Study on the Productivity in Classroom (Part 2)
Realistic Simulation Experiment on Effects of Air Quality/Thermal Environment on Learning Performance

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Summary: *Many research papers have been published on the potential effects of indoor environmental quality in classrooms and offices on productivity. This paper (Part 2) report on the laboratory experiments, focusing on varying the ventilation rate as in the field measurements, and will evaluate the consistency between the field measurements and the laboratory experiments.*

Keywords: *Productivity, Learning Performance, Realistic Simulation Experiment*

1. Introduction

This paper (Part 2) reports the results of realistic simulation experiment in climate chamber that was based on the results of the field intervention survey on learning performance reported in the previous paper (Part 1). The realistic simulation experiment was conducted on subjects in a climate chamber where the environmental conditions were replicated to be almost identical to conditions in the class-rooms used for the field measurements, and where the environmental factors were precisely controlled. The experiment reported in this paper aimed to study the quantitative effects of the Air quality and thermal environments on learning performance.

1. Outline of Experiment

In this realistic simulation experiment of learning performance, the air-conditioning and ventilation system in Nikken Gakuin College – i.e. the class-rooms used for the field intervention surveys – were exactly replicated, and various environmental conditions were created using HVAC system, which changed the percentage of outdoor air flow rate and returned air flow rate in the supplied air. In addition, the changes in the thermal environment with changes in the percentage of outdoor air flow rate (ventilation rate) were also replicated. The lecture (educational) contents and the time schedule for the lectures precisely simulated those of Nikken Gakuin College. While it is difficult to precisely control the physical environmental factors in field measurements, in the climate chamber experiment we were able to control these environmental factors and precisely evaluate the effects of the thermal and air quality environments on the learning performance. An in-depth study was also conducted using the quiz score data and self-assessed psychological factors to evaluate the consistency between the subjective and objective evaluations. Figure 1 shows a scene of the climate chamber experiment.

The realistic simulation experiment was carried out from November 1 to November 17, 2004 in the climate chamber at the Taisei Technology Center. The climate chamber has a space volume of dimensions 9.6 m × 6.4 m × 2.8 (h) m. The layout including desks, chairs and the density of people (the number of subjects per unit floor area) was set to match the conditions at Nikkei Gakuin College. The class was replicated by projecting DVD-based video image lectures from Nikken Gakuin College onto a screen installed at the front of the climate chamber as shown in Figure 1 and 2.

Figure 1 Photo of Realistic Simulation Experiment

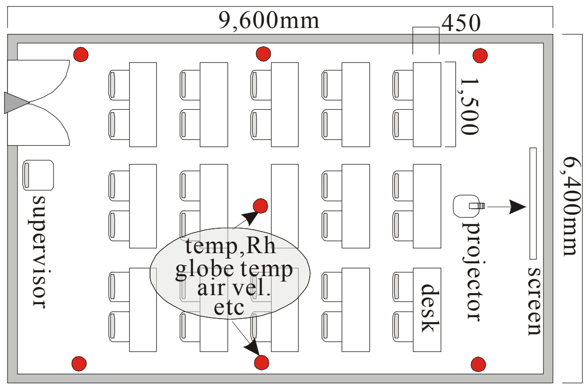


Figure 2 Plan of Climate Chamber

1.1 Experimental Conditions

This realistic simulation experiment in climate chamber was conducted in the winter season. The target environmental factor controlled is ventilation rate (percentage of outdoor air flow rate) and the environmental conditions were set for two cases; a

Table 1 Experimental Conditions

Outline of Climate Chamber		$9.6\times6.4\times2.8^h$ m ($61.4m^2$) AHU (Mechanical Vent Sys)	
Vent. Rate (outdoor air)	Lecture contents	Number of Subjects	Temp.&Rh
High ($2.7h^{-1}$), (458 m^3/h)	Memorization Subjects I	56 (M34,F22)	25.0(°C),45(%)
Low ($0.5h^{-1}$), (78 m^3/h)			27.3(°C),45(%)
High ($7.2h^{-1}$), (1230 m^3/h)	Memorization Subjects II	56 (M34,F22)	25.5(°C),40(%)
Low ($0.4h^{-1}$), (69 m^3/h)			28.3(°C),60(%)
High ($7.2h^{-1}$), (1230 m^3/h)	Memorization Subjects III	56 (M34,F22)	25.0(°C),50(%)
Low ($0.4h^{-1}$), (69 m^3/h)			27.0(°C),60(%)

Table 2 Questions of Standardized Quizzes for the Objective Evaluation (in the fields of architectural planning)

Question 10; Which is the **most improper one** among the following descriptions concerning various wiring methods used for the office construction?

(1) The free-access floor wiring method makes the floor a double floor, and it is a method of using between those as wiring space, and there is an effect of reducing the design load of the floor.
(2) The floor on the standard floor was made to the free-access floor of 6cm in height, and to correspond to the change in the layout of the office, considered in the office building.
(3) Under the carpet wiring method is a method to construct a thin cable directly in the above the floor level, and special floor finish is needed. However, it is possible to correspond to the change easily.
(4) It wires a necessary place, and the bus baton wiring method is large the maximum, permissible current, and in the method to accommodate and to protect the conductor in this, is suitable for a mass power supply.
(5) In general, the conductor used for the bus baton wiring method is copper or, aluminum.

Table 3 Part of Self-Assessment Form for the Subjective Evaluation

Question 5; **Air Environment** (Contamination and smell of air)

(1) Are you satisfied with a current air environment? [ ].
1.) Desatisfied 2.) Slightly Desatisfied 3.) Medium 4.) Slightly Satisfied 5.) Satisfied

(2) What influence does today's air environment give to the level of the lecture contents understanding? [ ].
1.) Disimproved 2.) Slightly Disimproved 3.) No Influence 4.) Slightly Improved 5.) Improved

Question 8; **Understanding level** of lecture contents

(5) Convert at the time (in minutes) lost due to factors in various indoor environment in the classroom today.
[ ].min

high-ventilation environment (All outdoor air) and a low-ventilation environment (100 % returned air only, with no intake of outdoor air). Taking into account the potential thermal environmental changes with changes in the ventilation rate, the thermal environments were controlled at about 25 °C, 50 % for the high-ventilation environment, and at about 27 °C, 60 % for the low-ventilation environment. Including the preliminary experiment to identify the ability of the individual subjects, totally six conditions were set for the experiments.
Table 1 shows the experimental conditions.

1.2 Subjects

The subjects were undergraduate and graduate students preparing for the qualifying examination for first-class authorized architects, and pre-screening was done to motivating them to study in class to the same degree as the Nikken Gakuin college students. The total number of subjects was 56 (34 males, 22 females) and they were put into two groups. To eliminate the effect of repeatedly partaking in the experiment, the order in which they were exposed to the environmental conditions in the high-ventilation environment and the low-ventilation environment was made different between the two groups. A reasonable fee was paid to the subjects after the whole experiment was completed. With the circadian rhythms of subjects taken into account, simulation experiments under the six different conditions were conducted during the same hours on the same day of the week, at one week intervals.
The amount of clothing was determined at approx. 0.7 [clo] assuming winter conditions, and the subjects were not allowed take off any clothes during the experiment.

2. Methods

An objective evaluation of learning performance was made by judging the scores on quizzes (tests) that measured the level of understanding of the lecture contents. The lecture content was corresponding to the contents of the qualifying examination for first-class authorized architects and it was changed every week so that the subjects would not take the same lecture again. We made sure that the lecture contents was selected from areas that the subjects had not previously studied at their respective universities, and thus the difference in the knowledge level should not have an impact on the learning performance. The quiz consisted of 20 questions, each of which was answered by choosing one out of five options and it was completed in 30 minutes after the class. The difficulty level differed depending on the lecture contents and the quiz level, so the average scores could not be simply compared with one another. We judged that Nikken Gakuin's average score data for the previous year (2004 FY) could be taken to represent the difficulty level of the quiz because the number of the students was very large. Therefore a correction was made to the score using Nikken Gakuin's average quiz score data for 2004 FY.

To gain a subjective evaluation of learning performance, self-assessment forms (Questionnaire) for subjective evaluation were distributed to the subjects. The part of the items in the self-assessment form is shown in Table 3. They included items that give a quantitative evaluation of the learning performance, such as the time lost due to the indoor environment and the improvement rate in the level of understanding of lecture content with improvements in the indoor environment.

In addition to the objective and subjective evaluations of learning performance, the number of subjects napping was measured at constant intervals as part of the effects of the ventilation rate on learning performance. A person (supervisor) positioned at the rear of the climate chamber recorded any subjects who were napping every 10 minutes.

Figure 2 also shows the respective measurement points for individual measurement factors of the physical environment. As the air quality environmental factors, in addition to carbon dioxide concentrations measured in a time series, the ventilation rate and concentration levels of volatile organic compounds (VOCs) were measured. Carbon dioxide concentrations were measured using an IAQ monitor (KANOMAX Co. ltd.). They were measured at one minute intervals continuously during the experiment. The ventilation rate was measured using the step-down method and a SF6 as tracer gas was used and concentrations were measured using a multi-gas monitor (INNOVA Co. ltd.). Volatile organic compounds were collected by active sampling on a Tenax TA, and were analyzed by GC/MS. Carbonyl compounds were collected by active sampling on a DNPH, and were analyzed qualitatively and quantitatively by HPLC. Background VOCs levels were measured while the experiment was not being conducted.

The air quality and thermal environmental factors, including air temperature, air speed, relative humidity, glove temperature (radiation temperature), and wall surface temperature were measured at one minute intervals continuously during the experiment. Further, desktop illumination levels were measured (at the center of each desk and the average of the values at 10 locations was determined as the desktop illumination in the climate chamber) with an illuminometer (KONIKA MINOLTA Co. ltd.) and indoor equivalent sound levels were measured with a noise meter (RION Co. ltd.). The sound level measurement was conducted with the air-conditioning system and the projector in operation.

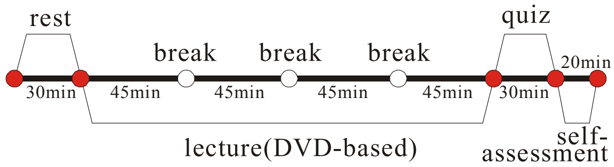


Figure 3 Experimental Procedure

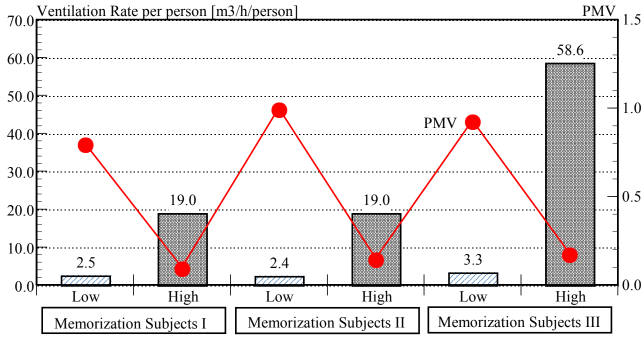


Figure 4 Ventilation Rate per Person and PMV

In addition to measuring the physical environment, the self-assessment forms were used to determine the psychological factors of the subjects; they were asked to record on the form their satisfaction levels and sensing levels for the thermal, air quality, lighting, sound, and spatial environments.

Figure 3 shows the experimental procedure of subjects. After entering the room, the subjects were seated on a chair quietly for 30 minutes to adapt themselves to the environment. The time schedule after that simulated the classroom at Nikken Gakuin College. They were allowed to change their posture or go to the restroom; however, eating and drinking were prohibited during lectures. After all lectures were finished, they took a 30-minute quiz and then filled in the self-assessment form.

The significance level was set at 5% and a corresponding t-test was used to compare quiz results with varying environmental conditions. The Wilcoxon matched-pairs signed rank test was used as a corresponding rank scale in comparing the results of self-assessment with varying environmental conditions.

3. Results

3.1 Physical Environment

Figure 4 shows the results of measuring ventilation rate per person and PMV. PMV calculated based on the results of measuring the thermal environment under conditions of a metabolic rate of 1.0 [met] and 0.7 [clo] of clothing. The outdoor air rate was 458 m^3/h (2.7 air changes per hour) for memorization subject I, 539 m^3/h (3.1 h^{-1}) for memorization subject II and 1230 m^3/h (7.2 h^{-1}) for memorization subject III in the high-ventilation environment, and 78 m^3/h (0.5 h^{-1}) for memorization subject I and II, and 69 m^3/h (0.4 h^{-1}) for memorization subject III in the low-ventilation environment. In the low-ventilation environment, the air was only returned and there was no intake of outdoor air; however, some infiltration in the air-conditioning system allowed a certain amount of outdoor air.

In the high-ventilation environment, the carbon dioxide concentration became almost constant at an average of 1000 [ppm] during the experiment. In the low-ventilation environment, the indoor concentration gradually increased due to air exhaled by the subjects in the room, who became sources of carbon dioxide emissions, and eventually reached a maximum 3700 [ppm] at the end of the experiment (average 2800 [ppm]).

Concerning VOCs concentrations, the low ventilation experiment recorded a somewhat higher concentration than in the high-ventilation environment; however, in neither case did the level of chemical compounds exceed the guideline values for WHO.

The physical factors related to the thermal environment were held almost constant during the experimental period.

The desktop illumination level was 631±24 [lx] as an average for all seats, and the equivalent noise level was 43.6 [dB].

3.2 Evaluation of Learning Performance

Figure 5 shows the results of objective evaluation of quizzes (average scores) taken after lectures. Since the lecture contents used for each set of environmental conditions was different, the difficulty level of the individual standardized quizzes (test) was standardized by correcting the scores based on Nikken Gakuin's average score data for 2004 FY. In this laboratory experiment, the lectures given only covered memorization subjects (in the fields of planning and construction).

For the Memorization Subject I, an improvement of 3.8 points (n.s.) resulted with the change in environmental conditions from low to high ventilation. For the Memorization Subject II, an improvement of 3.8 points ($p<0.09$) resulted with the change in environmental conditions from low to high ventilation. For the Memorization Subject III, an improvement of 4.4 points ($p<0.06$) resulted with the change in environmental conditions from low to high ventilation.

Figure 6(1) shows the results of the self-assessment of time lost due to the indoor environment (average values). Time lost due to the indoor environment is based on the response to the question; "Please convert the influence and/or the frequency of influences of the indoor environment in the classroom on your understanding of today's lecture contents into time deemed to be lost."

A significant increase in "time deemed to be lost due to the indoor environment" resulted in the low-ventilation environment compared with the high-ventilation environment. For the Memorization Subject II, a significant decrease of 34.8 minutes ($p<0.00001$) in "time lost due to the indoor environment" resulted with the change in environmental conditions from low to high ventilation.

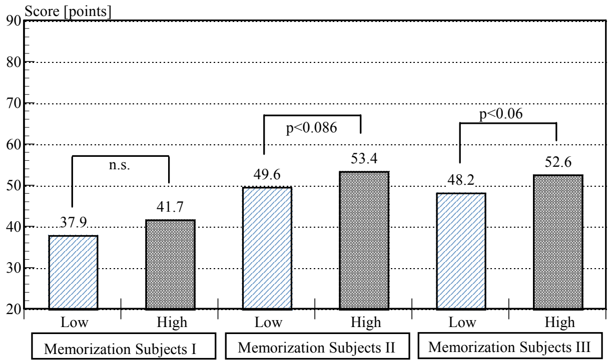
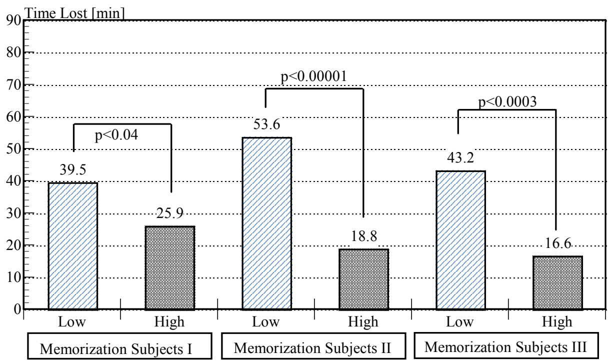
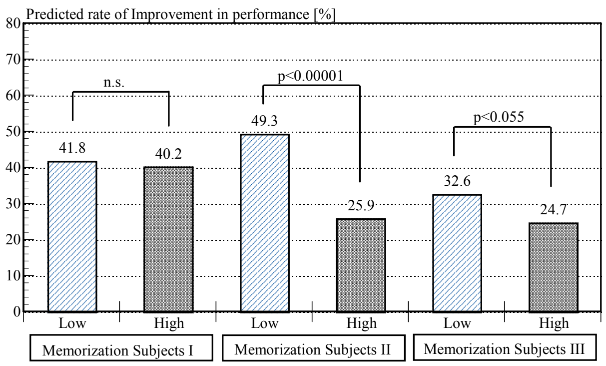


Figure 5 Results of Objective Evaluation



(1) Time lost due to the indoor environment



(2) Predicted rate of improvement in learning performance with an improvement in the environment

Figure 6 Results of Subjective Evaluation

Table 4 Percentage of Dissatisfied

	Air env. Dissatisfied [%]		Thermal env. Dissatisfied [%]	
Ventilation	Low	High	Low	High
Memorization Subjects I	59.0%	17.9%	33.3%	30.8%
	$p<0.00001$		n.s.	
Memorization Subjects II	59.0%	21.1%	87.2%	28.9%
	$p<0.00001$		$p<0.00001$	
Memorization Subjects III	61.3%	3.2%	80.6%	12.9%
	$p<0.00001$		$p<0.00001$	

Figure 6(2) shows the results of self-assessment of the "predicted rate of improvement in learning performance with an improvement in the environment." The subjects were requested to report the learning performance improvement rates that they expected if the indoor environment was improved. In this measurement, for the Memorization Subject

II, a significant decrease of 23.4[%] (p<0.00001) in the expected improvement rate resulted with the change in environmental conditions from low to high ventilation.

Table 4 shows the results of a self-assessment of the percentage of dissatisfied of indoor environment. For the Memorization Subject I, II and III, a significant improvement in the percentage of dissatisfied of Air and thermal environment resulted with the change in environmental conditions from low to high ventilation.

3.3 Evaluation of Consistency between the Objective and Subjective Evaluation of Learning Performance

Figure 7 shows learning performance improvement rates [%] for the quiz-based objective evaluation and self- assessment form-based subjective evaluation for the Memorization Subject I, II and III. The measurements show that the subjective evaluation used self-assessment form tends to overestimate the learning performance compared to the objective evaluation. A comparison between the evaluation based on the "expected improvement rate" and the evaluation based on the "effective lecture time" shows that the evaluation based on the expected improvement rate agrees more closely with the objective evaluation. This result of realistic simulation experiment was adverse result of the field intervention survey reported previous paper (Part1).

3.4 Discussion

Figure 8 shows the relationship between the results of objective evaluation (quiz score) and the air environmental factors. The logarithmic relationship was observed between quiz score of objective evaluation and ventilation rate per person [m^3/h/person]. The linear relation was observed between quiz score of objective evaluation and percentage of dissatisfied of air environment of subjective evaluation.

4. Consistency Between the Field Survey and Simulation Experiment of Relative Learning Performance

In order to evaluate the consistency between the field intervention survey and relalistic simlation experiment, relative learning performance was defined.

Concerning the relationship between quiz scores and ventilation rate per person, relative learning performance which is normalized value by the quiz score for the ventilation rate 1.0 [m^3/h/person] was defined. For the relationship between quiz scores and percentage of dissatisfied of air environment, relative learning performance which is normalized value by the quiz score for the percentage of dissatisfied of air environment 0 [%] was defined.

Consistency between the results of field survey and the results of simulation experiment are shown in Figure 9. For the consistency between the relative learning performance and ventilation rate per person, the difference of those were estimated about 2-3 %. For the consistency between the relative learning performance and the percentage of dissatisfied of air environment, these analyses show that the evaluation of realistic simulation experiment tends to underestimate the evaluation of the field intervention survey.

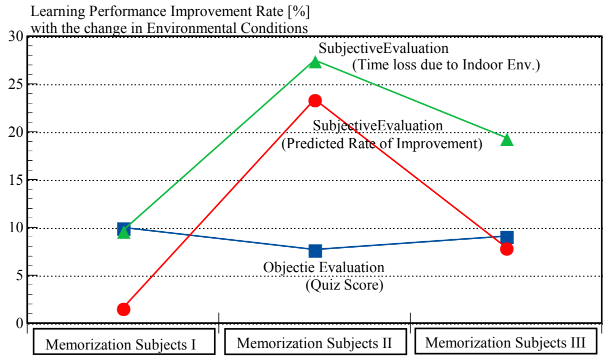
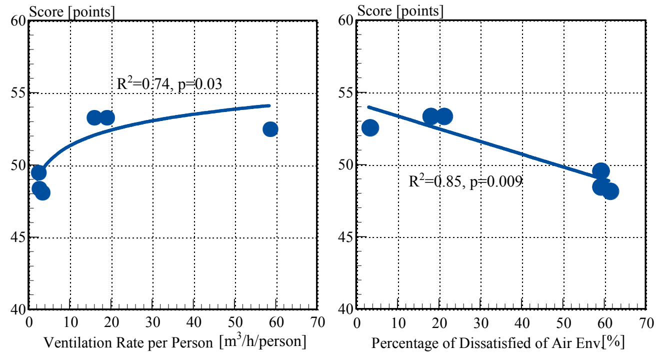
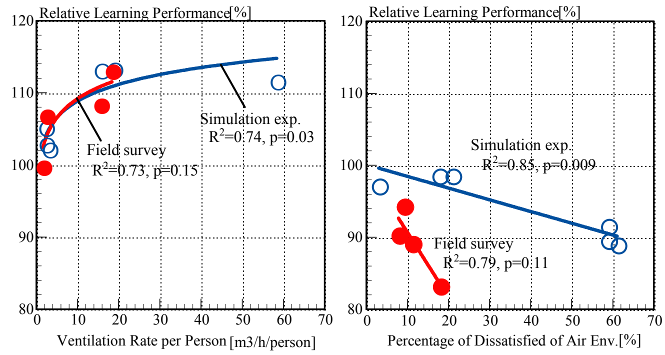


Figure 7 Learning performance improvement rates [%]



(1) Quiz score vs Vent. rate (2) Quiz score vs Dissatisfied

Figure 8 Objective Evaluation vs Air Environment



(1) Relative Performance vs Vent. rate (2) Relative Performance vs Dissatisfied

Figure 9 Consistency between field survey and simulation experiment

5. Comparison of Learning Performance by Scores

Based on the results of the quiz in the preliminary experiment conducted in the same environment with the same lecture cotents, the subjects were put into a higher score group and a lower score group.

Table 5 shows the results of the average scores on quizzes by score group. For the Memorization Subject I, the scores for the lower group decreased by approximately 17.8 points in the low ventilation environment. On the other hand, the scores for the higher group were almost the same in both environments. In this experiment the lower score group received a larger effect from the thermal and air quality environments.

Table 6 shows the average values for the self-assessment of time deemed to be lost due to the indoor environment by score group. For Memorization Subject I, II and III, time deemed to be lost in the low-ventilation environment was significantly longer in the case of the lower score group. Significant difference was not identified in the case of the higher score group compared with the case of lower score group.

Table 7 shows the average values for the self-assessment of improvements in the expected understanding of the lecture contents with improvements in impeding factors by score group.

For Memorization subject I, no significant difference was identified with high score group and lower score group. For Memorization subject II and III, the expected improvements in the higher score group with improvements in the impeding factors increased significantly in the low-ventilation environment ($p<0.006$ and $p<03$ respectively).

Table 5 Results for the objective learning performance by Score group [points]

	High Score Group		Low Score Group	
Vent. rate	Low	High	Low	High
Memorization	49.1±14.7	39.7±14.5	26.0±7.1	43.8±15.0
Subjects I	n.s.		p<0.00001	
Memorization	65.0±8.2	61.0±10.5	33.4±9.7	45.4±16.4
Subjects II	n.s.		p<0.02	
Memorization	60.2±9.1	65.1±8.5	35.3±7.7	39.3±14.1
Subjects III	n.s.		n.s.	

Table 6 Results for Time lost due to the indoor environment by Score group [min]

	High Score Group		Low Score Group	
Vent. rate	Low	High	Low	High
Memorization	34.0±29.1	27.0±31.4	45.3±32.4	24.7±36.4
Subjects I	n.s.		p<0.05	
Memorization	47.9±32.8	17.3±17.9	60.0±26.3	20.6±22.1
Subjects II	p<0.003		p<0.0005	
Memorization	43.4±20.5	18.4±23.6	43.0±47.8	14.7±22.2
Subjects III	p<0.003		p<0.06	

Table 7 Results for Predicted rate of improvement in learning performance with an improvement in the environment by Score group [%]

	High Score Group		Low Score Group	
Vent. rate	Low	High	Low	High
Memorization	40.8±19.9	37.0±20.1	39.4±16.1	45.3±19.5
Subjects I	n.s.		n.s.	
Memorization	47.3±28.4	24.0±19.5	51.7±15.1	28.1±17.3
Subjects II	p<0.006		p<0.0005	
Memorization	35.9±23.9	23.9±23.0	29.0±21.2	25.5±20.9
Subjects III	p<0.03		n.s.	

6. Concluding Remarks

The realistic simulation experiment was conducted on subjects in a climate chambe, and the effect of the thermal and air quality environments on learning performance was evaluated.

As a result, the following findings were obtained.

(1) Objective learning performance was improved in the high-ventilation environment.

(2) Subjective learning peformance was significantly improved in the high-ventilation environment.

(3) Objective and subjective evaluations tended to correspond with each other, however, the improvement in subjective learning efficiency tended to be overestimated.

(4) The results of realistic simulation experiment were enoughly consisntent with the results of field intervention survey. Especially, for the consistency between the relative learning performance and ventilation rate per person, the difference of those were estimated about 2-3 %.

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