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Insights into Adaptive Thermal Comfort on Learning Efficiency of Students-A Classroom-Based Case Study

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Abstract

In light of increasing concerns about climatic impacts, adaptive thermal comfort has become a research focus. This study tried to explore key factors of adaptive thermal comfort on learning efficiency of students based on the classroom-based spatial density and time history. We underlined that adaptability reflects people's adaptive regulation in the face of change; experience of thermal comfort in naturally ventilated space influences the comfort expectation of students who learn in natural ventilation (NV) and fully air conditioning (AC) space. Both the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) were used to examine both spatial density of the classroom and time history of the students, which influence learning efficiency. The results indicated that the learning efficiency of students is inferior as the density is 100%.As the density is 10%, the learning efficiency can be effectively improved. We argued that adaptive arrangement of indoor and outdoor thermal environment is crucial on improving learning efficiency of students. We concluded that adaptive actions of students in time history and the spatial density of the classroom depend on human-environment interplay; it revealed that the learning efficiency will be dominated by students' adaptability to be distracted not the temperatures.

Keywords: Predicted Mean Vote; Predicted Percentage of Dissatisfied; Spatial density; Time history; Thermal comfort; Learning Efficiency

Introduction

In light of increasing concerns about climatic impacts, adaptive thermal comfort (adaptive approach to thermal comfort) has become a research focus with the idea that occupants dynamically interact with their environment considering people as active rather than passive recipients in response to ambient physical thermal stimuli [1-8]. We underlined that the adaptability reflects young people's adaptive regulation in the face of change and people in different area can vary in their adaptability and comfortableness [9,10]. It is noted that today thermal comfort achieved by using a considerable amount of energy to reach people's demands for comfortable living spaces is unsustainable. In addition, comfort is not delivered to us by the indoor environment, but is instead something as a normal part of daily life through a variety of approaches [11]. It is also of concern that possible adaptive actions in line with effective arrangement of outdoor environment, and involving people can only be implemented properly when the interactions of the people with their environment in a changing climate are well understood [12,13]. Differences between the preferences and circumstances of different occupants can lead to a wide range of indoor conditions [14]. Moreover, the latest adaptive comfort methods consider outdoor temperature not only as a steady variable but also as the representation of occupants past thermal history [15].

Students spending more time at school than any other building except at home highlights the importance of comfortable indoor thermal learning environment [16]. This study tried to explore key factors of adaptive thermal comfort on learning efficiency of students based on the mixed mode of spatial density and time history (spatial and temporal conditions), underlining student's adaptability to control over the personal thermal environment [17-20]. As poorly designed indoor environments may negatively influence learning efficiency of students to thermal stress, we focused on the indoor thermal environments, and emphasized that the perceptual conditions constructed by spatial density and the time history of students to understand learning efficiency of students [21]. It is noted that both adaptation and learning are becoming increasingly essential and intertwined and dictate the response or behavior to climate change. We underline that learning is one of the primary means to effect adaptation in various forms, systems and structures. These influences incorporated social, cultural, temporal, and physical aspects [22].

The indoor thermal environment is related to the indoor air temperature, air humidity, airflow velocity, and *thermal radiation from the environment. We considered that natural ventilation (NV) and air conditioning (AC) are beneficial for improving the* learning environment, creating climate adaptive spaces suitable for adaptive thermal comfort, and enhancing learning efficiency of students [23-27]. Because every person has different adaptabilities and perceptions to the environment, we established the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) to evaluate learning efficiency [28-34]. The preferred values for indoor thermal environments were proposed and the perceptual conditions were discussed, both of which can serve as references for other relevant studies. The spatial density of classrooms and time history of students are related to the *level of crowdedness* of the space (i.e., spatial density)as well as how students acquire new adaptive approach to thermal comfort and learning experiences with changes over time [35].

Focus was placed on environmental perceptions, which were reflected on their thermal comfort and spatial experiences [36]. That is, an adaptive arrangement of indoor space and outdoor environment is crucial on improving learning efficiency of students; it refers to the adaptive actions of students in time history and the spatial density of the classroom. The study concluded that adaptive thermal comfort depends on human–environment interplay and also revealed the gap between concern about climate change and adaptive action of students on learning efficiency.

Materials and Methods

A sustainable achievement of indoor thermal environment and comfort is often more complex than a question of setting standards in order to meet the occupant demands. In a changing climate, adaptive thermal comfort should be the result of the equal interaction between the environment and occupants. That is, people will need to focus on adaptive approaches in order to maintain thermal neutrality, not only on changing the indoor thermal environment in order to meet their comfort criteria. Using a considerable amount of energy to achieve thermal comfort is unsustainable [37].

By linking the comfort vote to people's actions the adaptive approach links the comfort temperatures to the context in which subjects find themselves [38]. We considered that indoor space and outdoor environments, and adaptive thermal comfort need to involve the following three major basic aspects: air quality, thermal environment, and psychological satisfaction (Table 1).

Conceptualizing Adaptive Thermal Comfort on Learning Efficiency

To date people spend over 90% of their time indoors; therefore, *indoor air quality and human health are* closely connected [16]. Indoor air pollution influences human health and, in addition to causing respiratory diseases, causes poor mental states, slow responses, and a low learning efficiency in people. The indoor air quality directly reflects people's satisfaction level with the indoor air. According to the definition of indoor air quality promulgated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers [39], for a favorable indoor air quality, the air pollutant concentration cannot exceed the hazardous substances index recognized and confirmed by authoritative institutions and more than 80%of people exposed to the air should express no dissatisfaction with the air quality. This definition, except for an objective evaluation, particularly emphasizes subjective evaluation by people. Intelligent context-aware spatial environments are the trend of the future information society; however, instead of controlling the setting conditions of spaces and increasing the complexity for living, such spatial environments should correspond to the needs of the indoor environment of personal residences, learning, and entertainment to enhance the living quality as well as working and learning efficiency of people. By referencing relevant studies on spatial conditions *in classrooms or offices and related personnel*, an observational approach was employed in actual classrooms to develop the correlation between the overall indoor thermal environment and learning efficiency. In addition, the learning efficiency was increased through the intelligent context-aware spatial environments [40].

The study of comfort in teaching and learning environment is very limited, especially for schools. Thermal comfort is defined as "that condition of mind, which expresses satisfaction with the thermal environment" [41]. In Japan, Matsuda, et al. [42] adopted the evaluation instrument, Occupant Satisfaction Survey–Remote Performance Measurement (OSS–RPM), to conduct surveys (i.e., the "Survey Method of Learning Efficiency through Objective Evaluation and Actual Examples") and primarily investigated the influences of indoor air and the thermal environment on the learning efficiency of students in classrooms. To examine the environment that is closest to meeting the most satisfactory space as reported by staff members, a questionnaire survey on psychological satisfaction could be employed. For example, Chou, et al. [43] examined the influences of changes in thermal environments in Taiwanese regions on the psychological satisfaction with academic learning and working efficiency. Chou et al. recruited participants and conducted questionnaire surveys for measurements, set changes in the indoor thermal environment as the stimulating factor, employed a questionnaire rating scale, adopted the Likert Scale, and *scored the* expectation level and actual satisfaction level. Furthermore, the present study designed a rating scale in which both positive and negative questions were incorporated and scored on a positive and negative 5-point scale, in which 1 to 5 indicated *extremely dissatisfied* to *extremely satisfied*, respectively. The results indicated that the preferred thermal environment condition for improving work efficiency involved a temperature of 22°C and humidity of 40% and 60%.

Author	Methods	Key Information
Chong HC, (2010) [44]	Simulating the indoor environments at different temperatures, humidity, and wind velocities as well as referring to Taguchi methods to obtain the most suitable thermal environment module.	The most satisfying module for the youth group and middle-aged group had a temperature of 25 °C, humidity of 60%, and wind velocity of 0.5 m/s.
Chou, et al. (2009) [43]	Actual recruitment of personnel for measurements and questionnaire surveys were conducted to investigate the influences of different indoor environments on the psychological satisfaction and work efficiency of participants.	The preferred thermal environment condition for improving work efficiency involved a temperature of 22 °C and humidity of 40% and 60%.
Matsuda, et al. (2004) [42]	Offices or classrooms were used as the experimental sites, and the OSS–RPM was employed to evaluate the satisfaction level of office staff members and level of space function.	The OSS–RPM instrument was suitable for investigating office spaces in universities.
Raimo, et al. (2002)	Actual architectures were used as examples, and an observational approach was employed to investigate the correlation between the labor productivity and learning efficiency of employees and the thermal environments.	The observational approach indicated that learning efficiency is correlated with the overall indoor environment conditions and thermal environments.

Table 1: Key information about thermal environment and comfort.

According to the literature review, we summarized three factors that influenced adaptive thermal comfort: indoor thermal environment, spatial density, and time history (Figure 1). An evaluation questionnaire on the three aspects was employed to conduct the self-evaluation survey on learning efficiency. To determine the psychological feelings of the participants in different environmental modules, we arranged the semantic differential method. This method has been customarily employed in relevant experiments on environmental perception, for psychological evaluation, which is scored on a7-point Likert scale ranging from -3 to +3, emphasizing a *hierarchical result* beneficial for understanding and communicating the difference in psychological feelings [45]. An obtained numerical value near -3/ +3 indicates an increasingly uncomfortable / comfortable psychological feeling.

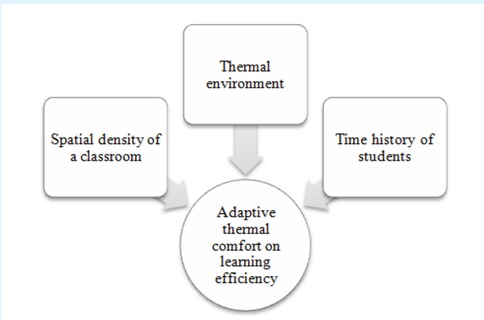

Figure 1: The conceptual framework of adaptive thermal comfort on learning efficiency.

Conducting Classroom-Based Experimental Project

As aforementioned, we focused on environmental conditions of the classroom (spatial density) and perceptual conditions of the students (time history), conducted the literature reviews to compile relevant research topics, and analyzed the primary variable influencing the adaptive thermal comfort level to achieve learning efficiency of students. Through the formulas of PMV and PPD, students' satisfaction level referred to spatial density, time history, and indoor thermal environment was calculated. The conditions of the experimental classrooms incorporated fully air-conditioned (FA) and naturally ventilated (NV) environments. In addition, continuous monitoring methods were employed to examine the influences of indoor and outdoor space to provide insights into students' adaptive actions that can effectively facilitate their learning efficiency. Figure 2 illustrates the structure of the experimental project that incorporated classroom environments and students' perceptions and involved fully air-conditioned environments, naturally ventilated environments, spatial density, and spatial history.

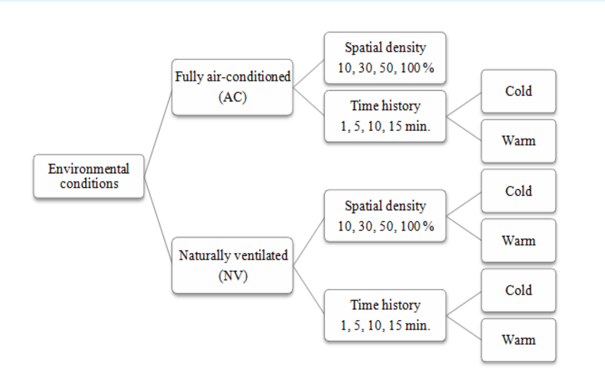

Figure 2: Structure of the experimental project.

The influence of spatial density and time history on the perception of students was particularly emphasized in this study. A theory proposed in previous studies explained that crowding phenomena resulting from different spatial densities influence the physical and psychological states of people and that, in the process of space usage, people's behaviors and cognitions *generate different* environment perceptions and reactions [46-48].

We focused on different spatial densities that involved different classroom conditions and students to examine the influences of spatial density on learning efficiency:

- The experimental site was centered on a classroom at the Chinese Culture University, divided into two spaces: a fully air-conditioned (AC) space that had no windows but an air-conditioning facility, and a naturally ventilated (NV) space that had windows but no air-conditioning facility. Both spaces measured 39 m^3 (5 min length, 3 min width, and 2.6 min height) and had 15 seats (Figure 3).
- The participants were students from the Chinese Culture University, and the number of 2, 6, 8, and 15 participants corresponded to the spatial density of 10%, 30%, 50%, and 100%, respectively (Figures 4 & 5).

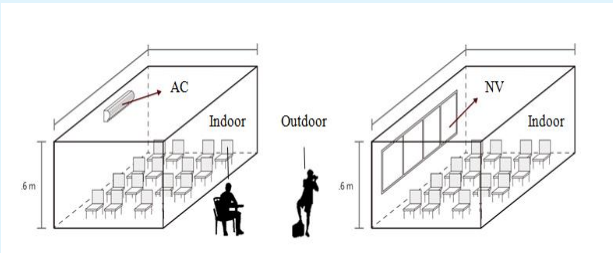

Figure 3: The classroom at the Chinese Culture University divided into two spaces: a fully air-conditioned (AC) space that had no windows but an air-conditioning facility (left), and a naturally ventilated (NV) space that had windows but no air-conditioning facility (right).

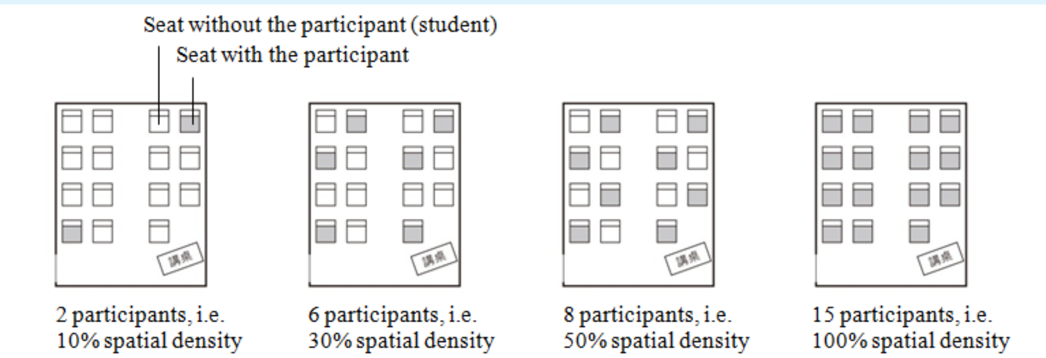

Figure 4: Classroom types based on spatial density: the number of 2, 6, 8, and 15 participants corresponded to the spatial density of 10%, 30%, 50%, and 100%, respectively.

Figure 5: Different number of participants and spatial densities of the classroom (from left to right): 6 participants (30% spatial density), 8 (50%), and 15 (100%).

On procedure of the experimental project, fifty minutes were allotted for evaluating learning efficiency that was evaluated in class and through a questionnaire (40 min and 10 min, respectively; Fig. 6). The experimental contents and procedures involved using films from the Discovery Channel as the teaching material. After all the experimental data were recovered, the data were compiled, and invalid questionnaires because of incorrectness or untruthfulness were excluded. The remaining valid questionnaires were statistically analyzed for correlative comparisons (Figure 6).

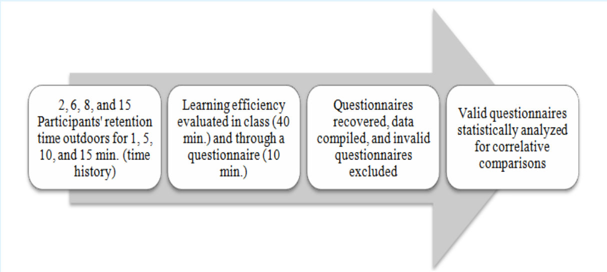

Figure 6: Procedure of the experimental project in the study.

Analysis of Indoor Thermal Environment

According to the experimental project, we employed thermal comfort theory proposed by Fanger [49,50] as the basis and used the functional relationship between PMV and PPD to derivate the standard for indoor thermal comfort level and evaluate the indoor physical environment. The explanation is as follows:

- PMV that indicates comfort level was employed to analyze the comfort (satisfaction) level. The most comfortable condition was when the environment condition in which a person is situated satisfies the thermal balanceequation.PMV refers to people's perception of the comfort level of the external environment. The range of the numerical values are frequently presented by (-3.0~+3.0). The meanings represented by the different numerical values range from hot to cold. However, the feeling of the human body in the thermal environment in any climate cannot be determined. Therefore, following Fanger's experimental statistics, the following PMV equation can be derived:

$$PMV = \{0.404\exp(-0.036M) + 0.028\} \times \{(M - W) - 3.05[5.73 - 0.007(M - W) - P_a] - 0.42[(M - W) - 58] - 0.0173M(5.87 - P_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 - (MRT + 273)^4] - f_{cl} \times h_c \times (t_{cl} - t_a)\} \quad (1)$$

- PPD that describes dissatisfaction level was employed to analyze the dissatisfaction level. The PPD proposed by Fanger was obtained by recruiting 1,300 participants of different races and altering the six variables for testing in the laboratory. Each PPD value relatively represented the percentage of the participants who were dissatisfied with the environment, and the proportion of the dis-satisfied participants was called the dissatisfaction level. The equation is as follows:

$$PPD = 100 - 95 \times EXP\left[-0.03353PMV^4 - 0.2179PMV^2\right] \quad (2)$$

Results and Discussions

We primarily focused on the fully air-conditioned (FA) and naturally ventilated (NV)indoor thermal environments in the classrooms to examine the influences of comfort level, dissatisfaction level, classroom spatial density (10%, 30%, 50%, and 100%), and student time history (retention time outdoors for 1, 5, 10, and 15 min) on learning efficiency of the students.

Comfort Level and Learning Efficiency

Changes in comfort level and learning efficiency were compared to determine the influences of different comfort levels in the fully air-conditioned and naturally ventilated spaces on learning efficiency. The standard scores for learning efficiency ranged from -3 to +3.

The experimental data are presented as follows:

- **AC (fully air-conditioning)**
  - The PMVs of -0.34, -0.41, -0.74, and -0.97reflected the learning efficiency score of 1.5, 2.16, 0.83, and 0.66, respectively. The learning efficiency was relatively higher when the PMV was at -0.34.
  - The PMV of -0.41 reflected the relatively highest learning efficiency score of 2.16. A reduction in PMV to -0.74 reduced the learning efficiency score from 2.16 to 0.83, indicating an evident decrease of 1.33 (approximately 22%) and that 0.83 reflected a poor learning efficiency.
  - When PMV was at -0.97, the learning efficiency was at the relatively lowest score of 0.66, suggesting that a PMV near 0 exhibited a high learning efficiency because the participants who were indoors (hereinafter referred to as indoor participants) experienced a favorable feeling of comfort.

- **NV (natural ventilation) with cold air**
  - The PMVs of -0.41, -0.86, -1.34, and -1.61 reflected the learning efficiency score of 0.66, 0.33, -1.33, and -0.83, respectively. The learning efficiency was relatively higher when the PMV was at 0.66.
  - A reduction in PMV to -0.86 reduced the learning efficiency score from 0.66 to 0.33, indicating a slight decrease of 0.33 (approximately 5%). A PMV of -1.34 reduced the learning efficiency score from 0.33 to -1.33, showing an evident decrease of 1.66 (approximately 11%).
  - The PMV that ranged between -1 (slightly cool) and-2(cool) reflected poor learning efficiency because the indoor participants experienced an unfavorable feeling of comfort.

- **NV with warm air**
  - The PMVs of 0.02, 0.61, 0.91, and 2.01 corresponded to the learning efficiency score of 1.83, 0.83, 1, and -1.16, respectively. When the PMV was 0.02, the learning efficiency was at the relatively highest score of 1.83.
  - A reduction in PMV to 0.61and 0.91 reflected the learning efficiency score of 0.83 and 1, respectively, both of which were close.
  - When the PMV was 2.01, the learning efficiency score reduced from 1 to -1.16, indicating an evident decrease of 2.16 (approximately 19%).
  - APMV higher than 0 reflected a poor learning efficiency because the indoor participants experienced unfavorable feelings of comfort that may have influenced them physically and psychologically.

To summarize the aforementioned analysis, in the comparison between the fully air-conditioned and naturally ventilated environments, the PMV ranged approximately between -0.5 and 0.1, and the reflected learning efficiency was relatively higher (Table 4 and Figure 9).

	Temperature (°C)	Humidity (%)	Wind speed(m/s)	Comfort level (PMV)	Learning efficiency
AC (fully air conditioning)	14.16	77.50%	0.01	-0.97	0.66
	17.18	77.50%	0.01	-0.41	2.16
	15.9	65.94%	0.01	-0.74	0.83
	17.7	67.57%	0.03	-0.34	1.5
NV (natural ventilation) with cold air	15.09	86.85%	0.15	-0.86	0.33
	13.93	50.65%	0.48	-1.61	-0.83
	14.64	47.94%	0.34	-1.34	-1.33
	17.78	71.36%	0.12	-0.41	0.66
NV with warm air	20.33	69.50%	0.17	0.02	1.83
	23.54	66.15%	0.24	0.61	0.83
	25.44	49.64%	0.24	0.91	1
	27.55	60.77%	0.21	2.01	-1.16

Table 2: Relationship between comfort level (PMV) and learning efficiency.

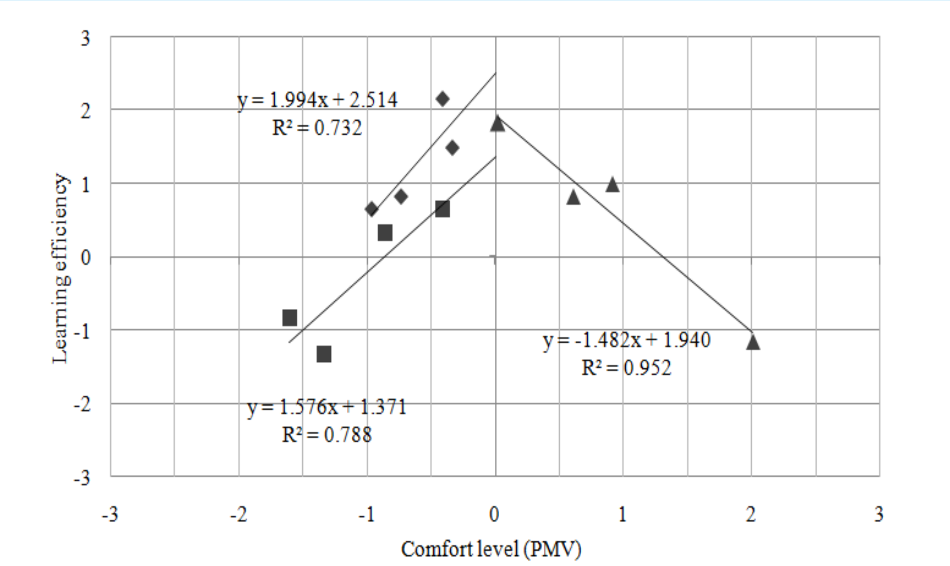

Figure 7: Relationship between PMV and learning efficiency (◆: AC; ■: NV with cold air; ▲: NV with warm air).

Dissatisfaction Level and Learning Efficiency

We compared the changes in dissatisfaction level and learning efficiency to investigate the influences of different comfort levels on learning efficiency in fully air-conditioned and naturally ventilated environments separately. The standard scores for learning efficiency ranged from -3 to +3.

The experimental data are presented as follows:

- **AC (Fully Air-Conditioning)**
  - The PPD of7.70%, 8.51%, 18.25%, and 25.33% corresponded to the learning efficiency scores of 1.5, 2.16, 0.83, and 0.66, respectively.
  - APPD of7.70% reflected a high learning efficiency.
  - When the PPD value was at 8.51%, learning efficiency attained the highest score of 2.16.
  - APPD that increased to 18.25 reduced learning efficiency from 2.16 to 0.83, indicating an evident decrease of 1.33 (approximately 22%). Thus, a score of 0.83indicated poor learning efficiency.
  - APPD of25.33%reflectedtherelatively poorest learning efficiency score of 0.66, indicating that a numerical value near 0suggested a high learning efficiency because the indoor participants demonstrated a low dissatisfaction level and more favorable feelings toward the indoor environments.
  - A high PPD suggested a high dissatisfaction level and low learning efficiency demonstrated by the participants.

- **NV with Cold Air**
  - The PPD of 8.64%, 21.46%, 50.49%, and 56.49% corresponded to the learning efficiencyscoresof0.66, 0.33, -1.33, and -0.83, respectively.
  - When the PPD value was at 8.64%, learning efficiency, which attained a score of 0.66,was at the relatively highest.
  - An increase of PPD to 21.46% reduced the learning efficiency score from 0.66 to 0.33, suggesting a slight decrease of 0.33 (approximately 5%).
  - When the PPD was higher than 50% and at 50.49%, the learning efficiency score reduced from 0.33 to -1.33, showing an evident decrease of 1.66 (approximately 11%).

- **NV with Warm Air**
  - When the PPD was at 5.47%, 14.46%, 23.11%, and 76.70%, the corresponding learning efficiency score was 1.83, 0.83, 1, and -1.16, respectively.
  - The PPD at 5.47% suggested the relatively highest learning efficiency, which attained a score of 1.83.
  - The PPD that increased to 14.46% reduced the learning efficiency score to1.
  - When the PPD was higher than 70% and at 76.70%, the learning efficiency score reduced from 1 to -1.16, evidently decreasing2.16 (approximately 19%).

The indoor participants with a low dissatisfaction level demonstrated a high learning efficiency, indicating that an appropriate reduction in dissatisfaction level can effectively increase learning efficiency. To summarize the aforementioned analysis, a PPD of less than10% indicated a high learning efficiency (Table 5 & Figure 10).

	Temperature (°C)	Humidity (%)	Wind Speed (m/s)	Dissatisfaction level (PPD)	Learning efficiency
AC	14.16	77.50%	0.01	25.33%	0.66
	17.18	77.50%	0.01	8.51%	2.16
	15.9	65.94%	0.01	18.25%	0.83
	17.7	67.57%	0.03	7.70%	1.5
NV with cold air	15.09	86.85%	0.15	21.46%	0.33
	13.93	50.65%	0.48	56.49%	-0.83
	14.64	47.94%	0.34	50.49%	-1.33
	17.78	71.36%	0.12	8.64%	0.66
NV with warm air	20.33	69.50%	0.17	5.47%	1.83
	23.54	66.15%	0.24	14.46%	0.83
	25.44	49.64%	0.24	23.11%	1
	27.55	60.77%	0.21	76.70%	-1.16

Table 3: Relationship between dissatisfaction level (PPD) and learning efficiency.

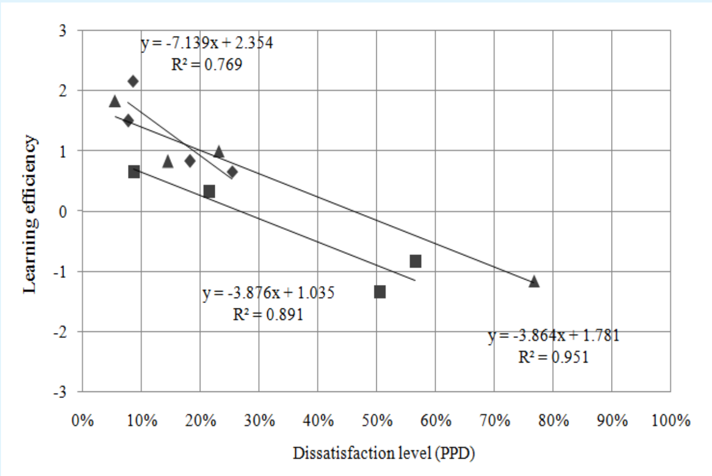

Figure 8: Relationship between dissatisfaction level and learning efficiency (◆: AC; ■: NV with cold air; ▲: NV with warm air).

Spatial Density and Learning Efficiency

We compared the changes in spatial density and learning efficiency to examine the relationship between the spatial densities of 10% (approximately two people), 30% (approximately six people), 50% (approximately eight people), and 100% (approximately 15 people) and learning efficiency separately. The standard scores for learning efficiency ranged from -3 to +3.

The experimental data are shown as follows:

- **AC (fully air-conditioning)**

➢ The spatial density of 10% reflected the highest learning efficiency, which was scored2.5. An increase in spatial density reduced learning efficiency. An increase in the spatial density from 30% to 50% reduced the learning efficiency score from 2.16 to 0.25, an evident decrease of1.91 (approximately 27%). The indoor participants experienced a sense of crowdedness because of an increase in spatial density, which influenced the learning efficiency of the participants.

➢ The spatial densities of 50% and 100% reflected the learning efficiency scores of 0.25 and -0.2, respectively, suggesting a difference of 0.45 between the scores of the two densities. The proximity of the two spatial densities in their scores indicated that the sense of crowdedness generated from the spatial density of 50% and 100% were similar, and thus, changes in learning efficiency were few and less than those when the spatial density was low.

➢ The spatial density of 100% reflected the poorest learning efficiency. In comparison, when the spatial density was 10%, learning efficiency reduced from 2.5 to -0.2, suggesting a decreaseof2.7 (approximately 45%). In addition, in a naturally ventilated (cold air) space, the spatial density of 10% reflected the highest learning efficiency, which attained a score of 0.5. An increase in the spatial density reduced learning efficiency. An increase in the spatial density from 10% to 30% reduced learning efficiency from 0.5 to -1.33, an evident decrease of 1.83 (approximately

13%), indicating that an increase in the spatial density increased the sense of crowdedness experienced by the indoor participants and influenced their learning efficiency.

- When the spatial density was 30%, 50%, and 100%, the corresponding difference among all of the learning efficiency scores was less than0.3, suggesting that the sense of crowdedness that resulted from changes in the three types of spatial density had little influence on learning efficiency, which was poor. The learning efficiency was the poorest when the spatial density was 100%. When the spatial densitywas10%, the learning efficiency reduced from 0.5 to -1.8, suggesting a decrease of 2.3 (approximately 21%).

• **NV**

- The spatial density of 10% reflected the highest learning efficiency, which attained a score of 1.
- An increase in the spatial density reduced learning efficiency, and an increase in spatial density from 10% to 30% reduced learning efficiency from 1 to 0.66, indicating a decreaseof0.34 (approximately 5%).
- An increase in the spatial densityfrom30% to 50% reduced learning efficiency from 0.66 to -1.66, indicating an evident decrease of 2.32 (approximately 22%). A high sense of crowdedness was generated under such a condition and influenced learning efficiency.

To summarize the aforementioned analysis, when comparing the spatial density with full air-conditioning and that with natural ventilation (cold and warm air), we determined that the temperature and humidity in the fully air-conditioned space were close to the comfort range for people. In addition, the fully air-conditioned space had a lower wind speed, was associated with a higher satisfaction level, and reflected higher learning efficiency compared with the naturally ventilated space. Therefore, learning efficiency differed in spaces with the same spatial density but different indoor physical environments. Table 2 and Figure 7 provide the influences of comfort level on learning efficiency with different changes in temperature, humidity, and wind speed.

	Temperature (°C)	Humidity (%)	Wind Speed (m/s)	Spatial density	Learning efficiency
AC	18.39	71.70%	0.01	10%	2.5
	17.18	77.50%	0.01	30%	2.16
	17.74	74.63%	0.01	50%	0.25
	17.85	72.83%	0.01	100%	-0.2
NV with cold air	13.95	50.13%	0.48	10%	0.5
	14.64	47.94%	0.34	30%	-1.33
	14.96	46.28%	0.38	50%	-1.5
	15.08	46.08%	0.5	100%	-1.8
NV with warm air	27.55	60.77%	0.21	30%	0.66
	27.1	62.72%	0.25	50%	-1.66
	26.3	64.18%	0.27	100%	-1.5

Table 4: Relationship between spatial density and learning efficiency.

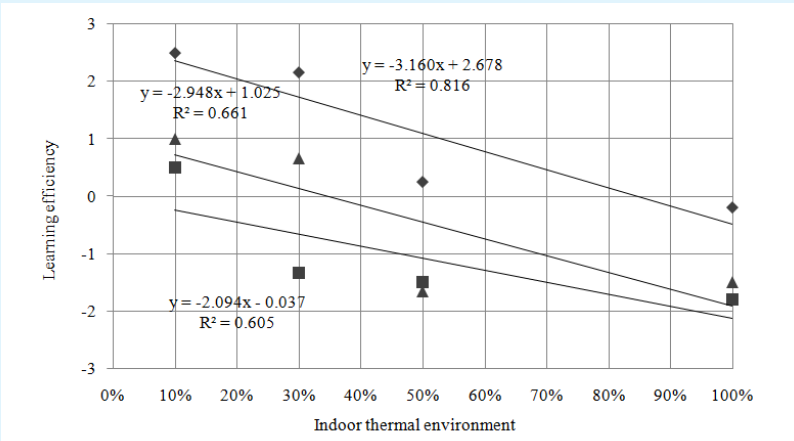

Figure 9: Comparison between indoor thermal environment and learning efficiency (◆: AC; ■: NV with cold air; ▲: NV with warm air).

Time History and Learning Efficiency

We compared changes in different spatial histories and learning efficiency to examine the relationship between the retention time of 1, 5, 10, and 15 min outdoors and learning efficiency separately. The standard scores for learning efficiency ranged from -3 to +3. The experimental data are presented as follows:

- **AC space and the time history (of students) with cold air**
  - The experiment of the spatial history (the retention time outdoors) of 1 min reflected the highest learning efficiency, which attained a score of 1.33. An increase in the retention time outdoors reduced learning efficiency.
  - Compared with the learning efficiency when the retention time outdoors was 1 min, the learning efficiency score reduced from 1.33 to 0.83, a slight decrease of 0.5 (approximately 8%), in the spatial history of 5 min.
  - An increase in the spatial history to 10 min reduced the learning efficiency score from 0.83 to -0.83, an evident decrease of 1.66 (approximately 27%). The wind speed in outdoor spaces was higher than that in the fully air-conditioned spaces and thus indirectly influenced the comfort level of outdoor environments. Therefore, the comfort level of an outdoor space was poorer than that of a fully air-conditioned space. An increase in spatial history increased the time in which the indoor participants were exposed to outdoor environments and may thus influence the participants' physical and psychological states as well as their learning efficiency.
  - The spatial history of 10 and 15 min both reflected the learning efficiency score of -0.83, indicating that the retention time outdoorsof10 and 15 min exerted similar influences on the participants who were exposed to outdoor spaces. Therefore, no significant difference was shown in learning efficiency between the two experiments, and the learning efficiency was the most inferior.

- **AC space and the time history with warm air**
  - The spatial history of 1 min reflected the highest learning efficiency.
  - Compared with learning efficiency during which the retention time outdoors was 1 min, learning efficiency reduced from 1.66 to 1.16, a slight decrease of 0.5 (approximately 8%), in the spatial history of 5 min.
  - When the spatial history increased to 10 min, learning efficiency reduced from 1.16 to 0.33, with a decrease of 0.83 (approximately 13%).

To summarize the aforementioned analysis, in a fully air-conditioned environment, the changes in spatial history influenced the learning efficiency of the indoor participants. An increase in the retention time outdoors reduced learning efficiency.

In addition, in a naturally ventilated environment with cold air, the spatial histories (retention time outdoors) of 1, 5, 10, and 15 min reflected the learning efficiency scores of -1.5, -1.16, -1.33, and -1.16, respectively. All of the scores were between -1 and -2, and the differences among them were less than0.4, which was minor. In a naturally ventilated environment with cold air, the experiments in which the spatial histories were1, 5, 10, and 15 min revealed the learning efficiency scores of 0.16, -0.5, -0.33, and -0.66, respectively. All of the scores were between 0.3and -0.7, indicating minor differences among them. Therefore, the changes in spatial history slightly influenced the learning efficiency of the indoor participants, and learning efficiency was consistently low. Because in a naturally ventilated environment, no significant difference was observed between the comfort levels of indoor and outdoor spaces, the influences of retention time on the participants outdoors were thus relatively minor, and learning efficiency was poor (Table 3 and Figure 8).

	Indoor/Outdoor temperature (°C)	Indoor/Outdoor humidity (%)	Indoor/Outdoor wind speed (m/s)	Time history (min)	Learning efficiency
AC with cold air	15.61/14.23	63.74%/65.66%	0.01/0.26	1	1.33
	15.74/14.45	63.9%/66.85%	0.01/0.31	5	0.83
	15.75/14.36	63.83%/66.66%	0.01/0.23	10	-0.83
	15.66/14.73	63.37%/65.56%	0.01/0.33	15	-0.83
AC with warm air	20/25.6	63.06%/65.33%	0.01/0.31	1	1.66
	21.37/25.83	60.66%/63.66%	0.01/0.28	5	1.16
	20.6/26.1	63.4%/65.84%	0.01/0.33	10	0.33
	20.43/25.43	65.98%/66.31%	0.01/0.24	15	0.5
NV with cold air	15.4/15.36	70.65%/70.6%	0.17/0.15	1	-1.5
	15.28/15.2	66.5%/66.2%	0.25/0.31	5	-1.16
	15.24/15.18	68.55%/69.12%	0.24/0.28	10	-1.33
	15.34/15.26	69.49%/69.23%	0.21/0.26	15	-1.16

	Indoor/Outdoor temperature (°C)	Indoor/Outdoor humidity (%)	Indoor/Outdoor wind speed (m/s)	Time history (min)	Learning efficiency
NV with warm air	27.75/28.1	50.03%/50.12%	0.27/0.22	1	0.16
	28.55/28.73	46.56%/47.12%	0.19/0.21	5	-0.5
	27.86/28.12	48.35%/47.96%	0.32/0.29	10	-0.33
	27.77/28.03	46.77%/46.45%	0.26/0.28	15	-0.66

Table 5: Relationship between time history and learning efficiency.

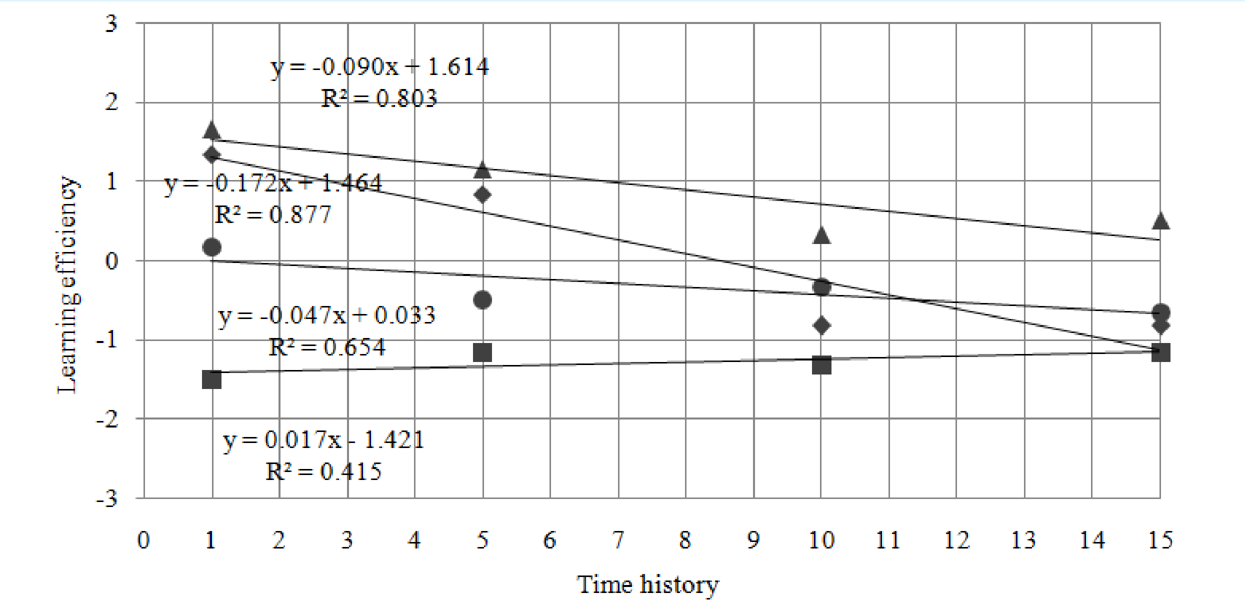

Figure 10: Relationship between time history and learning efficiency (◆: AC with cold air; ■: NV with cold air; ▲: AC with warm air; ●: NV with warm air).

Conclusion

Climate changes will affect different aspects of the indoor thermal environment as well as the stakeholders of that indoor environment. Indoor thermal environment prompts a relative increase in people's demands for comfortable living spaces. According to a relevant survey, most people currently spend 80%–90% of their time indoors. The indoor environments of poorly designed architectures negatively influence the learning efficiency and health condition of people. To ensure that people who are indoors have healthy and comfortable indoor experiences and to increase the learning efficiency of people, the satisfaction level of people and quality of indoor environments are crucial topics.

We investigated the influences of indoor thermal environments on learning efficiency, focused on the environment perception performed by students at different spatial densities and histories, and employed PMV and PPD to examine the conditions of the indoor thermal environments. In addition, we proposed key information that can effectively increase the learning efficiency of people and serve as a reference for improving teaching environments.

The primary conclusion is as follows:

- **PMV:** The trend line indicated that a PMV near 0 suggested a favorable comfort feeling experienced by the indoor participants, and thus, a high learning efficiency was reflected. In the comparison between a fully air-conditioned space and a natural environment space, the PMV that ranged from approximately -0.5 to 0.1 reflected a high learning efficiency. Shoko et al. indicated that the learning efficiency was at its highest when the PMV and PPD was -0.1% and 5%, respectively, during which the learning efficiency can increase to approximately 8.7%.

- **PPD:** The trend line suggested that a PPD near 0 reflected a learning efficiency because the indoor participants demonstrated a low dissatisfaction level and favorable feeling toward the indoor environment. The results suggested that a numerical value of less than 10% reflected a high learning efficiency. Murakami (2004) indicated that a high satisfaction level demonstrated by indoor participants suggested a high learning efficiency, which supported this study.

- **Spatial Density:** A spatial density of 10% reflected the highest learning efficiency, and an increase in the spatial density reduced learning efficiency. The learning efficiency was poor when the spatial density was 100%. For the indoor participants, an increase in the spatial density increased the sense of crowdedness, thus generating changes in the feelings and perceptions of the participants and influencing their learning efficiency. An appropriate reduction in the spatial density can effectively increase learning efficiency. In a fully air-conditioned space with a spatial density of 10%, learning efficiency was the highest.

• **Time History:** An experiment in which the retention time of 1 min outdoors reflected the highest learning efficiency. An increase in the retention time outdoors reduced the learning efficiency because the temperature and wind speed of the outdoor environment indirectly influenced the comfort level. Therefore, the comfort level of the outdoor environment was lower than that of the indoor environment. An increase in the spatial history lengthened the exposure time of the indoor participants in outdoor environments and may thus influence their physical and psychological states as well as their learning efficiency. In addition, in a naturally ventilated space and an environment with an outdoor climate (cold and warm), because no significant difference was observed between the comfort levels of indoor and outdoor spaces, the influences of retention time on the participants outdoors were relatively minor and consistent, and learning efficiency was poor.

Overall, learning efficiency can be effectively increased when an environment is fully air-conditioned, its spatial density is appropriately reduced, the PMV ranges between -0.5 and 0, and the PPD is less than 10%. This finding can serve as a reference for future educational location designs. In addition, the spatial density of the classroom and the spatial history of the students influenced the learning efficiency of the students, and these influences were social, cultural, temporal, and physical. We considered that learning efficiency depends on human–environment interaction, which is related to the cultural backgrounds of the students. Thus, the values in which the students were being shaped resulted in their different perceptions and attitudes, which influenced their learning efficiency [51]. In the teaching environments, the feelings and behaviors of people that generated from the human-environment interaction involves a series of cycles. In short, the classroom condition and outdoor environment influence the learning efficiency of students and are related to their environmental perceptions, which are reflected in the students' comfort levels and experiences of being in different indoor and outdoor spaces [52]. We underlined the adaptability that reflects young people's adaptive regulation in the face of change. We concluded that adaptive actions of students in time history and the spatial density of the classroom depend on human-environment interplay and revealed that the learning efficiency will be dominated by students' adaptability to be distracted not the temperatures.

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Availability of Data and Material

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Authors' Contributions

All authors contributed to the interpretation of finding and equally in the preparation of this manuscript.

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