Effects of humidity and indoor air chemical pollutants on human comfort and productivity

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ABSTRACT
Subjective experiments were conducted in summer and winter in order to clarify the effects of humidity and indoor chemical pollutants on subjective comfort and productivity, and evaluate the seasonal differences in their reactions. Subjects were exposed to three levels of humidity conditions and 2 indoor air quality levels in a climate chamber performing the simulated office works. For all conditions, SET* was constant. Subjects adapted to the indoor air quality during the 180-min exposures under the polluted conditions. The differences of the general humidity sensation among the conditions were small in both seasons. Eye irritation got higher during the exposure. The seasonal difference due to the adaptation to outdoor air was found. Environmental humidity had the larger effects on skin moisture than indoor air quality. The correct answer speed of the addition task tended to be faster under the clean conditions than the polluted conditions in both seasons although the differences were small.

INDEX TERMS
Humidity; Indoor air quality; Seasonal difference; Human comfort; Performance

INTRODUCTION
In Japan, 'Law for Maintenance of Sanitation in Buildings' is applied to the offices whose total floor areas exceed 3000 m^2. It states that relative humidity in the office space should be kept between 40 and 70%RH. ASHRAE Standard 55-92 (1992) prescribes the lower boundary humidity of 4.5 g/kg which is equivalent to 30%RH at 20.5°C. ASHRAE Standard 62-2001 (2001) recommends 30–60% of relative humidity. The lower boundaries of these criteria are intended to limit the low humidity condition in winter. However, the improvements of the recent HVAC technologies allow engineers to use cold air distribution systems in many office buildings, creating thermal environment with humidity lower than 40%RH in summer. Further studies on the effects of low humidity on occupants' comfort and performance in summer are needed as well as in winter.

On the other hand, air tightness, reduction of ventilation rate for saving energy and use of chemical materials cause the problems of high indoor air concentration of formaldehyde or volatile organic compounds (VOCs) in many office buildings (Yanagi, 2001). Indoor chemical pollutants irritate occupants' mucous membranes and they possibly perceive this irritation as the dryness sensation caused by low humidity.

Subjective experiments were conducted during the summer and winter seasons in order to clarify the effects of environmental humidity and indoor chemical pollutants on subjective comfort and productivity. In this study, formaldehyde was selected as the indoor chemical pollutant. Concentration of formaldehyde is considered to be higher under high humidity conditions because formaldehyde is hydrophilic. Although the dryness sensation caused by environmental humidity itself reduces as humidity increases, the dryness sensation due to

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irritation of mucous membranes by formaldehyde is expected to increase in high humidity environments.

Furthermore, by comparing the results of subjective experiments conducted in summer and winter, it is possible to evaluate the seasonal differences in their reactions.

METHODS

Experimental Design

Subjective experiments were carried out in the summer of 2001 and the winter of 2002 for the purpose of clarifying the effects of humidity and indoor chemical pollutants on subjective comfort and productivity, and evaluating the seasonal differences in their reactions.

Experimental conditions are shown in Table 1. Three levels of humidity condition, 30%, 50% and 70%RH, and two indoor air quality levels, 'clean condition' and 'polluted condition', were examined. An air cleaner (Shinryo Eco Business Inc.) was used under the 'clean conditions'. MDF boards (Medium-density fibreboards) were used as the pollution source under the 'polluted conditions'. Total emission area of MDF boards was 64.8 m^2, which was constant for all polluted conditions. For all conditions, SET* was kept at 25.2°C and ventilation rate was controlled to be constant. In addition to the six conditions mentioned above, a 'pre-condition' with 25.0°C/50%RH was set to avoid the learning effects of the subjects.

The climate chamber was separated into two parts with a partition, in one of which the air cleaner or MDF boards were set and subjects stayed in the other part.

Eighteen college-aged subjects were exposed for 180 min in the climate chamber for each season. All subjects were volunteers, who were paid for participating in the experiments. Considering their circadian rhythms, all subjects took part in the experiments at the same time of day. Each subject wore the clothing ensembles that consisted of a long-sleeve shirt, trousers and socks. All subjects wore their own underwear. The clo value was estimated to be 0.6 clo. Subjects performed simulated office work during the 180-min exposure and metabolic rate was estimated to be 1.2 met.

Table 1 Experimental conditions

	IAQ	Air temperature (°C)	Relative humidity (%RH)	Air velocity (m/s)	Clothing (clo)	Metabolic rate (met)	SET* (°C)
30c	Clean	25.4	30	<0.15	0.6	1.2	25.2
50c		25.0	50				
70c		24.6	70				
30p	Polluted	25.4	30				
50p		25.0	50				
70p		24.6	70				
Pre	Clean	25.0	50				

Experimental Procedure

In both summer and winter, the experiments were carried out with the same procedure. Experimental procedure is shown in Figure 1. After subjects seated quietly in the anteroom for 30 min, they went out to rate the perceived air quality of outdoor air. When subjects entered the chamber and rated their sensations, exposure time started. Subjects performed two kinds of simulated office work, 'addition task' and 'text typing', during the 180-min exposure.

The 'addition task' is the simple calculation task in which two 2-digit numbers were added together. Subjects answered questions shown on the computer screen. Subjects performed the 20-min addition task twice during the exposure. Subjects typed English sentences from simple stories for 25 min for the 'text typing'. English stories used for this task were changed every time the subjects performed text typing to avoid their learning effects. Text typing was conducted three times during the exposure. During ten-minute intervals between each task, subjects rated their sensations.

Break-up time of eyes (BUT) and skin moisture on left forearm were recorded four times during the exposure. BUT is the time from one blink to the next blink measured by subjects themselves using stopwatches (Wyon and Wyon, 1987). Skin moisture was measured with SKICON-200 (IBS) (Tagami, 1984).

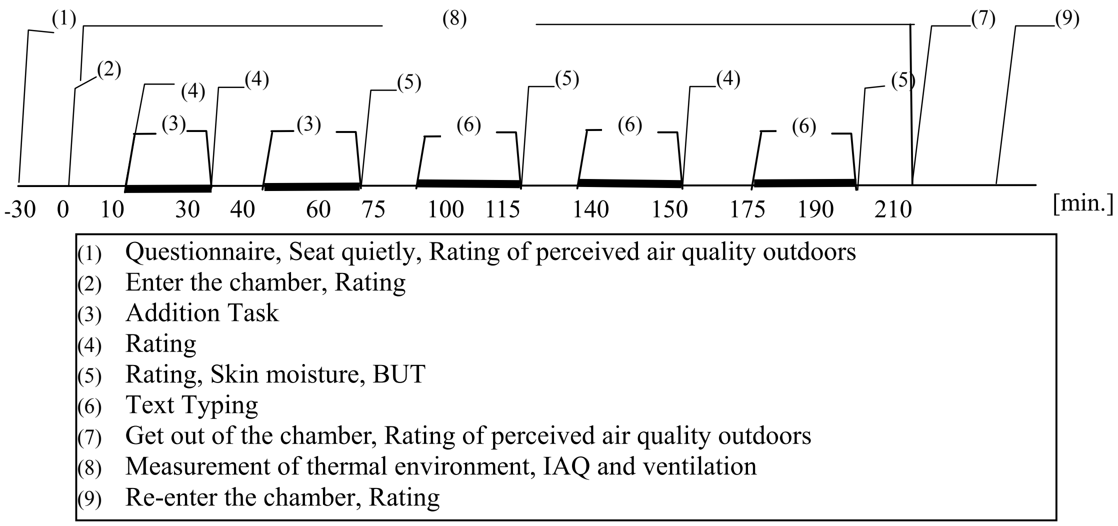

Figure 1 Experimental procedure

Air temperature, relative humidity and globe temperature in the chamber were recorded every minute. Measurements of air velocity were made before and after each exposure. The concentration of formaldehyde measured with passive samplers and VOCs with an active method are presented in Figure 2. Under the polluted conditions, the concentration of formaldehyde was higher at high humidity in both of summer and winter.

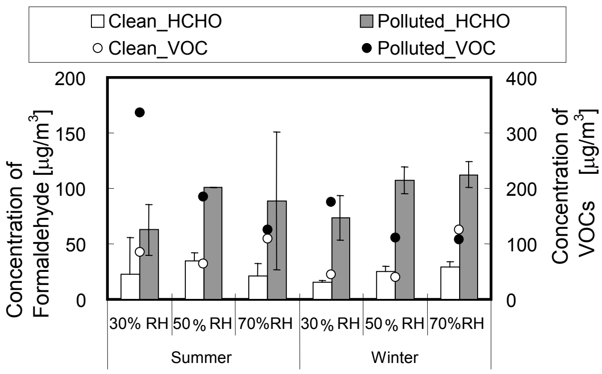

Figure 2 Concentration of formaldehyde and VOCs.

Table 2 Rating scales

Indoor air acceptability	Odour intensity	Humidity sensation (general, eyes)	Irritation of eyes
+1:Clearly acceptable	0: No odour	+3: Extremely dry	0: No irritation
	1: Slight odour	+2: Dry	1: Slight irritation
:Just acceptable	2: Moderate odour	+1: Slightly dry	2: Moderate irritation
0	3: Strong odour	0: Neutral	3: Strong irritation
: Just unacceptable	4: Very strong odour	–1: Slightly humid	4: Very strong irritation
	5:Overpowering odour	–2: Humid	5:Overpowering irritation
–1: Clearly unacceptable		–3: Extremely dry	

RESULTS

Psychological Reactions

Rating scales for the subjective sensations reported in this paper are shown in Table 2. The scales were given as visual analogue scales. Subjects were allowed to record their sensation both just on the numbers and between the numbers.

Indoor air acceptability: Indoor air acceptability rated when the subjects entered the chamber (the first vote) and the exposure time was over (the last vote) is given in Figure 3.

Acceptability was the highest under the 30%RH/clean condition at the beginning of the exposure in both seasons. Friedman non-parametric analysis revealed that in winter indoor air acceptability at low humidity in clean air was significantly higher than at high humidity in clean air ($p < 0.02$). Compared them in the polluted environments, it was the lowest under the 70%RH condition due to the high formaldehyde concentration. The Wilcoxon Matched-Pairs Signed Ranks test showed the acceptability votes at the end of the exposures were significantly higher than at the beginning under all humidity levels in both summer and winter ($p < 0.05$). Subjects adapted to the indoor air quality after the 3-h exposure.

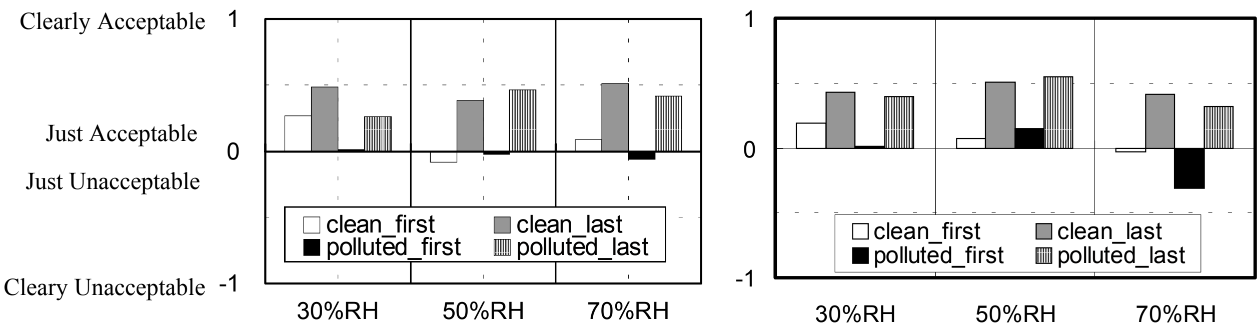

Figure 3 Indoor air acceptability (left, summer; right, winter).

Odour intensity: Odour intensity rated when the subjects entered the chamber (the first vote) and the exposure time was over (the last vote) and its change as a function of the exposure time in summer are shown in Figure 4. Odour intensities under the polluted conditions for all humidity levels were higher at the beginning of the exposure than under the clean conditions in both seasons. On the other hand, all odour intensity votes were at the same level at the end of the exposure. The odour intensity votes were getting lower during the exposure. The same tendencies were also found in winter.

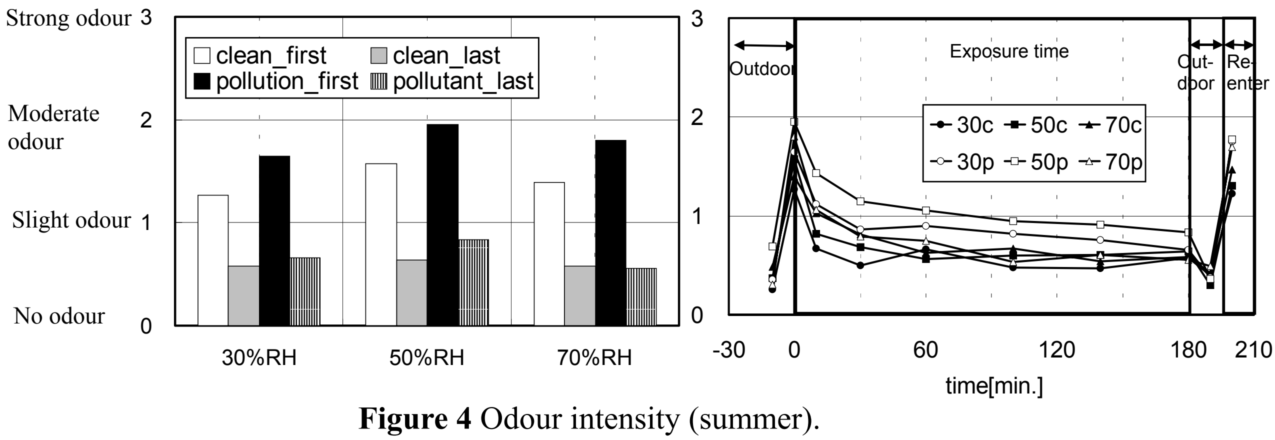

Figure 4 Odour intensity (summer).

Humidity sensation: A significant difference of the general dryness sensation was observed among the humidity levels under polluted condition in winter ($p < 0.003$). However, all votes for general humidity sensations were scattered between –0.8 and +0.6 throughout the exposure time in both seasons. Therefore, it is concluded that humidity levels and indoor quality levels did not affect the general humidity sensation.

The sensation of eye dryness got higher as the time passed in both summer and winter. The increase of eye dryness was greater in summer than in winter. At the beginning of the exposure the eye dryness votes in winter were a little higher than in summer. It is concluded that subjects felt their eyes to be dryer because of the adaptation to the dry outdoor air in winter.

Eye irritation: Eye irritation as the function of the exposure time in summer and winter are given in Figure 5. Contrary to indoor air acceptability and odour intensity, eye irritation did not decline during the exposure time in both seasons. In summer, eye irritation votes increased as the exposure time passed. In winter, eye irritations kept at the same level throughout the exposure time. According to the weather records obtained by the Tokyo Meteorological Agency, the average of humidity ratio outdoors during the experiments in summer was about 9.7 g/kg, which is equivalent to the 50%RH at 25.0°C, and in winter it was about 3.7 g/kg, which is equal to the half of 30%RH at 25.4°C. It is considered that increase of eye irritation as the exposure time passed in the winter was less due to the higher humidity ratio in the climate chamber as compared with outdoor air under all conditions.

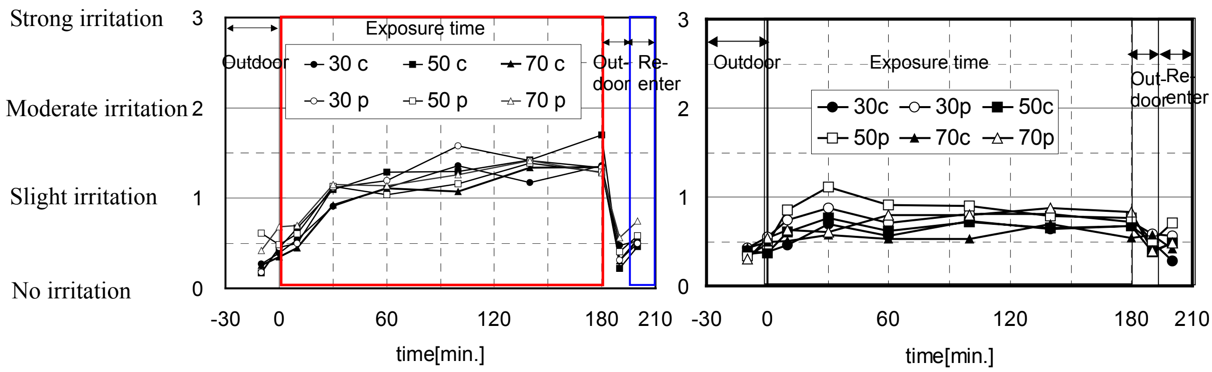

Figure 5 Eye irritation (left, summer; right, winter).

Physiological Reactions

Break-up time (BUT): Significant difference of BUT measured at the end of the exposure was not obtained either between the clean and polluted conditions or among the humidity levels. However, more subjects' BUT got shorter during the exposure under the polluted conditions in both seasons. BUT measured in summer was longer than in winter for all conditions.

Skin moisture: The skin moisture on left forearm measured at the end of the exposure is shown in Figure 6. Friedman non-parametric analysis and the Wilcoxon Matched-Pairs Signed Ranks test revealed that in both summer and winter the skin moisture was higher in high humidity environment. Environmental humidity had the stronger effects on subjective skin moisture than pollutants. However, under both clean and polluted conditions, the differences in skin moisture due to the humidity difference in winter were smaller than in summer. This can be considered as an adaptation to the dry condition outdoors in winter.

Performance Measurement

The correct answer speed of addition task, which indicates the number of correct answers a subject could input every minute, is shown in Figure 7. Compared under the same humidity condition, the correct speeds were faster in clean air than in polluted air in both summer and winter. However, significant difference was not observed by Friedman non-parametric analysis and the Wilcoxon Matched-Pairs Signed Ranks test either among the humidity conditions or between the clean and polluted condition in summer season. In winter, no significant difference was observed by Friedman test among the humidity conditions.

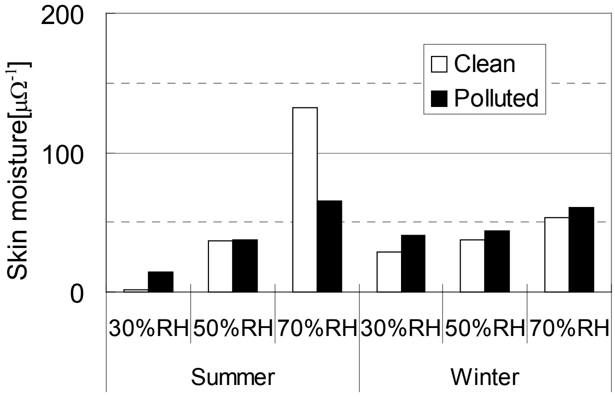

Figure 6 Skin moisture on left forearm measured at the end of the exposure.

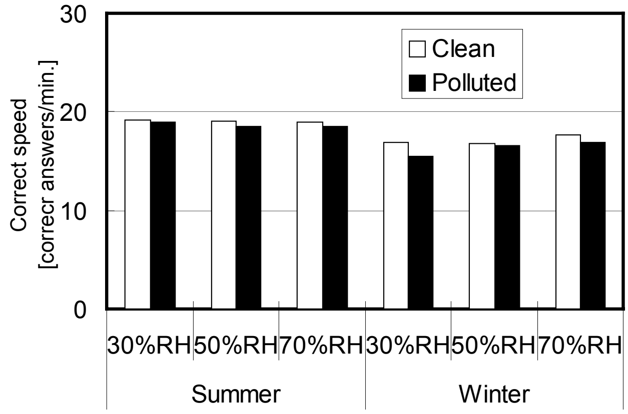

Figure7 Correct answer speed of addition task [correct answers/min.]

DISCUSSION AND CONCLUSION

Subjective experiments were conducted with three humidity levels and two indoor air quality levels in summer and winter in order to clarify the effects of humidity and indoor chemical pollutants on subjective comfort and productivity, and evaluate the seasonal differences in their reactions. Acceptability was the highest under the 30%RH/clean condition at the beginning of the exposure in both seasons, while it was lowest at 70%RH among the 3 polluted conditions due to the high formaldehyde concentration. Subjects adapted to the indoor air quality during the 180-min exposure under the polluted conditions. The differences of the general humidity sensation among the conditions were small in both seasons. Eye irritation got higher during the exposure. The seasonal differences due to the adaptation to outdoor air were found. Environmental humidity had the larger effects on skin moisture than indoor air quality.

The correct answer speed of the addition task tended to be faster under the clean conditions than under the polluted conditions in both seasons although the differences were small.

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