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Impact of thermal comfort on online learning performance

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Abstract

Online learning has drawn much more attention since the outbreak of COVID-19. Most related studies have focused on online platform design and instructional design. However, the physical environment where online learning is conducted (e.g., students' homes) is rarely studied. To understand the thermal conditions in students' online learning environment and its impact on students' thermal comfort and their performance during online learning, an experiment, including both objective measurement and subjective assessment, was conducted in a student's apartment. Thirty university students participated in this experiment, and they were randomly assigned into six groups (three thermal conditions (i.e., control, cold, and hot) × two-course durations). Both environmental parameters (i.e., air temperature, radiant temperature, air velocity, etc.) and physiological parameters (i.e. skin temperatures) were measured at the same time. Besides, students' thermal sensation, acceptance, and learning performance were self-evaluated and collected through questionnaires. Results showed that participants' thermal sensation was positively correlated with their mean skin temperature (MST) and the operative temperature (T_o) in the apartment (MST: ρ=0.94, p<0.001; T_o: ρ=0.91, p<0.001), yet no significant relation with their personal characteristics was observed in the current study, which might be caused by the small sample size. Moreover, inverted U-shape relationships were identified between participants' perceived performance and their thermal sensation/MST/ T_o. When students felt slightly cool (TSV=-0.3), their thought they could reach their best performance. This study revealed the impacts of the thermal environment on students' online learning performance, more performance tasks could be conducted in the future to examine the impacts in more detail.

Abbreviations			
IEQ	Indoor environmental quality	TSV	Thermal sensation vote
MST	Mean skin temperature (°C)	PMV	Predicted mean vote
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	WHO	World Health Organization
		SD	Standard deviation
V	Air velocity (m/s)	BMI	Body Mass Index
RH	Relative humidity (%)	t_{chest}	Skin temperature of chest (°C)
T_a	Air temperature (°C)	t_{thigh}	Skin temperature of thigh (°C)
T_r	Radiant temperature (°C)	t_{leg}	Skin temperature of leg (°C)
T_o	Operative temperature (°C)	t_{arm}	Skin temperature of arm (°C)
I_{cl}	Insulation value of clothing (clo)		

1. Introduction

Because of the spread of COVID-19, many schools were closed for a long time to control the pandemic during the past two years. As a result, most education had to change from traditional face-to-face learning to online learning [1]. To ensure the quality of education, many researchers and educationists have put a lot of effort into the improvement of online learning platforms and instructional design [2]. Actually, online learning has been promoted and offered by a lot of universities long before the pandemic [3] and it will be an important component of the future education system. Although online learning reduces the limitation of time and location, it still needs to be carried out at a specific location. However, little attention has been given to the physical environment of online learning [4].

Lots of studies have shown that indoor environmental quality (IEQ), including thermal comfort, indoor air quality, visual quality, and acoustic quality, could have significant impacts on occupants' comfort, health, and productivity [5]–[9]. Among the four factors of IEQ, thermal comfort was found to be the most important factor and has a higher influence on IEQ-acceptable conditions [10], [11]. To maintain a comfortable thermal environment, many standards, such as ASHRAE 55, and ISO 7730, have been developed. However, according to previous studies, lots of investigated indoor spaces could not meet these related thermal requirements or satisfy occupants' thermal comfort, and study space (such as classrooms) is one of the typical examples [12]. A field study conducted in three schools in Italy showed the operative temperature in one of these schools was as high as nearly 29 ℃, which was higher than the maximum temperature required by EN 15251:2007 and outside the comfort zone defined by ASHRAE 55, and this high temperature triggered many complains from students [9]. Similar discomfort thermal conditions were also found in schools in Cyprus [13], Portuguese [14], the Netherlands [15], and Denmark [16], [17]. More extreme situations were found in schools in tropical regions, such as Taiwan [18] and Singapore [19], where almost no investigated classrooms could meet the requirement of ASHRAE 55.

Thermal discomfort in study places, especially caused by high temperatures, could negatively affect students' learning performance. Precious studies found that higher temperatures in classrooms could impair students' ability to perform school tasks [16], [17] and reduce their scores in national exams [20]. To be specific, these effects were found on students' cognitive performance, answer speed, and mathematic test scores. According to a three-day survey among university students in Brazil, feeling 'slightly warm' 'warm' and 'hot' could negatively impact students' cognitive performance, while feeling 'cool' or 'slightly cool' could have a positive effect [21]. Additionally, a liner negative relationship between temperature and students' mathematics scores was established by Haverinen-Shaughnessy and Shaughnessy [22]: decreasing 1°C in temperature within the range of 20–25°C could increase students' mathematics scores by 12–13 points. A similar relationship between temperature and students' answer speed was found by Wargock and Wyon [16] that reducing the temperature by 1°C could improve students' speed by 2%. However, most of these studies focused mainly or only on physical thermal conditions in the environment, and relationships between physiological thermal parameters and students' performance were rarely studied.

Mean skin temperature (MST) is one of the commonly used physiological parameters to reflect people's thermal reaction toward a specific environment [23] and it plays a vital role in determining people's thermal comfort [23], [24]. The relationship between skin temperature and thermal comfort has been studied since half a century ago [25]–[27], and it was found that the normalized skin temperature (which takes into account of person's body surface area and clothing insulation) or MST could better predict people's thermal states [26], [28]. To get an accurate value of MST, Yao et al. compared 14 existing MST calculation methods and concluded that the Burton three-points [29] and Ramanathan four-point [30] methods are more suitable for the prediction of people's thermal sensation [31].

Considering the above-mentioned two gaps, the current study was developed to investigate the thermal condition of students' online learning environment and its impact on their academic performance. Besides, the relationships between students' personal characteristics/ MST/ thermal sensation and their thermal comfort during online learning and the impacts of the length of the online lesson on students' thermal comfort and their performance were studied as well. The results of this study could shed light on students' thermal comfort during the online learning process and its impact on their learning performance.

2. Methodology

2.1 Study design

To close to the real online learning environment, this study was conducted in a student's apartment and only one student participated in the experiment in one session. Each session of the experiment was scheduled for either 107 minutes or 54 minutes, depending on the experiment procedure (see section 2.2), between 12:00 to 18:00 during the weekend from November 2020 to January 2021. Thirty local students who were familiar with the online learning platform volunteered to participate in this experiment. Two online lessons on positive psychology with two lengths (77 minutes and 24 minutes) were prepared and played during the experiment. The reasons for selecting these lessons are as follows: i) the participants had different science and engineering backgrounds, to avoid bias, the topic of the courses should not be specialized; ii) to make sure the participants could stick through until the end, the courses should be easy to understand and relevant; iii) the time duration of online courses varies from 20 minutes to four hours, to test the impact of the course length, two typical online course lengths, namely “between 15-30 minutes”, and “not exceed 1.5 hours” [32], were decided as the tested time durations.

Besides, to investigate the impact of students’ thermal comfort on their performance, two uncomfortable thermal environments (i.e., cold and hot) were created with the help of air conditioning and a heater. In total, three different thermal conditions were tested in this study: control (neutral), cold, and hot. For the cold/hot conditions, the air conditioning or the heater was turned on to set the temperature outside the comfort zone suggested by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55 [33], and participants were not allowed to change their clothing during the experiment. For the control condition, participants could wear normal clothing that helped them reach thermally neutral. To obtain a wider range of thermal environment and thermal comfort in this study, the physical thermal environment was not set to the same level, and it varied with the outdoor climate. The thirty students were equally and randomly divided into six groups: a short lesson with a controlled environment (group 1); a short lesson with a cold environment (group 2); a short lesson with a hot environment (group 3); a long lesson with a controlled environment (group 4); a long lesson with a cold environment (group 5); a long lesson with a hot environment (group 6).

2.2 Experiment Procedure

The experiments lasted 107 minutes or 54 minutes, depending on the duration of the online course. For the long experiment (see Figure 1 a)), the detailed procedures are shown below:

1. Before the online learning started, participants were asked to stay in the apartment for 30 minutes. During which, a detailed explanation was given about the procedure of this experiment and the content of the questionnaire. Additionally, participants’ skin temperatures were measured at 30mins, 20mins, 10mins, and 0mins before the online learning process to ensure that they reached a steady thermal state before the course started.
2. The environmental condition was measured at 30mins before, the same time as, and 30mins after the online course started to ensure the thermal condition had no changes.
3. During the online course, participants’ skin temperatures were measured at 15mins, 30mins, 45mins, 60mins, and 75mins after the course started to record the changes in their skin temperature.
4. After the online course, participants were asked to fill in a questionnaire to record their thermal comfort and performance evaluation.

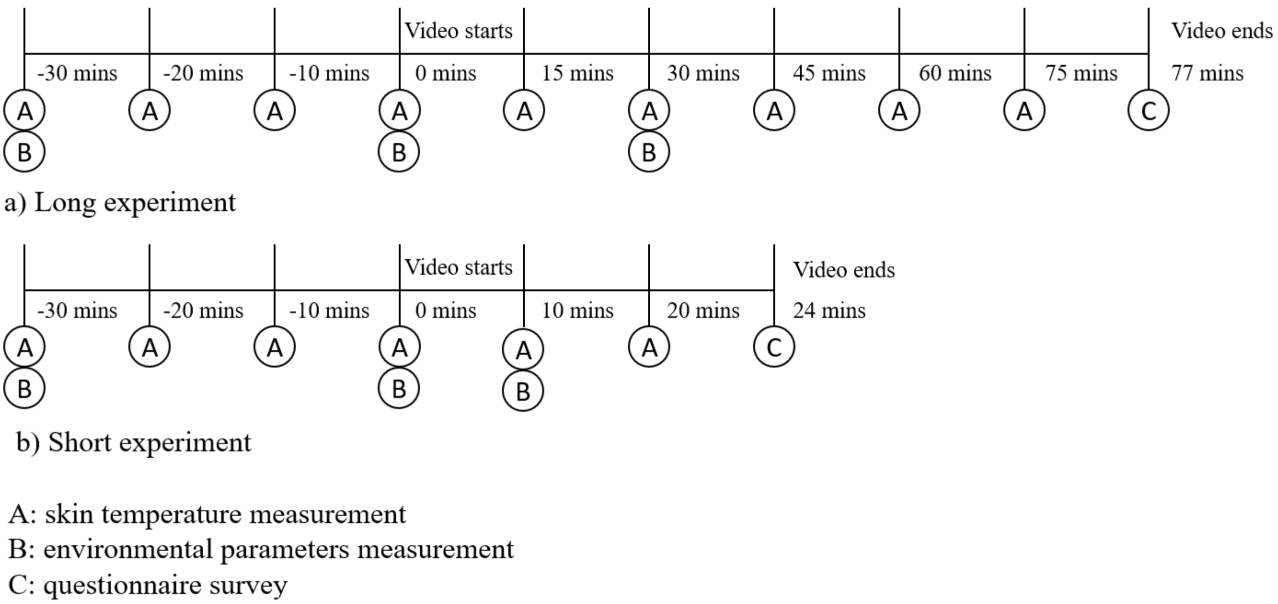


Figure 1. Experimental procedures.

For the short experiment, the procedure was the same as the long one, as illustrated in Figure 1 b), only the online learning process was shorter, and participants' skin temperatures were therefore measured at 10mins, 20mins, and 24mins after the online course started.

2.3 Subjective data collection

A series of environmental parameters were measured during this experiment, using Kata-thermometer and heat index WBGT meter (WBGT-2009). The range and accuracy of the device are shown in Table 1. All instruments were calibrated according to instructions given by the manufacturer prior to all measurements, and their specifications met the ASHRAE 55 [33] and ISO 7730 [34] standards. The measurement probe was placed at the point (1m above the floor) nearest the sitting respondents, according to the requirements stated in CIBSE TM68 [35] and ISO 7726 [36].

Table 1. Measurement range and accuracy of the devices.

Parameters	Device	range	accuracy
Air velocity (v)	Kata-thermometer	0-1 m/s	1%
Relative humidity (RH)	WBGT-2009	5-95 %	±3%
Air temperature (T_a)		0-50 °C	±0.8°C
Radiant temperature (T_r)		0-80 °C	±0.6°C
Skin temperature	Pt 1000	-50-600 °C	±0.3°C
	DT-830LN	200 to $2x10^6$ Ω	0.8%

Based on the recorded T_a and T_r, the corresponding operative temperature (T_o) was calculated using the following Equation:

$$T_o = \frac{T_r + (T_a \times \sqrt{10v})}{1 + \sqrt{10v}} \quad [36] \qquad (1)$$

The skin temperature of the subjects was measured and recorded using a platinum resistance temperature sensor (Pt1000; resistance = 1000 Ω at 0°C) and a multimeter (DT-830LN). The Pt1000 sensor measures the resistance of a platinum element which changes along with the measured temperature. In order to minimize the impact of ambient conditions, each sensor was attached and covered by medical tapes on the participants' four selected body parts including chest, thigh, leg, and arm. The skin temperatures were determined based on the Pt1000 resistance table. Then, MST was calculated by the Ramanathan four-point method [30]:

$$MST = 0.3t_{chest} + 0.3t_{arm} + 0.2t_{thigh} + 0.2t_{leg} = 0.3(t_{chest} + t_{arm}) + 0.2(t_{thigh} + t_{leg}) \qquad (2)$$

2.4 Objective data collection

After the online learning process, a questionnaire (see Appendix) was given to the participants. As they had stayed in the room and kept sitting for at least 50 minutes, the participants were assumed to have a steady metabolic rate and be under a steady thermal condition when they were filling in the questionnaire. The questionnaire included general questions (age, gender, height, and weight), questions about thermal comfort (thermal sensation, activity, insulation of clothing (I_{cl}), and acceptance), and questions about performance evaluations (reading, understanding, typing, and calculating). Before applying the questionnaire in this experiment, it was distributed among a number of students, in order to verify its understandability. In general, it took the participants 5-10 minutes to fill in the questionnaire. The questionnaire was developed based on previous studies [8, 15, 16]. Three different types of questions were designed. For thermal sensation, it was assessed by the prominent ASHRAE 7- point scale which consists of seven semantic different answers: "cold, cool, slightly cool, neutral, slightly warm, warm, hot". For acceptance, it was collected through the question: "Is the thermal comfort acceptable to you?" (Acceptable vs. Unacceptable). For learning performance, it was assessed through the question "what is your web learning performance in reading/ understanding/ typing/calculating in the same setting?". A percentage scale (0%, 15%, 30%, 50%, 70%, 85%, 100%) was provided and participants were asked to select the one that best illustrates their performance. Additionally, based on the collected thermal sensation vote (TSV) and I_{cl}, the measured RH and air velocity, and the calculated T_o, the predicted mean vote (PMV) was calculated using the CBE Thermal Comfort Tool [37].

2.5 Ethical aspects

Only participants older than 18 were allowed to participate in this experiment. Before the experiments, they received an invitation letter with a detailed procedure of the intended measurements and surveys, as well as the promise that all the data collected in this experiment will only be used in the current study. To guarantee participants' health, no extreme thermal condition was included in the experiment (T_a was between 20-30℃ and RH was around 60%). Moreover, participants could opt out at any time if they felt uncomfortable and no longer wanted to participate.

2.6 Data analysis

All the measurement data of air temperature, skin temperature, relative humidity, and air velocity were imported to IBM SPSS Statistics 26.0 (SPSS Inc. Chicago, IL, USA). Then the data was checked based on Z-scores, and all outliers (the absolute Z-scores higher than three) were filtered out [47]. The information collected through the questionnaires was manually checked and typed in IBM SPSS Statistics 26.0. All the data were analyzed using two types of methods - descriptive analysis and correlation analysis- with IBM SPSS Statistics 26.0. First, the mean, standard deviation (SD), minimum, and maximum values of all the measurement data and the continuous data collected through questionnaires (personal characteristics, thermal sensation, and performance evaluations) were calculated per group. While for questions about thermal comfort, the frequencies of each answer were calculated per group. Then, to check the influence of personal characteristics and the length of lessons on students' thermal comfort during online learning and the influence of thermal comfort and the length of lessons on students' online learning performance, a series of Chi-square tests, Pearson correlations, and t-tests (depending on the type of variables) were performed. A p-value less than 0.05 means statistically significant.

3. Result

3.1 Descriptive Analysis

In total 30 questionnaires were collected with a 100% response rate. The general information of the participants, including their age, gender, height, weight, and I_{cl}, are presented in Table 2. As shown, the personal information of the participants in different groups was basically similar: the average ages were 21-22 years old; the average sex ratios were around 50/50, except for group 4 where most participants were female; the average Body Mass Indexes (BMIs) in all groups were belong to the normal weight defined by World Health Organization (WHO; 18.5-24.9); the average I_{cl}s were 1.0-1.3 clo (representing the typical winter indoor clothing insulation), except for group 6 where the average I_{cl} was 1.6 clo.

Table 2. General information of the participants.

	Group 1 (N=5)	Group 2 (N=5)	Group 3 (N=5)	Group 4 (N=5)	Group 5 (N=5)	Group 6 (N=5)	All (N=30)
Age [a]	22.0 (2.1)	21.3 (1.7)	21.3 (1.5)	21.8 (1.5)	21.0 (3.0)	21.0 (1.4)	21.4 (1.7)
Gender [b] F M	3 (60%) 2 (40%)	3 (60%) 2 (40%)	2 (40%) 3 (60%)	4 (80%) 1 (20%)	2 (40%) 3 (60%)	3 (60%) 2 (40%)	16 (53%) 14 (47%)
Height [a] (mm)	160.8 (11.7)	162.3 (5.6)	154.0 (12.8)	157.4 (8.0)	166.0 (9.8)	165.3 (9.2)	160.6 (9.7)
Weight [a] (kg)	50.8 (11.0)	49.8 (5.1)	56.3 (15.1)	46.2 (8.6)	59.3 (8.1)	57.5 (15.5)	52.7 (11.1)
BMI [a]	19.4 (1.5)	18.9 (0.7)	21.0 (3.0)	18.5 (1.6)	21.5 (2.3)	20.7 (3.6)	19.9 (2.3)
I_{cl} [a] (clo)	1.0 (0.0)	0.9 (0.2)	1.0 (0.3)	1.2 (0.4)	1.0 (0.1)	1.6 (0.2)	1.1 (0.3)
TSV [a]	-1.0 (0.0)	-2.0 (1.0)	2.0 (1.0)	-0.6 (0.5)	-2.2 (0.8)	2.0 (0.7)	-0.3 (1.9)
PMV [a]	-0.8 (0.2)	-1.9 (0.9)	1.6 (0.9)	-0.5 (0.4)	-2.1 (0.8)	1.6 (0.7)	-0.3 (1.6)
Acceptance (%)	100	40	40	100	20	20	53
T_r [a] (℃)	22.4 (0.4)	19.9 (2.1)	32.6 (0.7)	22.2 (0.8)	19.1 (3.2)	32.1 (1.5)	24.7 (5.8)
T_a [a] (℃)	22.3 (0.5)	20.2 (2.5)	30.2 (1.6)	22.0 (0.8)	19.3 (3.0)	28.1 (2.9)	23.7 (4.6)
T_o [a] (℃)	22.3 (0.5)	20.3 (2.9)	29.4 (2.7)	22.0 (0.8)	19.2 (2.9)	28.2 (2.9)	23.5 (4.4)
RH [a] (%)	65.0 (8.1)	60.7 (5.6)	64.4 (8.1)	61.9 (5.2)	58.9 (6.9)	67.6 (6.3)	63.1 (6.8)
v [a] (m/s)	0.5 (0.1)	0.4 (0.1)	0.7 (0.3)	0.5 (0.0)	0.5 (0.2)	1.3 (0.8)	0.6 (0.4)

Note: a. the numbers are mean (standard variation) values in each group; b. the numbers are n (%) in each group.

Regarding participants' thermal sensation, it can also be seen from Table 2 that, on average, participants in the control environment (groups 1 and 4) felt slightly cool; participants in the cold environment (groups 2 and 5 felt cool; while participants in the hot environment (groups 3 and 6) felt warm. The calculated PMV values were similar as participants' TSV values. In terms of their total acceptance of the environment, all the participants in the control environment (groups 1 and 4) thought the environments were acceptable, 40% of participants who took the short lesson (groups 2 and 3) accepted the treatment environments, no matter it was hot or cold, while only 20% of participants who took the long lesson (groups 5 and 6) accepted the corresponding treated environments.

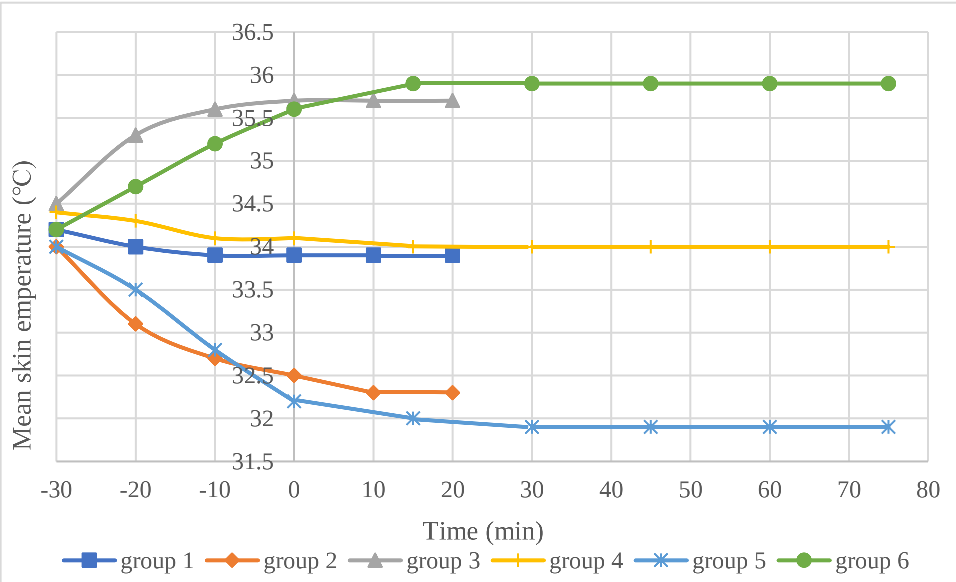


Figure 2. Average Mean skin temperate (MST) in different groups at different time.

Figure 2 shows the change in MST of participants before and during the online course. At the beginning of this experiment, namely 30 minutes before the online course started, the average MSTs of the participants in different groups were similar (34°C), and they did not change a lot in the control groups (groups 1 and 4). However, in the cold environment, the average MSTs of participants in the groups with short and long lessons decreased by 1.6 and 2.1 °C, respectively, in the first 40 minutes of the experiment, and the opposite changes were identified in the hot environments. Apart from that, as shown in Figure 2, participants' MSTs basically remained constant after the course started, which confirmed that occupants were under a steady thermal condition during the online lesson.

3.2 Thermal Comfort

Figure 3 illustrates the correlation between the measured sensation vote and the PMV index. As it shows, the PMV and TSV were highly matched ($\beta = 0.86$; $R^2=0.98$) with each other during the online learning process. For participants who voted neutral for their thermal sensation (TSV = 0), their corresponding PMVs were also neutral (-0.06). In addition, it can also be seen from the figure that all the participants who voted slightly cool, neutral, or slightly warm felt the environments were acceptable, while all the others (participants who voted cold, cool, warm, or hot) felt the environments were unacceptable.

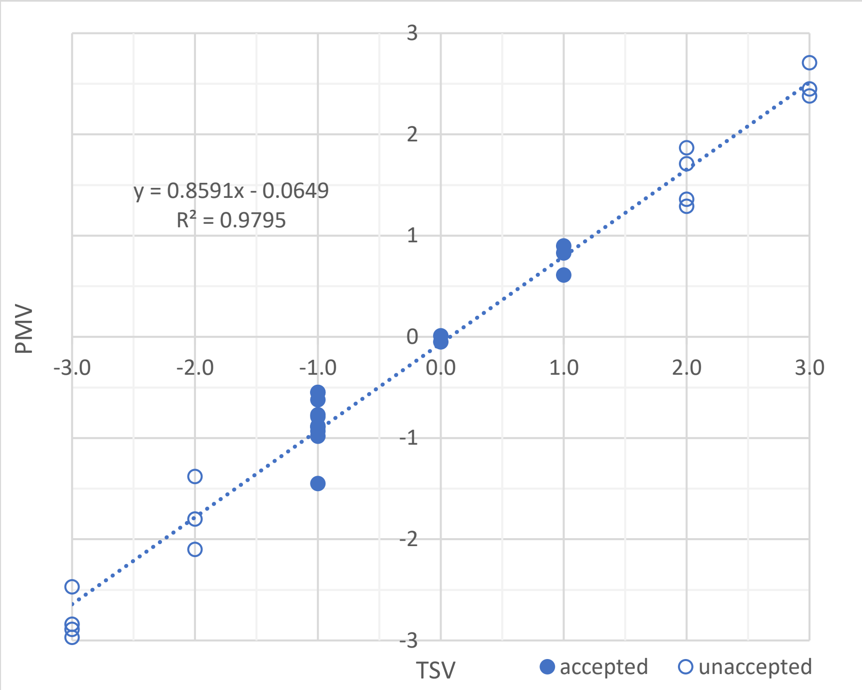


Figure 3. Relationship between the TSV and PMV during the online learning.

To identify the potential influence factors of students' thermal comfort, the relationships between participants' thermal comfort and their personal characteristics, MSTs, the operative temperature, and the duration of online lessons were analyzed and discussed in the following subsections.

3.2.1 Impact of personal characteristics on thermal comfort

A series of Chi-square tests were conducted to test the impact of gender on participants' thermal sensations and their acceptance of the thermal environment. As demonstrated in Table 3, all participants' TSVs were between -1 and 0 in the control environment; between -3 and -1 in the cold environment; and between 1-3 in the hot environment. No significant difference in TSV was identified between female and male participants in different treated environments (p>0.05). For the acceptance rate, although no significant difference was identified between female and male participants, more female participants in the cold environment and more male participants in the hot environment accepted their corresponding environments. In terms of BMI, according to the statistical analysis, it has no impact either on TSV or on acceptance. Also, no trend between BMI and participants' TSV can be identified in Figure 4.

Table 3. Relationships between gender and TSV.

	Control environment		Cold environment		Hot environment		All	
	female	male	female	male	female	male	female	male
TSV	p=0.301		p=0.717		p=0.217		p=0.382	
Cold			40%	40%			12.50%	14.30%
Cool			20%	40%			6.30%	14.30%
Slightly cool	71.4%	100%	40%	20%			43.80%	28.60%
Neutral	28.6%						12.50%	
Slightly warm						50%		21.40%
Warm					50%	33.30%	12.50%	14.30%
Hot					50%	16.70%	12.50%	7.10%
Acceptance rate	/		p=0.490		p=0.091		p=0.732	
Acceptance	100%	100%	40%	20%	0%	50%	50%	56.3%

Note: p-values obtained from the Chi-square tests; empty cells mean 0%.

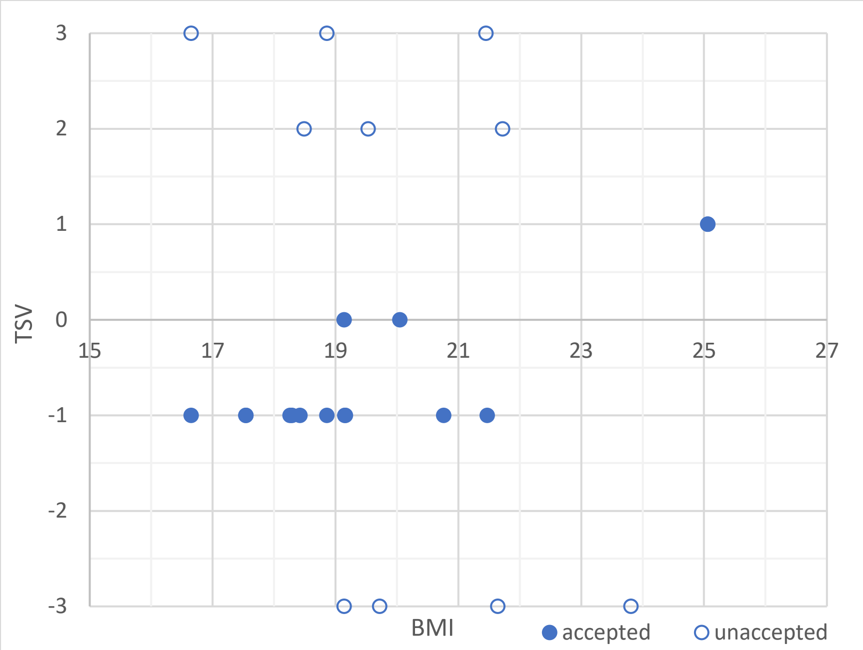
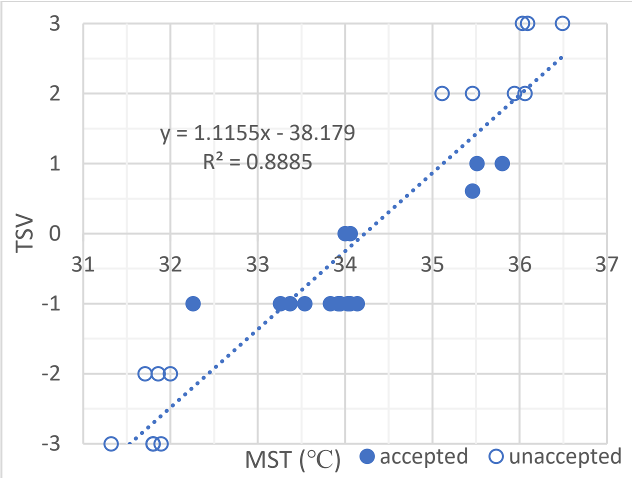


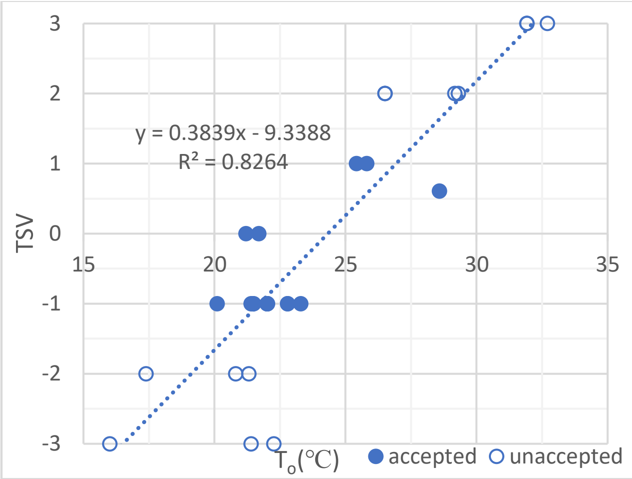
Figure 4. Relationship between participants' TSV and their BMI.

3.2.2 Impact of (skin and operative) temperature on thermal comfort

As shown in Figure 2, participants' MSTs were steady during the online course, hence, the MSTs measured at the end of the online course were used as the representative to establish the relationship between participants' MSTs and their TSVs by means of Pearson correlation. Besides, to investigate the impact of T_o on participants' thermal sensation, the relationship between the TSV and T_o during the online course (which is calculated based on the Ta, Tr, and v measured at 10 minutes after the short lesson started and 30 minutes after the long lesson started) was also analyzed by Pearson correlation. As illustrated in Figure 5, statistically significant positive relationships between the TSV and MST/T_o were identified (MST: $\rho=0.94$, $p<0.001$; T_o: $\rho=0.91$, $p<0.001$). According to the regression equations, the thermal neutral (TSV=0) MST and T_o were 34.2 and 24.3 °C, respectively. In most cases the results were homogeneous, when the MST was lower than 32 °C or higher than 36°C, participants felt cool/cold or warm/hot and unaccepted the thermal environment, while when MST was between 32 - 34 °C, they felt slightly cool and accepted the environment. However, when the MST was between 35 - 36 °C, results were not consistent, some participants felt slightly warm and accepted the environment, yet others felt warm and unaccepted it. Similar results were also found for T_o. When it was lower than 20 °C or higher than 30 °C, participants unaccepted the environment, while when it was between 20 – 25 °C, participants' thermal sensations differed widely (ranged from cold to neutral) and most of them felt slightly cool and accepted the environments, and when it was between 25 - 30 °C, participants felt either slightly warm and accepted the environments or warm and unaccepted the environments.



a) Relationship between TSV and MST



b) Relationship between TSV and T_o

Figure 5. Relationships between TSV and temperature during the online learning.

3.2.3 Impact of the length of online lessons on thermal comfort

Concerning the impact of the length of the online course on participants' thermal sensation, as shown in Table 4, no significant difference in TSV was found between the groups with short and long lessons. Participants in both groups felt slightly cool on average. For the acceptance rate, although more participants in the groups with the short lesson (60%) accepted the environment than in the groups with the long lesson (46.7%), the difference was not significant either.

Table 4. Relationships between the length of lessons and TSV.

	Short lesson	Long lesson	p
TSV [a]	-0.33 (1.91)	-0.26 (1.90)	0.925
Acceptance [b]	60%	46.7%	0.464

Note: a. results obtained from the t-test; b. results obtained from the Chi-square test.

3.3 Perceived Learning Performance

Figure 6 shows participants' average perceived learning performances (i.e., the arithmetic means of their selected performance scales) in different groups. Generally speaking, participants' perceived performances were much better in group 1(short lesson with control environment), while they were much worse in group 6 (long lesson with hot environment). Based on the results obtained from the one-way ANOVA tests, differences between these groups were statistically significant (see the legends in Figure 6). However, no significant difference was identified between different performance types (F(3,116)=0.63, p=0.60). Consequently, they were not analyzed separately, and the average performance levels were used in the following sections.

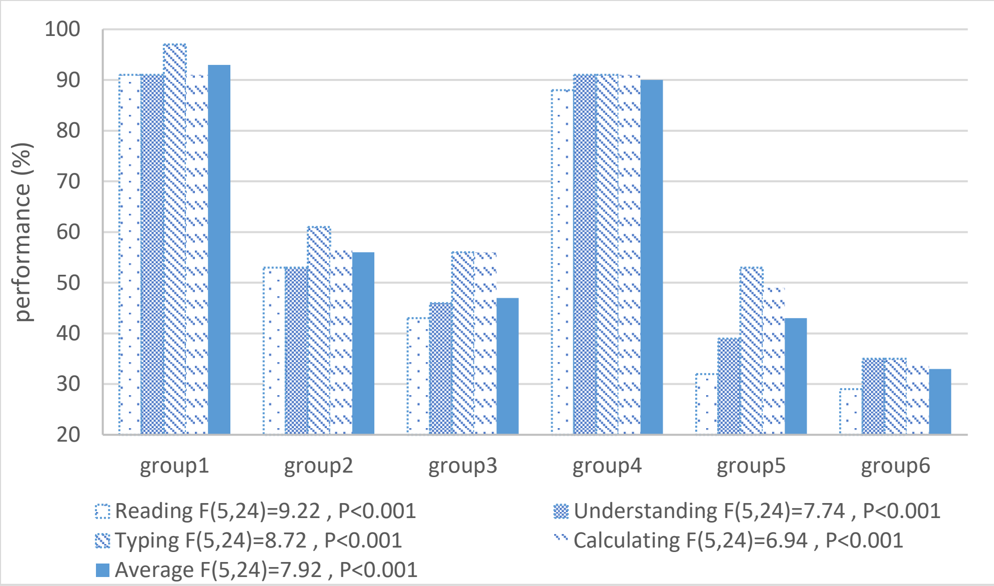


Figure 6. Participants' perceived performance in different groups.

According to the results shown in Table 5, students' perceived performances, no matter in which aspects, were slightly higher in the groups with short lessons than in the groups with long lessons, however, these differences were not statistically significant (p>0.05). In terms of the impact of the environmental treatment, participants' perceived performances were significantly better in the control environment than in the cold environment than in the hot environment.

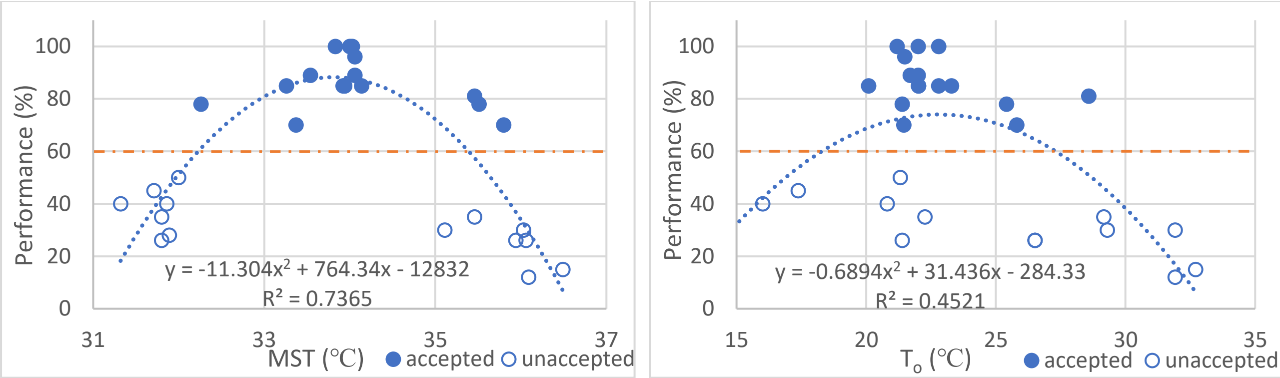
Table 5. Students' self-evaluated performances under different environments.

	Lesson length [a]			Environment treatment [b]			
	Short lesson	Long lesson	p-value	Control	Cold	Hot	p-value
Reading	62 (28.8)	50 (33.3)	0.275	90 (7.2)	43 (24.7)	36 (24.4)	**<0.001**
Understanding	63 (29.4)	55 (31.1)	0.457	91 (7.7)	46 (22.8)	41 (24.9)	**<0.001**
Typing	71 (25.7)	60 (28.9)	0.253	94 (7.7)	57 (17.5)	46 (25.5)	**<0.001**
Calculating	68 (25.5)	58 (29.9)	0.348	91 (7.7)	53 (21.0)	46 (25.5)	**<0.001**
Average	65 (28.7)	56 (30.4)	0.382	91 (6.8)	50 (20.9)	40 (25.9)	**<0.001**

Note: a. results obtained from t-test; b. results obtained from one-way ANOVA tests.

3.3.1 Impact of temperature on participants' perceived learning performance

Quadratic regression analyses were performed to quantify the impact of MST/To on participants' average perceived performance. The regression equations were displayed in Figure 7. Results indicated that there were statistically significant relationships between the participants' perceived overall performance and their skin temperature ($F(2, 27) = 37.62$, $p < 0.001$) and T_o ($F(2, 16) = 11.16$, $p < 0.001$). For MST, the relationship was clearer: participants performed better when their MST was around 34 °C; while for T_o, results were relatively scattered, and participants' best perceived performances were reported when the T_o was round 22°C. Additionally, it can be seen from Figure 7 that the self-evaluated performances of students who accepted the thermal environment were better (higher than 60%) than those who did not accept the thermal environment (lower than 60%).



a) Relationship between performance and MST b) Relationship between performance and T_o

Figure 7. Relationship between performance and temperature during online learning.

3.3.2 Impact of thermal sensation on participants' perceived learning performance

Figure 8 shows the average performances of participants who selected the same thermal sensation. Similar as the correlation between participants' performance and temperature, a statistically significant quadratic relationship was also found between their performance and thermal sensation ($F(2,27)=59.6$, $P<0.001$). As shown in Figure 8, participants' best perceived performances were reported when they felt neutral or slightly cool. Furthermore, based on the regression equation, when the TSV=-0.3, participants' perceived performance reached its highest level.

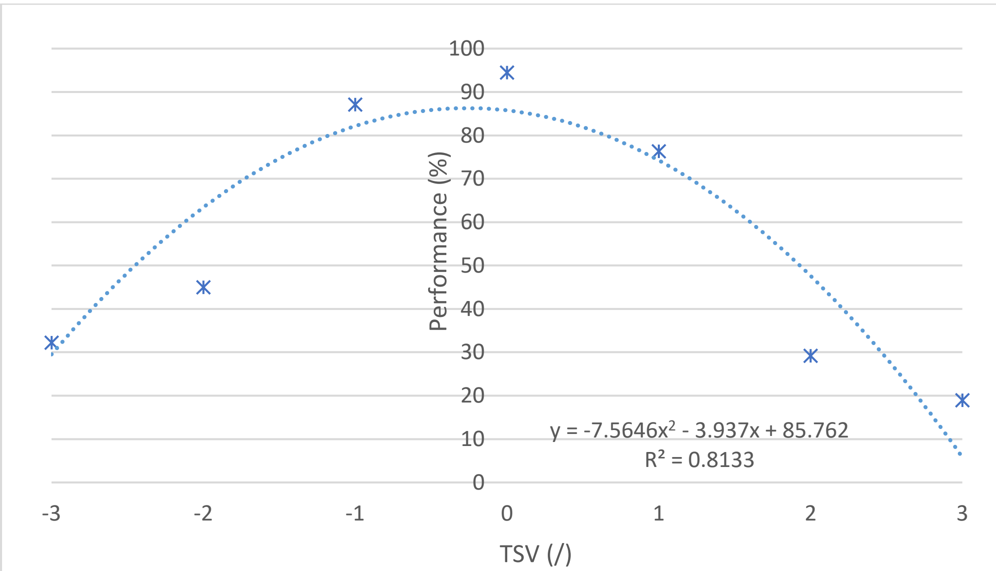


Figure 8. Relationship between participants' perceived performance and their thermal sensation.

4. Discussion

4.1 Students' thermal comfort during online learning

According to the relationship established by this study (Figure 3), the PMV calculated by CBE Thermal Comfort Tool could accurately predict participants' thermal sensations during online learning, only with a small underestimation. However, the opposite result, namely the PMV model overestimated occupants' thermal sensation, was found by previous studies [38]–[40]. Broday et.al [38] exanimated two PMV models and found both of them overestimated the welders' thermal sensation. Similar results were found by Maiti [39] among Indian male college students and by Indraganti [40] among Japanese office clerks. All these studies showed a relatively larger difference between the PMV and TSV, compared with the current study. The difference might be caused by different PMV calculation methodologies [39] or by different environmental conditions [38].

The current study didn't find any impact of participants' personal characteristics, such as their gender and BMI, on their thermal sensation nor on their acceptance rate. This result might seem contradict to previous research findings that females tend to feel cold discomfit than males [41] or females' comfortable temperature range was higher than males' comfortable temperature range [42], [43]. However, previous studies also indicated that gender differences in thermal comfort were only significant in cool environments (less than 20 °C) and they can be negligible in moderate environments [41]–[43]. For the impact of BMI, previous research found that obese subjects tend to feel hot compared with non-obese subjects [44]–[46]. However, all the participants in the current study were healthy and with normal BMIs, therefore no relationship between their BMIs and TSVs was established.

Different linear relationships between participants' thermal sensation and T_o were identified by previous studies. For example, in the study conducted in a university classroom in Colombia, the relationship between T_o and TSV was expressed by equation (3) [47], however much gentler slopes of the relations were found in another study conducted in residential buildings in China (see equation (4) and (5) for females and males respectively) [43]. The result found by the current study (Figure 5b) was much closer to the latter one, which confirms the inference drawn by Wang [43] that the thermal sensation of Chinese people's thermal sensitivity, in terms of their thermal sensation changes toward the variation of T_o, was lower than that of foreign people.

$$TSV = 0.925T_o - 11.568 \quad (3)$$
$$TSV = 0.243T_o - 5.330 \quad (4)$$
$$TSV = 0.199T_o - 4.158 \quad (5)$$

In addition, a linear relationship between participants' TSV and MST was also developed by this study, which is similar to the equation proposed by Takada et. al (see equation (6)) [48]. Actually, the time differential of MST was also involved in their original equation since they investigated the thermal sensation in the non-steady state [48]. However, they also mentioned that by setting the dMST/dt to 0, the equation could be used to predict TSV in a steady state (which is the condition investigated in the current study), therefore, their equation was transferred to equation (6). When MST is 35.37 °C, the TSV calculated by this question is the same as the result calculated using the equation found by the current study, while when MST is lower than 35.57 °C, the TSV calculated by the current study is slightly lower than the result calculated by equation (6), and vice versa.

$$TSV = 0.746MST - 25.110 \quad (6)$$

4.2 Impact of thermal condition on students' performance during online learning

Inverted 'U-shaped' relationships between participants' online learning performance and their thermal comfort/MST/T_o were identified by this study. Participants' perceived performances increased with the increment of MST and T_o when they were lower than 34 and 22 °C respectively, while beyond these critical points, the opposite effect was observed. The impact of T_o is in agreement with the results of previous studies. For example, Pepler [49]found that subjects' performance increased when temperature increased from 10 to 17 °C, while Wyon [50] and Haverinen-Shaughnessy and Shaughnessy [22] found that when temperature increased from 20 to 24 °C, participants' performance decreased. For the impact of MST on students' performance, related studies were relatively few. Yeom and Delogu [51] investigated the relationship between subjects' local skin temperatures and their cognitive performances and found that the local skin temperatures of subjects with worse cognitive performance were relatively higher than subjects with high cognitive performance. However, an opposite result was found by Khan et al. [52] that skin temperature was positively related to students' answer accuracy. Although their conclusions seem to be contrary to each other, the skin temperatures measured in the study conducted by Khan et al [52] were lower than 34°C, and in the study conducted by Yeom and Delogu [51]were partly (e.g., chest, back, and neck) higher than 34 °C, hence, they all, to some extent, supported by the results found by the present study.

Besides, participants reported the best performance when they felt slightly cool, which is consistent with the result found by Mendell and Heath [53] that cooler temperatures within the comfortable range could improve office workers' performance. However, unlike the results found by Kolarik et al. [54], no difference in performance among different types of tasks was identified in the current study, which might be caused by the difference between participants' perceived performances and their real performances. The performances investigated in this study were estimated by the participants themselves and it might be difficult for them to precisely assess their performance for different tasks.

4.3 Contributions and limitations

This study, for the first time, tried to investigate the impact of the thermal environment on students' learning performance during online learning. The relationships between the thermal environment and students' thermal sensation and performances identified in this study could help environmental designers, educators, and online learners understand how the physical environment support or constrain online learner' online learning performance. Compare with traditional education in physical classrooms, the advantage of online learning is that students have the flexibility in deciding where to study and even the ability to control the thermal environment. Therefore, understanding the impact of thermal environment on learning performance could help online learners to find or set a better learning environment. Besides, these results also provide a reference for designing and maintaining a good thermal environment in libraries or cafés which were often used as online learning spaces.

Despite the practical implications of this study, two limitations should be noted. First, this study was limited by the small sample size. As mentioned in section 3.2.1, the small sample made it difficult to investigate the impact of personal characteristics. The second limitation is the absence of real performance assessments. Only self-evaluations were collected in this study, which might be subjective and susceptible to bias. However, according to the study conducted by Zell and Krizan [55], when the evaluation target was specific and familiar, people's self-evaluation results were quite closer to their performance outcomes. Considering these limitations, future research is suggested to involve more participants. Additionally, to get a comprehensive and objective understanding of subjects' performance, different online courses might be considered and real performance tasks are recommended in future studies.

5. Conclusion

This study investigated students' thermal comfort during online learning and its impact on their performance through objective measurements and subjective assessments in a student's apartment. Similar to previous studies conducted in classrooms or offices, significant and positive relationships were found between participants' thermal sensation and MST/T_o during online learning (MST: $\rho=0.94$, $p<0.001$; T_o: $\rho=0.91$, $p<0.001$), and the thermal neutral MST and T_o were found to be 34.2 and 24.3 ℃, respectively. Besides, inverted U-shaped relationships were found between participants' performance and MST/T_o. When MST is 34 ℃ or when T_o is 22 ℃, participants' self-evaluated performance levels were the highest, and some of them even selected 100%. A similar relationship was also found between participants' performance and their thermal sensation, their best performance was reached when they felt slightly cool (TSV=-3). In conclusion, the thermal condition during online learning could significantly improve or hinder students' academic performance, and maintaining a slightly cooler environment could help students achieve their best performance.

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