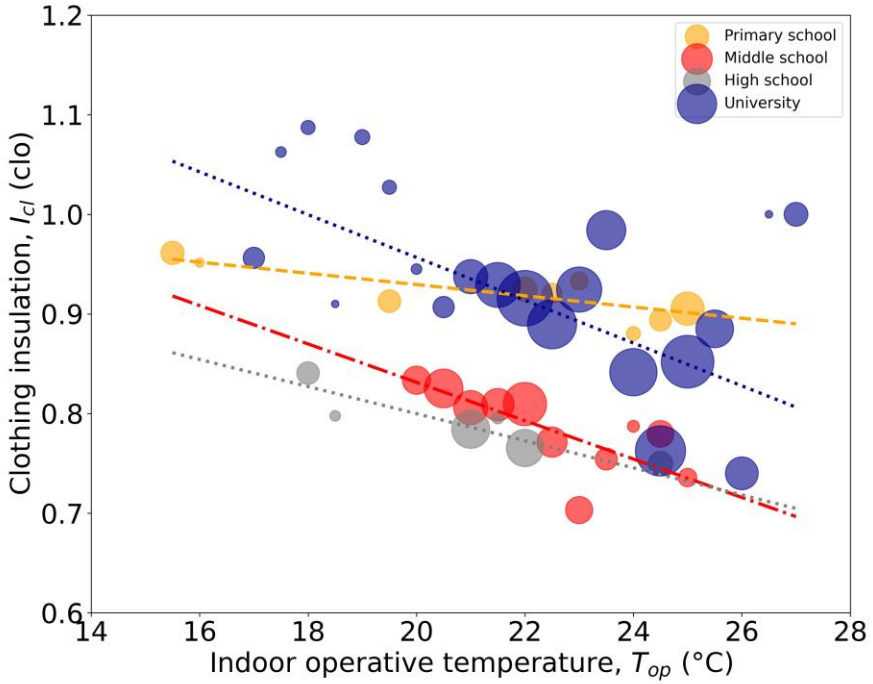
3. Weighted linear analysis and regression models

Primary School (R^2 = 0.70, p-value<0.05) $I_{cl} = - 0.0056 \cdot T_{op} + 1.0421$

Middle School (R^2 = 0.55, p-value<0.05) $I_{cl} = - 0.0193 \cdot T_{op} + 1.2165$

High School (R^2 = 0.88, p-value<0.05) $I_{cl} = - 0.0136 \cdot T_{op} + 1.0718$

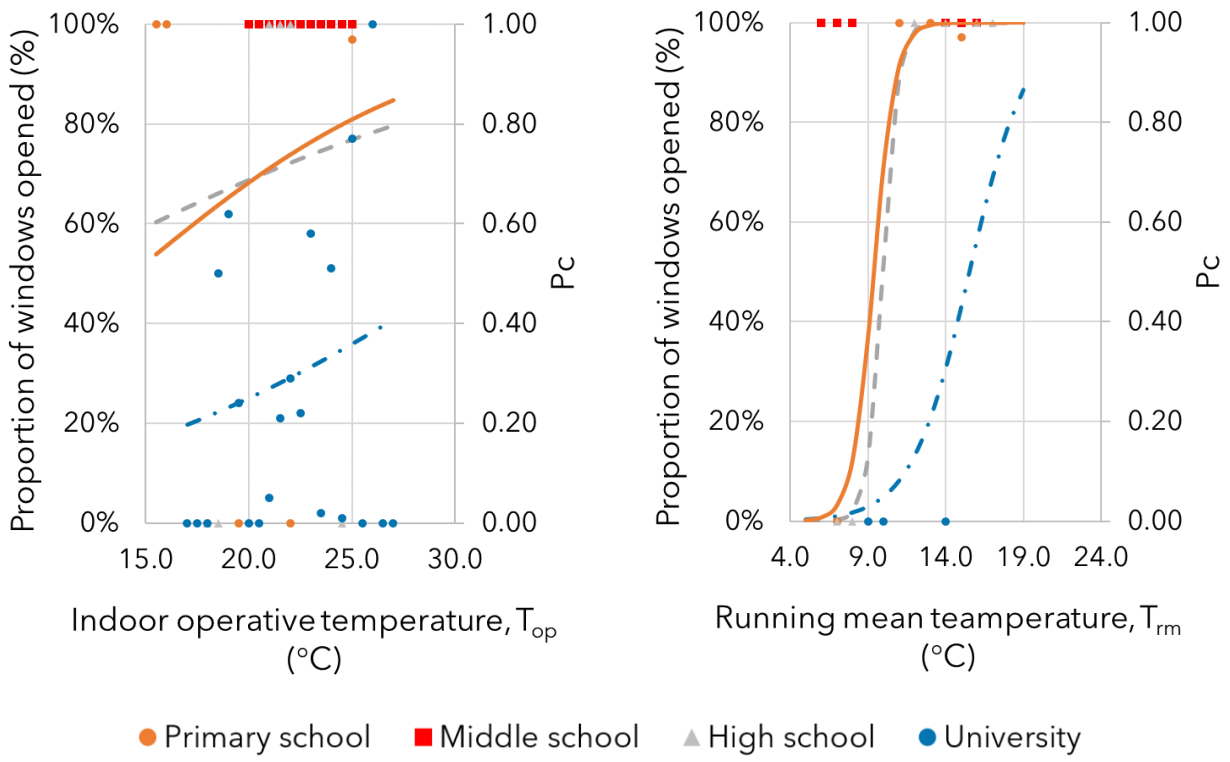
University (R^2 = 0.34, p-value<0.05) $I_{cl} = - 0.0215 \cdot T_{op} + 1.3862$



[1] ISO 7730, "Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria", 2006.

RESULTS AND DISCUSSION

EVIDENCE OF ADAPTATION – WINDOW OPERATION



Logistic regression analysis: probability that windows are opened (p_c [0-1])

$$\text{Logit}(p_c) = \ln(p_c) - \ln(1-p_c) = \ln(p_c/(1-p_c)) = c + d \cdot T$$

$$P_c = (\exp(c+d \cdot T))/(1+\exp(c+d \cdot T))$$

T = temperature index (T_{op}, T_{rm})
c = intercept
d = slope

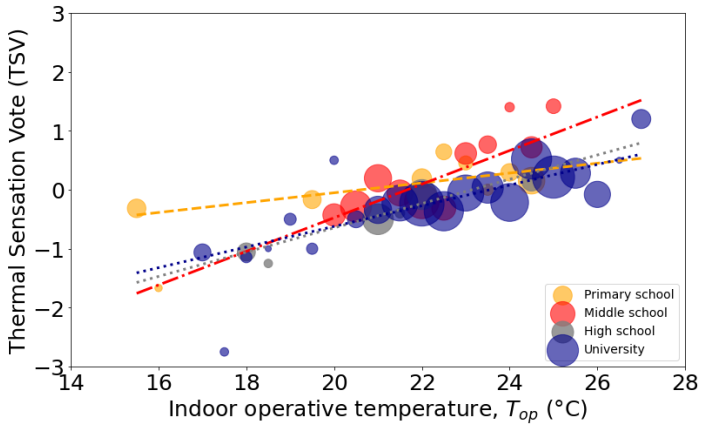
RESULTS AND DISCUSSION

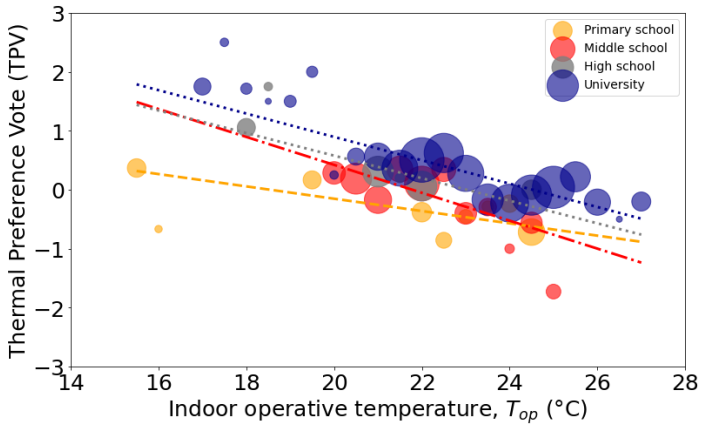
NEUTRAL, PREFERRED, AND ACCEPTABLE TEMPERATURES

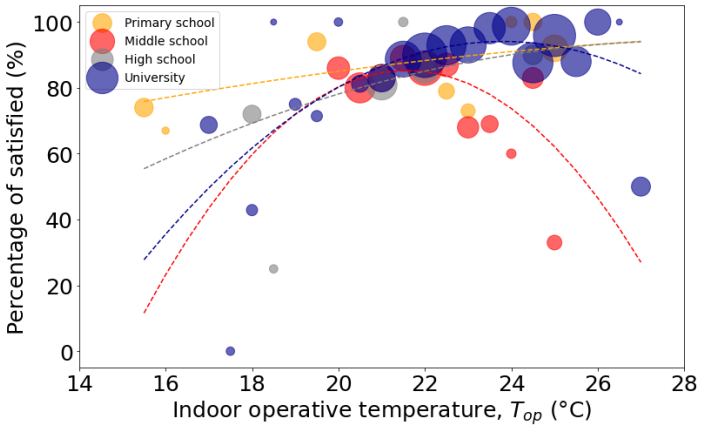
1. Binning method (T_{op} = 0.5 °C)

1. Weighted linear and polynomial analysis – regression models

		Primary school	Middle school	High school	University
TSV = 0	Neutral temperature (°C)	**20.6**	**21.7**	**23.1**	**23.6**
TPV = 0	Preferred temperature (°C)	**18.5**	**21.8**	**23.0**	**24.1**
TAV = max	Acceptable temperature (°C)	**21.9**	**21.2**	**22.2**	**25.0**







RESULTS AND DISCUSSION

NEUTRAL TEMPERATURE AND STUDENTS' AGE

1. **Deriving neutral temperature for each of the 1548 sample**

$$T_{neutral} = T_{op} + TSV/G$$

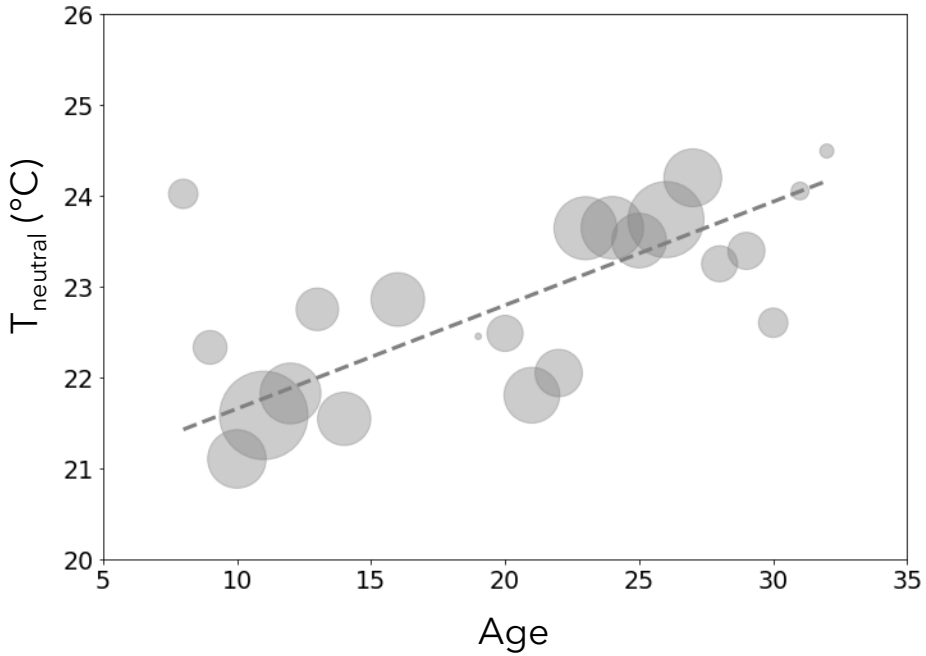
(G = 0.5 °C^{-1} Griffiths' costant)

2. **Binning method ($T_{neutral}$ = 0.5 °C)**

3. **Weighted linear analysis and regression models**

$$T_{neutral} = 0.1139 \cdot Age + 20.5146$$

$R^2 = 0.60$
P-value<0.05



RESULTS AND DISCUSSION

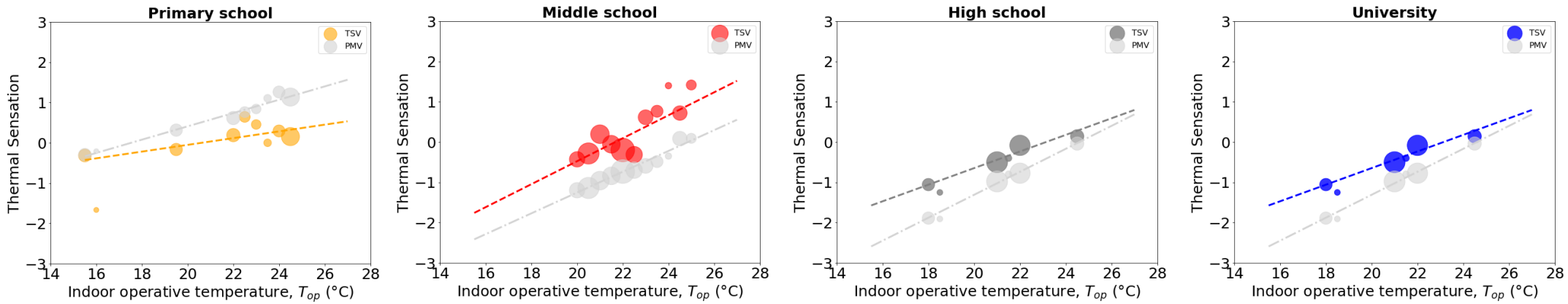
PREDICTIVE PERFORMANCE OF PMV-PPD MODEL

1. Correcting the metabolic rate by considering the different body surfaces of each student [5]

$$Met_{corrected} = Met_{ISO\ 8996} \cdot (A_{Adult} / A_{student}) = 1.2\ met \cdot (1.8\ m^2 / A_{student})$$

2. Calculating the PMV [1]

PMV = f(metabolic rate, clothing insulation, T_a, RH, V_a, MRT)



[1] ISO 7730, "Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria", 2006.
[5] ISO 8996, "Ergonomics of the thermal environment - Determination of metabolic rate", 2005.

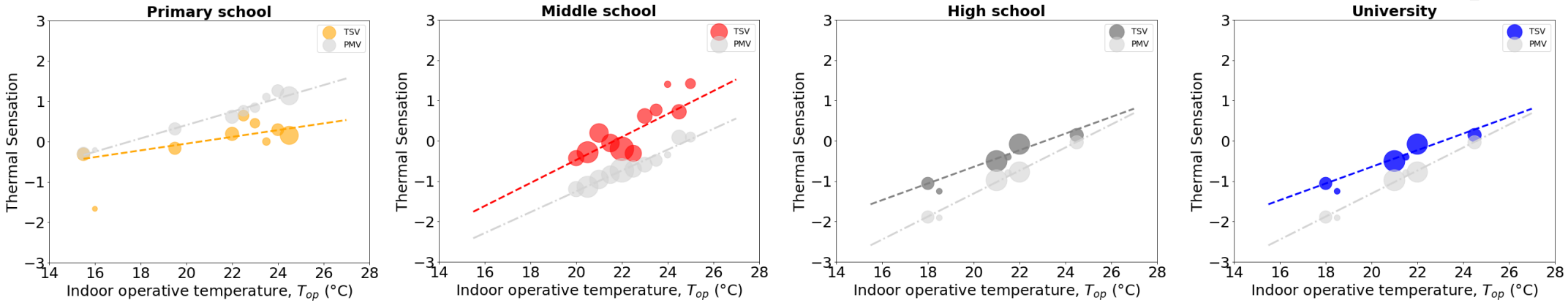
RESULTS AND DISCUSSION

PREDICTIVE PERFORMANCE OF PMV-PPD MODEL

3. Comparing the PMV with the TSV

Mean absolute error (MAE) = $(\Sigma_i^n |PMV_i - TSV_i)/n$
(n = number of samples = 1548)

	Primary school	Middle school	High school	University
MAE	**1.02**	**1.11**	**0.9**	**0.72**



RESULTS AND DISCUSSION

IMPACT OF PERCEIVED CONTROL ON THERMAL COMFORT

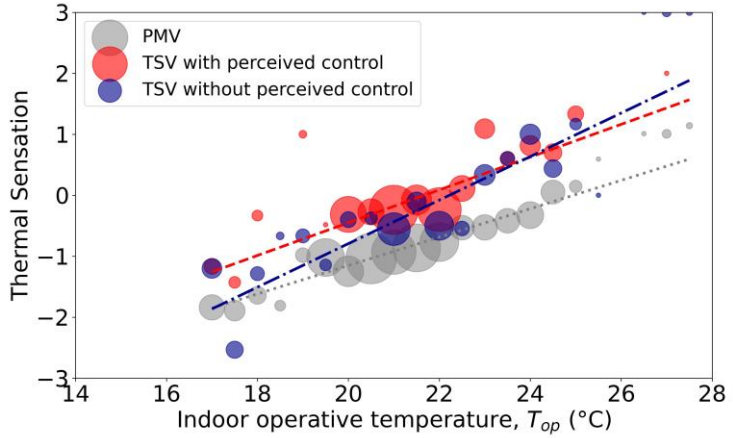
1. Binning method (T_{op} = 0.5 °C)

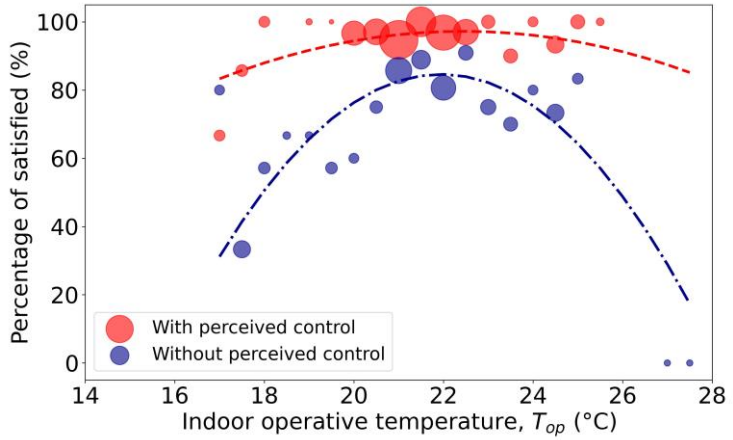
2. Thermal sensation – linear regression analysis

With perceived control	$TSV = 0.25 \cdot T_{op} - 5.58$ (R^2= 0.82, p-value<0.05)	$T_{neutral}$ = 21.7 °C
Without perceived control	$TSV = 0.32 \cdot T_{op} - 7.13$ (R^2= 0.88, p-value<0.05)	$T_{neutral}$ = 22.3 °C

3. Thermal acceptability – polinomial regression analysis

With perceived control	$\%_{Satisfied} = -0.29 \cdot T_{op}^2 + 1.24 \cdot T_{op}$ (R^2= 0.44, p-value<0.05)	T_{accept} = 21.4 °C
Without perceived control	$\%_{Satisfied} = -0.01 \cdot T_{op}^2 + 0.30 \cdot T_{op}$ (R^2= 0.90, p-value<0.05)	T_{accept} = 22.0 °C





RESULTS AND DISCUSSION

IMPACT OF PERCEIVED CONTROL ON IAQ

1. Binning method (T_{op} = 0.5 °C)

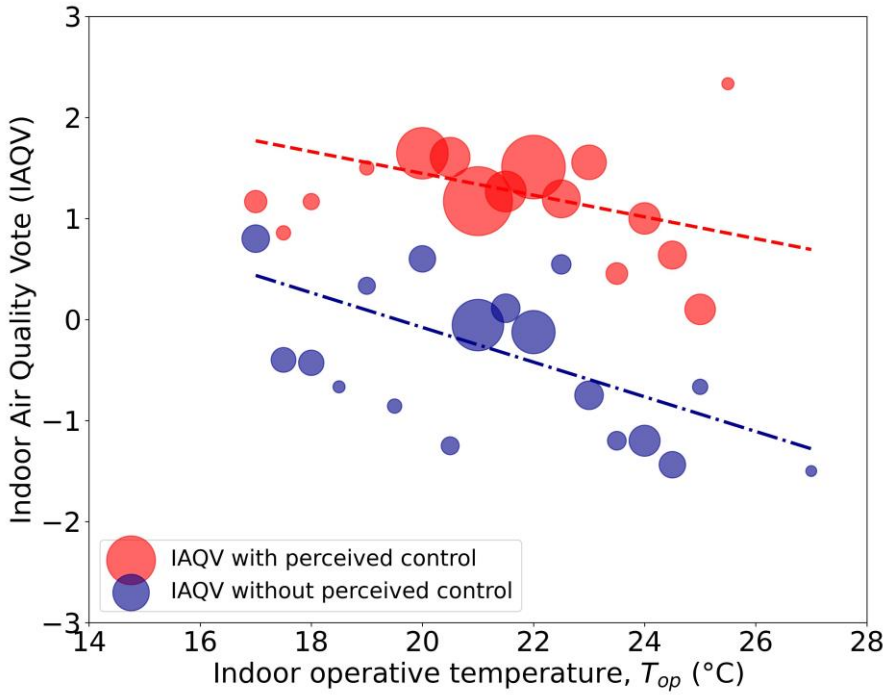
2. IAQ– T_{op} linear regression analysis

With perceived control: $IAQV = -0.16 \cdot T_{op} + 4.34$ (R^2= 0.45, p-value<0.05)

Without perceived control: $IAQV = -0.12 \cdot T_{op} + 2.49$ (R^2= 0.29, p-value<0.05)

2. IAQ– CO_2 linear regression analysis

No strong correlation between the two parameters (R^2<0.1, p-value=0.9)



CONCLUSIONS

- This is the first study that involves **all educational stages** (from primary schools to universities) under the same period and geographical area.
- Furthermore, this is the first work investigating the **impact of perceived control** on indoor comfort in school buildings.
- The ability to **adapt** to the environment **increases with the educational stage**.
- **Neutral, preferred, and acceptable temperatures increase with students' age** (e.g. the neutral temperature increases by 1 °C on average at every educational stage).
- **Current comfort standards**, which are based on the PMV–PPD method**, are not accurate** in predicting the thermal sensations of students, and correcting the metabolic rate is insufficient .
- In winter, the **neutral operative temperatures** of students with **perceived control** are **lower** than those of the students without perceived control. (→ **energy savings**)
- Subjects with perceived control are also more satisfied with IAQ than subjects without perceived control.

More information:

- Torriani, G., Lamberti, G., Fantozzi, F., & Babich, F. (2023). **Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools**. *Journal of Building Engineering*, 63, 105419.
- Torriani, G., Lamberti, G., Salvadori, G., Fantozzi, F., & Babich, F. (2023). **Thermal comfort and adaptive capacities: Differences among students at various school stages**. *Building and Environment*, 110340.

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Thank you for your attention