EFFECTS OF LOW HUMIDITY
ON HUMAN COMFORT AND PRODUCTIVITY

低湿度環境が在室者の快適性・知的生産性に与える影響に関する研究

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HITOMI TSUTSUMI

Waseda University
Graduate School of Science and Engineering
Major in Architecture and Civil Engineering
Architecture Specialization

ACKNOWLEDGEMENT

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The present Ph.D thesis is based on the research work carried out since 1999 at Tanabe Laboratory, Department of Architecture, Waseda University, and Department of Human Environmental Engineering, Ochanomizu University, and at the International Centre for Indoor Environment and Energy, Technical University of Denmark.

For the completion of this dissertation, I would like to express sincere gratitude to my supervisor, Professor S. Tanabe, Department of Architecture, Waseda University, for his valuable advices and giving a lot of opportunities to experience many things at each stage of my study.

I wish to acknowledge to Professor T. Ojima and Professor Y. Hasemi, Department of Architecture, Waseda University, and Associate Professor J. Kusaka, Department of Mechanical Engineering, Waseda University, for their sharp and useful advices.

Heartful thanks are due to Associate Professor T. Akimoto, Department of Architectural Environmental Engineering, Kanto Gakuin University, for his devoted interest and encouragement to this work.

I would also like to thank Professor K. Kimura, Waseda University, Professor Y. Hasebe, Professor T. Tanaka, Professor S. Ogawa, Professor Y. Aikawa, Professor M. Komaki, Professor T. Nakanishi and Professor M. Otaki, Department of Human Environmental Engineering, Ochanomizu University, who have encouraged me to make efforts since I was an undergraduate student.

I would like to acknowledge Mr. J. Harigaya, researcher, Tanabe laboratory, for his help to conduct this research.

My stay in 2001 and 2002 at the International Centre for Indoor Environment and Energy, Technical University of Denmark, was very fruitful and I wish to express my heartful thanks for their hospitality. Thanks are due to Professor P.O. Fanger, Dr. G. Clausen, Professor D.P. Wyon, Professor J. Sundell, Dr. L. Fang, Professor C.J. Weschler, Dr. P. Wargocki, Dr. A. Melikov, Dr. J. Toftum, Mr. L.P. Lagercrantz, Mr. P. Strøm-Tejsen, Ms. L.M.S. Pedersen, International Centre for Indoor Environment and Energy, Technical University of Denmark; Dr. H.W. Meyer, Bispebjerg University Hospital; Dr. T. Agner, Department of Dermatology, Gentofte University Hospital; Ms. C.G. Weirsøe, Ms. N. Sederberg-Olsen; Copenhagen University Medical School, and all the staffs and colleagues.

Professor P.O. Fanger and Dr. G. Clausen gave me the precious opportunity to study at the Centre and a lot of useful suggestions.

I thank warmly Professor D.P. Wyon, Dr. L. Fang, Ms. L.M.S. Pedersen, Ms. C.G. Weirsøe, Ms. N. Sederberg-Olsen who carried out the experiments at the Centre described in Chapter 5. The discussions on the results of the experiment with Professor D.P. Wyon, Professor J. Sundell, Dr. L. Fang, and Professor C.J. Weschler, Dr. H.W. Meyer, and Dr. T. Agner were very inspiriting.

I especially thank Mr. L.P. Lagercrantz, Mr. P. Strøm-Tejsen, Ms. L.M.S. Pedersen for their carefully proofreading, correcting the English language and commenting on the first draft of this thesis.

I appreciate Professor T. Fujita, Tokyo University of Mercantile Marine, who provided important references in order to conduct the calibration of sensors at low air pressure

described in Chapter 6. I also thank Professor Y. Hasebe and Professor T. Nakanishi for lending some instruments for the experiment.

Thanks are also due to the people who participated the experiments as subjects and those who helped me to measure air temperature and humidity in some transportations, for instance aircraft cabins.

I am grateful to the following people who have generously spent their time and effort to realize successful subjective experiments presented in this thesis: Mr. A. Sugino and Mr. N. Fukui of Matsushita Techno Trading Co., Ltd.; Mr. K. Kayama and Mr. N. Takeuchi of Shin Nippon Air Technologies Co. Ltd; T. Suzuki and T. Takagi of Tokyo Electric Power Company.

Special thanks are due to Ms. Y. Chen, Mr. Y. Tanaka, Mr. Y. Akasaka and Mr. M. Kato of Tanabe Laboratory, Waseda University; Mr. A. Toyota of Shinryo Corporation; Mr. T. Kato of Tonets Corporation; Mr. J. Matsuda and Mr. D. Katahira of Akimoto Laboratory, Kanto Gakuin University for their assisting me plan and conduct this research.

I wish to thank all colleagues, present and past, for their warm help, discussions and encouragement.

I am thankful to all friends for their friendship and concern at various aspects of my life.

Finally, I would like to express my sincere appreciation to my dear parents and brother for their unlimited support.

March 2004

Hitomi Tsutsumi

Architecture Specialization**,** Major in Architecture and Civil Engineering,
Graduate School of Science and Engineering,
Waseda University
Room 701, Building 55N, Okubo 3-4-1,
Shinjuku-ku, Tokyo, 169-8555, JAPAN

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GENERAL INTRODUCTION

1.1 OBJECTIVE OF RESEARCH

In Japan, the “Law for Maintenance of Sanitation in Buildings (1970)” is applied to offices whose total floor areas exceed 3,000 m^2. It states that the relative humidity in an office space should be kept between 40 and 70%RH. The ASHRAE Standard 55-92 (1992) prescribes a lower boundary humidity of 4.5 g/kg which is equivalent to 30%RH at 20.5°C. The ASHRAE Standard 62-2001 (2001) recommends the relative humidity of 30-60%RH. The lower boundaries of these criteria are intended to limit the low humidity conditions in winter. However, improvement of recent HVAC technology has allowed engineers to use cold air distribution systems in many office buildings, creating a thermal environment with humidity lower than 40%RH during summer. Outdoor air cooling system can reduce indoor air humidity in spring and autumn. Further studies on the effects of low humidity on occupants’ comfort and performance in other seasons are needed, as well as in winter.

Many previous studies have pointed out that the effects of low humidity on thermal comfort were modest under thermally neutral conditions. However, many non-thermal problems such as eye irritation, dry skin, respiratory infection and dryness sensation occur in the spaces with low humidity. Further studies are required to clarify the non-thermal effects of humidity.

Air tightness, the reduction of the ventilation rate for saving energy and use of chemical materials cause problems of high indoor air concentration of formaldehyde or VOCs (Volatile Organic Compounds) in many office buildings today. Indoor chemical pollutants irritate occupants’ mucous membranes and they possibly perceive this irritation as dryness sensation caused by low humidity.

Also, due to the usage of HVAC system, computers and contact lenses, the problem of dry eye syndrome has been getting more serious in office spaces recently. It is generally said that contact lenses wearers might be more sensitive to low humidity than non-wearers. It is because contact lenses are used on their cornea.

The objective of this study is to investigate the effects of low humidity on human comfort and productivity.

1.2 BACKGROUND

1.2.1 Standards for Indoor Environment

The “Law for Maintenance of Sanitation in Buildings (1970)” is applied to specially designed buildings such as offices, entertainment facilities, assembly halls, libraries, museums and stores, whose total floor areas exceed 3,000 m^2 and schools exceed 8,000 m^2 in Japan. It outlines suggested values for the concentration of carbon dioxide (CO_2), airborne particles, carbon monoxide and formaldehyde, air temperature, air humidity and air velocity for designing indoor climate, as listed in Table 1-1.

The “Society of Heating, Air-conditioning and Sanitary Engineering of Japan” (SHASE) established a standard for ventilation, SHASE-S 102-1997 “Ventilation” (1997). In this standard, the guideline concentration of indoor pollutants is prescribed as shown in Table 1-2. The CO_2 concentration of 1,000 ppm, shown in Table 1-2, is not based on the health effects of CO_2 itself, although it is defined as an indicator of total potency of all gases indoors. This concentration can be used for estimating the concentrations of other gases, whose concentrations are unknown, when CO_2 concentration reaches 1,000 ppm. Note that even when the CO_2 concentration is below 1,000 ppm, indoor contaminants might cause health problems.

Table 1-1. Guideline for indoor climate stated in the "Law for Maintenance of Sanitation in Buildings"

Amount of Suspended Particles	Not more than 0.15 milligrams per cubic meter of air
Content of Carbon Monoxide (CO)	Not more than 10 parts per million (<10 ppm)
Content of Carbon Dioxide (CO_2)	Not more than 1,000 parts per million (<1,000 ppm)
Temperature	1. Not less than 17 degrees and not more than 28 degrees 2. When lowering the temperature in rooms less than the temperature of the outside air, that difference shall not be significant
Relative Humidity	Not less than 40 percent and not more than 70 percent
Air Flow	Not more than 0.5 meters per second
Content of Formaldehyde	Not more than 0.1 milligrams per cubic meter of air

Table 1-2. Guidelines of indoor contaminants for designing indoor climate

(a) CO_2 concentration as an indicator of total potency of all gases

	Concentration	
Carbon Dioxide	1,000ppm	Based on Law for maintenance of sanitation in buildings

(b) Guideline concentrations of individual gases

Carbon Dioxide	3,500 ppm	Based on the Canadian standard
Carbon Monoxide	10 ppm	Based on the Law for Maintenance of Sanitation in Buildings
Airborne Particles	0.15 mg/m^3	Based on the Law for Maintenance of Sanitation in Buildings
Nitrogen Dioxide	210 ppb	Based on the WHO guideline
Sulphur Dioxide	130 ppb	Based on the WHO guideline
Formaldehyde	80 ppb	Based on the WHO guideline
Radon	150 Bq/m^3	Based on the EPA guideline
Asbestos	10 /l	Based on the guideline established by Japanese Ministry of Environment
Total Volatile Organic Compound (TVOC)	300 µg/m^3	Based on the WHO guideline

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The ASHRAE Standard 55-92 (1992) prescribes a lower boundary humidity of 4.5g/kg which is equivalent to 30%RH at 20.5°C. The ASHRAE Standard 62-2001 (2001) recommends relative humidity of 30-60%RH. The “Law for maintenance of sanitation in buildings” states that the humidity should be kept between 40 and 70%RH in office spaces in Japan. These standards were established considering skin dryness, infection and eye dryness as well as thermal comfort. However, the lower boundaries of these criteria are intended to limit the low humidity conditions in winter. Only a few studies on the effects of low humidity on occupants in the summer season has been conducted.

The Tokyo Metropolitan Government organized groups of employees in 1971 to inspect a cross section of buildings which need to meet the criteria. A total of 69,159 buildings had been inspected during the period from 1971 to 1998. Air temperature was reported to be about 25.0°C from April to October, 24.0°C from November to March. Air temperature change through the year was only 0.5-1.0°C. Air temperature tended to be between 24.5 and 25.0°C throughout the year during the 4 years from 1995 to 1998.

Tokyo Metropolitan Government recommends that owners of buildings and designers should install humidifiers to meet the guideline of relative humidity, 40-70%RH. The environment with 50%RH at 22°C, where the humidity ratio is about 8.2g/kg, is the standard used for calculating the required amount of humidification. However, in fact, air temperature inside the buildings was kept at 24-25°C. Thus the relative humidity tends to be lower than the guideline in winter. In some buildings, it is either not done or it is impossible to humidify indoors because of the cooling load, avoiding condensation, saving energy consumption and the effects on PCs. This results in extremely low humidity in winter. On the other hand, few complaints were reported about low humidity during the summer season.

1.2.2 Thermal Comfort

Thermal comfort is defined in ASHRAE Standard 55-92 (1992) as the condition of mind that expresses satisfaction with the thermal environment. This standard also specifies conditions as comfort zone where 80% or more of the occupants find the environment thermally acceptable.

Man's thermal sensation is mainly related to the thermal balance of the body as a whole. This balance is influenced by the physical activity and clothing, as well as air temperature, mean radiant temperature, air velocity and air humidity. People do not perceive these individual factors but a combination of them. Many indices have been suggested to express this combination.

1.2.2.1 Comfort Equation

The comfort equation developed by Fanger (1970) can provide, for any type of clothing and any type of activity, all reasonable combinations of air temperature, air humidity, mean radiant temperature and relative air velocity which will create optimal thermal comfort under steady state conditions. Three conditions are defined for a person to be in thermal comfort: 1) the body is in heat balance, 2) sweat rate is within comfort limit and 3) mean skin temperature is within comfort limit. Mean skin temperature and evaporative heat loss from the skin are assumed as a function of the metabolic rate. This makes it possible to express the heat balance equation with 6 factors.

1.2.2.2 PMV (Predicted Mean Vote)

Fanger (1970) defined "Predicted Mean Vote (PMV)". The PMV index was internationally standardized in 1984 as ISO-7730. The PMV is an index that predicts the mean value of votes of a large group of people on the following 7-point thermal sensation scale:

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The PMV index can be determined when the activity (metabolic rate) and the clothing (thermal insulation) are estimated, and the following environmental parameters are measured: air temperature, mean radiant temperature, relative air velocity and air humidity. The PMV index is based on heat balance of the human body. Human beings are in thermal balance when the internal heat production in the body is equal to the loss of heat to the environment. In the PMV index the physiological response of the thermoregulatory system has been related statistically to thermal sensation votes collected from more than 1,300 subjects.

Fanger (1970) also related the predicted percentage of dissatisfied (PPD) to the PMV index. The PPD index predicts the percentage of thermally dissatisfied persons among a large group of people. A PPD of 10% corresponds to the PMV range of ±0.5, and even with PMV=0, about 5% of people are dissatisfied. ISO-7730 (1984) recommends the condition of –0.5<PMV<+0.5 and PPD<10% as the comfort zone.

1.2.2.3 ET*(New Effective Temperature), SET* (Standard New Effective Temperature)

The effective temperature was developed by Gagge et al. (1973). It combines temperature and humidity into a single index. Therefore, two environments with the same ET* should evoke the same thermal response, even if they have different temperatures and humidities. However, in order for ET* to evoke the same thermal response in the two different environments, the air velocity must be the same.

Since the index is defined in terms of operative temperature, it combines the effects of three parameters (mean radiant temperature, air temperature and humidity) into a single index.

The permeability index and skin wettedness must be specified, and are constant for a given ET* line in a particular situation. The two-node model is used to determine skin wettedness in the zone of evaporative regulation.

Since ET* depends on clothing and activity, it is impossible to generate a universal ET* chart. A standard set of conditions representative of typical indoor applications is used to define a standard effective temperature (SET*) (Gagge et al. 1987). SET* is defined as the equivalent air temperature of an isothermal environment at 50%RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress and thermoregulatory strain as in the actual environment.

The ET* can be used to evaluate hot and cold conditions as well as comfort conditions because the evaporative heat loss of sweat secretion is taken into consideration in the ET* index. Evaluations with PMV and ET* were not so different from each other under the comfort zone although ET* is applicable for the hot condition (Kimura et al., 1985).

Figure 1-1 presents the comfort zone given in the ASHRAE Standard 55-92 addeddum (1994), where 80% of sedentary or slightly active persons find the environment thermally acceptable. Since people typically change their clothing for the seasonal weather, the standard specifies summer and winter comfort zones appropriate for clothing insulation levels are 0.5 clo and 0.9 clo respectively. One clo is equivalent to the thermal insulation of clothing of 0.155 m^2°C/W. The warmer and cooler temperature borders of the comfort zones are affected by humidity and coincide with lines of constant ET*. In the middle region of a zone, a typical person wearing the prescribed clothing would have a thermal sensation at or very near neutral. Near the boundary of the warmer zone, a person would feel about +0.5 warmer on the ASHRAE thermal sensation scale. Near the boundary of the cooler zone, that same person may have a thermal sensation of –0.5. Comfort zones for other clothing levels can be approximated by decreasing the temperature borders of the zone by 0.6 °C for each 0.6clo increasing in clothing insulation and vice versa. Similarly a zone's temperature can be decreased by 1.4 °C per met in activity above 1.2met. The met is a unit to express the person's metabolic rate. One met is defined as 58.2W/m^2.

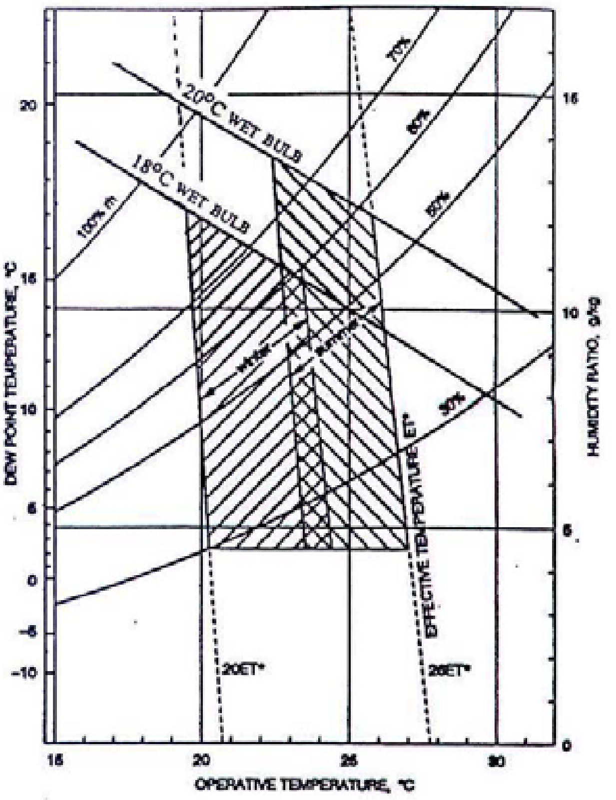


Figure 1-1. Comfort zone proposed in ASHRAE Standard 55-92(1992)

1.2.3 Ventilation

Thermal environment, perceived air quality and concentration of chemical contaminants, are all affected by ventilation. They might have some impacts on human comfort, health and productivity.

The term “ventilation” is defined in ASHRAE Standard 62-2001 (2001) as the process of supplying air to or removing air from a space, for the purpose of controlling air contaminant levels, humidity or temperature within the space. Contaminants in offices and houses are carbon dioxide (CO_2), carbon monoxide (CO), airborne particles, odour, formaldehyde and volatile organic compounds (VOC).

Ventilation includes general ventilation and local ventilation. The former is the method for removing contaminants by changing indoor air. The later is used to locally ventilate at the place where contaminants are emitted.

Two methods of ventilation are available; 1) natural ventilation, that is ventilation provided by temperature difference, wind, or diffusion effects through doors, windows or other intentional openings in the building, and 2) mechanical ventilation, that is ventilation provided by mechanically powered equipment, such as motor-driven fans and blowers, but not by devices such as wind-driven turbine ventilators and mechanically operated windows.

The “Building Standard Law of Japan (established in 1950, revised in 2003)”, states that mechanical ventilation systems shall be installed in order to keep air change rate more than 0.5 times per hour in habitable rooms and more than 0.3 times per hour in other rooms.

Outdoor air requirement is defined as the minimum volume of outdoor air needed to keep the concentration of contaminants indoors below guideline values. SHASE-S 102 (1997) shows the calculation methods of required ventilation rate using concentration of indoor contaminants, such as CO_2 and VOCs. It gives 30 $m^3/(h \cdot person)$ of outdoor air requirement when people’s activity and CO_2 concentration are assumed not to be extreme. The Building Standard Law of Japan suggests 20 $m^3/(h \cdot person)$. ASHRAE Standard 62-2001 (2001) prescribes 10 $l/(s \cdot person)$ of outdoor air, which is equivalent to 36 $m^3/(h \cdot person)$, in office spaces. These values of required outdoor air are listed in Table 1-3.

Table 1-3. Outdoor air requirement in office spaces

SHASE-S102	30m^3/(h·person)
Building standard law of Japan	20m^3/(h·person)
ASHRAE Standard 62-2001	36m^3/(h·person)

Air tightness in recently constructed buildings causes lower ventilation rates. Moreover, more chemical materials are used in the spaces. These facts result in the problem of sick building syndrome. Ventilation is essential to remove the indoor contaminants and improve indoor air quality (IAQ).

Systems that can obtain good air change effectiveness are required for ventilation. Energy consumption should also be taken into consideration. Ventilation effectiveness is a description of an air distribution system’s ability to remove internally generated pollutants from a building, zone, or space. Air change effectiveness is a description of an air distribution system’s ability to deliver ventilation air to a building, zone, or space (ASHRAE Fundamentals Handbook, 2001).

The age of air is the length of time that some quantity of outside air has been in a building, zone, or space. The “youngest” air is at the point where outside air enters the building by forced or natural ventilation, or through infiltration. The “oldest” air may be at some location in the building or in the exhaust air.

Tracer gas methods are applied to measure the air change rate of an existing building. The types of tracers used in ventilation measurements are usually colourless, odourless inert gases not normally present in the environment.

All tracer gas measurement techniques are based on a mass balance of the tracer gas within the building. Assuming the outdoor concentration is zero and the indoor air is well mixed, this total balance takes the following form:

$$V\left(\frac{dC}{d\theta}\right) = F(\theta) - Q(\theta)C(\theta)$$

where

V = volume of space being tested [m^3]

C(θ) = tracer gas concentration at time θ

dC/dθ = time rate of change of concentration, [s^{-1}]

F(θ) = tracer gas injection rate at time θ, [m^3/s]

Q(θ) = airflow rate out of building at time θ, [m^3/s]

θ = time, [s]

In the equation, density differences between indoor and outdoor air are generally ignored for moderate climates; therefore, Q also refers to the airflow rate into the building. While Q is often referred to as the infiltration rate, any measurement includes both mechanical and natural ventilation in addition to infiltration. The ratio of Q to the volume V being tested has units of 1/time and is the air exchange rate. The equation is based on the assumptions that: 1) no unknown tracer gas sources exist, 2) the airflow out of the building is the dominant means of removing the tracer gas from the space, and 3) the tracer gas concentration within the building can be represented by a single value. Three different tracer gas procedures are used to measure air exchange rates: 1) concentration-decay, 2) constant concentration, and 3) constant injection (INNOVA, 2003).

The most basic method to measure air change rate using tracer gases is the concentration-decay method. In this method, a small quantity of tracer gas is thoroughly mixed into the room air. The source of gas is then removed and the decay in the concentration of tracer-gas in the room is measured over a period of time.

The constant concentration method is used for continuous air change rate measurements in one or more zones. It is particularly useful for conducting analyses in occupied buildings. When using the constant-concentration measurement method, the concentration of tracer gas in a zone is measured by a gas monitor. This information is then sent to a computer that controls the amount of tracer-gas “dosed” into the zone in order to keep its concentration constant. A small fan is normally used to help mix the tracer gas with the room air.

The constant injection method is used for long-term, continuous air change rate measurements in single zones, or for measurement of the airflow through ventilation ducts. When using the constant-emission method, tracer-gas is emitted at a constant rate for the duration of the measurement period.

1.2.4 Perceived Air Quality

Fanger (1988, 1992) introduced new units, “olf” and “decipol”, for quantifying the indoor pollutants perceived by occupants. Perceived air quality may be expressed as the percentage of dissatisfied. The dissatisfied are people who are predicted to perceive the air as being unacceptable just after entering a space. One olf is defined as the emission rate of air pollutants (bioeffluents) from a standard person who is an average adult working in an office or similar non-industrial work place. The person is sedentary and in thermal comfort with a hygienic standard equivalent of 0.7 bath/day. A smoker emits 6 olf with an average smoking rate of 1.2 cigarettes/hour and CO emission rate of 44 ml/cigarette. Pollutants emitted from the building materials in ceilings, walls, floors and furniture can also be given in olf unit. It is possible to evaluate perceived air quality of a certain space as a whole by adding individual olf values. Figure 1-2 presents the concept of the olf units.

Perceived air quality can also be expressed in decipol, where 1 decipol is the air quality in a space with a pollution source strength of one olf, ventilated by 10 l/s of clean air, i.e. 1decipol = 0.1 olf/(l/s).

The olf and decipol concepts are used in European standards such as CR1752 (1998) and DIN 1946-2 (1994).

A low level of humidity has a significant effect on perceived air quality. Studies by Berglund (1991, 1994) and Berglund and Cain (1989) showed that at a fixed temperature the air is perceived to be fresher and less stale as the humidity is decreased.

Fang et al. (1998a, 1998b) reported that temperature and humidity had a significant impact on perceived air quality. The acceptability of air was linearly related to enthalpy and decreases with increasing air temperature and humidity. Figure 1-3 shows the relationship between perceived air quality and enthalpy studied by Fang et al.(1998a) under the conditions with pollution sources introduced.

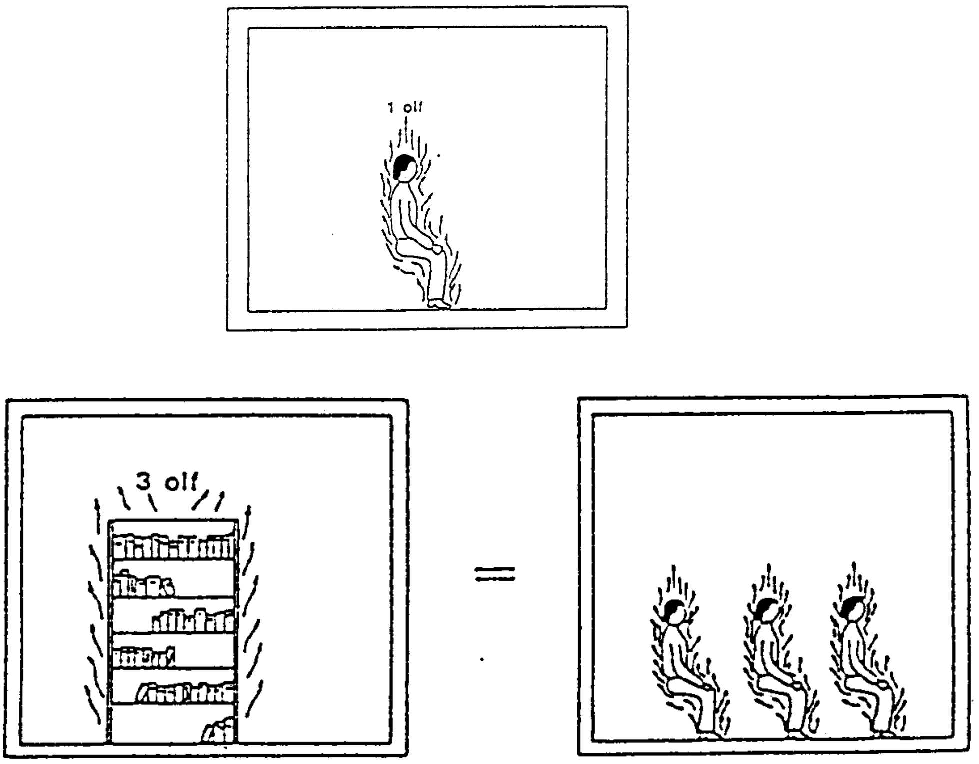


Figure 1-2. Concept of the olf unit (Fanger, 1992)

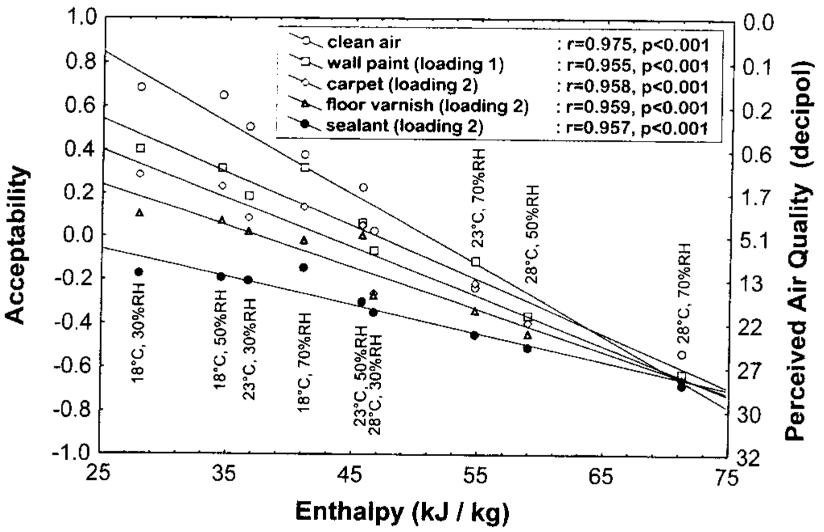


Figure 1-3. The relationship between enthalpy and perceived air quality (Fang et al., 1998a)

1.3 LITERATURE SURVEY OF RELATED RESEARCH

1.3.1 Thermal Effects of Humidity

Many studies have been conducted on the effects of indoor humidity on thermal comfort.

Rohles (1975) summarized the effects of humidity on subjective thermal comfort. He exposed 1600 males and females to environments for 3 hours. The air temperature changed every 1.1 °C from 15.6°C to 36.7°C. For each temperature there were eight degree of relative humidity: 15%RH, 25%RH, 35%RH, 45%RH, 55%RH, 65%RH, 75%RH and 85%RH. In this experiment, subjective thermal comfort sensation was examined. The results of the experiment showed that it was possible to increase 0.5°C in temperature by decreasing 15% relative humidity in the comfort zone, keeping subjects' thermal sensation at the same level.

In general, 1°C air temperature increase saves 5-10% in energy consumption.

Increased comfort at lower humidity levels is due to reduced skin moisture and perspiration. In a warm environment with a low humidity level, a person will experience little discomfort if the perspiration evaporates immediately and the skin remains dry. The friction between the skin and clothing also decrease at lower humidity levels so that fabrics feel smoother, and clothing is less sticky.

Tanabe et al. (1994, 1995) made subjective experiments in a climate chamber. They pointed out that the effects of low humidity on subjective thermal comfort were modest when SET* was constant, but further study was required to clarify the non-thermal effects of humidity.

Remarkable improvements in recent HVAC technology allow engineers to use the cold air distribution systems in many office buildings, creating a thermal environment with humidity lower than 40%RH during summer. Cold air distribution systems are defined in the United State of America as the system that utilize supply air between 4 and 10°C, although conventional air distribution systems supply air between 10 and 15°C (Kirkpatrick and Elleson (1996)). In Japan, SHASE (2004) defines cold air distribution systems as the systems that supply air below 13°C. SHASE (2004) also shows the merits of cold air distribution systems, such as saving energy consumption and downsizing fans, ducts and AHU.

Based on the results of experiments conducted by Berglund (1991), Kirkpatrick and Elleson (1996), it was concluded that it is possible with a cold air distribution system to increase the dry-bulb temperature from 23.9 to 24.4°C if relative humidity is decreased from 50 to 35%RH, maintaining an equivalent comfort sensation.

As listed in Table 1-4, the representative relative humidity in cold-air distribution system are about 40%RH, which is about 10%RH lower than the representative 50%RH of a conventional system (Kirkpatrick and Elleson, 1996).

The research committee (1997-2000), organized by the Society of Heating, Air-conditioning and Sanitary Engineering of Japan (SHASE), studied thermal comfort in office spaces with cold air distribution system.

Fukai et al. (2000) made subjective experiments simulating transient conditions. Thermal comfort of subjects who walked in hot environments and then entered the indoor environment was examined. Under the low humidity condition subjects felt more comfortable due to quick evaporation of sweat.

Ibamoto et al. (2000) reported that a low humidity made it possible to provide comfort to both those who are in thermal transient and those who are in a steady state, based on the results of subjective experiments.

Table 1-4. Representative room conditions with cold air distribution system and conventional systems (Kirkpatrick and Elleson, 1996)

Space conditions	Room Conditions		
	Dry-Bulb Temperature [°C]	Relative Humidity [%RH]	Dew Point [°C]
Conventional System	23.9	50	12.8
Cold-Air Distribution System	23.9	40	9.5

1.3.2 Non-Thermal Effects of Humidity

1.3.2.1 Mucous Dryness

The human respiratory passages are covered with a mucus layer which both moisturizes the air inhaled and simultaneously traps germs and particles. The dust-laden mucus is constantly driven towards the mouth by a carpet of fine hairs. These hairs flick the mucus upwards at a speed of approximately 5 mm/min. If the mucus loses moisture it will become more viscous and would be expected to move more slowly and in extreme cases dry up completely. This dryness is noticeable in the nose and throat at low humidity and leads to discomfort. Subjects have reported dry noses when the indoor relative humidity falls to 25%RH (Proetz, 1956).

Winslow et al. (1949) recorded the degree of moisture present on the surface of the oral mucosa under conditions with air temperatures of 10.0, 15.5, 21.0, 26.5°C and relative humidites ranging from 16%RH to 90%RH in order to evaluate the influence of dry air on human membranes. The experiment concluded that vapour pressure affected the amount of moisture of the oral mucosa. Under conditions with an absolute humidity above 8.42g/kg (Dew point: 11.5 °C), the surface of the oral mucosa is relatively moist. On the other hand, under 8.42g/kg of absolute humidity, a marked drying of the oral mucosa was evident. It is considered to be basic knowledge for establishing Japanese Law for Maintenance of Sanitation in Buildings.

Andersen et al. (1974) exposed young healthy men to clean air at 23°C in a climate chamber. Following 27 hours at 50%RH subjects stayed for 78 hours at 9%RH, and then they returned to the initial level of 50%RH for 20 hours. No significant changes were observed in the nasal flow rate and nasal respiration. The mean value of subjective humidity ratings were always in comfort range. No discomfort was reported from the body surface. Skin resistance did not change. This study concluded that there was no physiological need for humidification of the air. Humidity criteria in Europe and the United States of America seem to be based on this study.

Concentrations of indoor chemical pollutants have been getting higher recently. Indoor chemical pollutants causes mucous irritation. Occupants possibly perceive the air to be dry instead of feeling their mucosa is irritated when exposed to chemical pollutants. The field survey conducted by Sundell and Lindvall (1993), in which questionnaire reports from 4943 office workers, measurements of indoor climate from 540 office rooms in 160 buildings, and measurements of TVOC in 85 rooms were used for an analysis, concluded that the frequency of reports of perceived “dry air” was an important indicator of the “sickness” of a building, although indoor air humidity is not an indicator of that.

1.3.2.2 Eye Dryness

Studies on eye dryness are relatively new, and it is only during the last 30 years that the physical mechanism of the fluid layer has been understood in its subtle complexity.

Laviana et al. (1988) exposed 24 soft contact lens (SCL) wearers to 10%RH and 30%RH at an air temperature of 23.9°C for 10 hours with a SCL on one eye. Acuity, refractive errors, and cornea curvatures of the eye were not significantly affected by humidity, while a perceivable level of annoyance was felt in the eyes with and without soft contact lenses after a 4-hour exposure at relative humidity of 30% or less. However, only SCL were examined in this study, and further study on hard contact lens wearers is required.

Matsubayashi et al. (2000) made subjective experiments in a climate chamber for 30 minutes, using 48 males and 48 females under conditions at 22°C and 25°C of air temperature and at 20%RH, 30%RH, 40%RH and 50%RH. It was reported that occupants blinked more frequently at below 7.0 g/kg of absolute humidity.

Many people use contact lenses in office spaces these days. At the same time, more and more people are suffering from dry eye syndrome. Studies on the effects of the air at low humidity on dry eye syndrome are needed. For more detailed information on contact lenses see Section 1.3.3.

1.3.2.3 Dry Skin

The first effects of dry air on body skin is that the dead flattened skin cells which form the outermost layer of skin lose their cohesion and the skin surface becomes rough. This condition can occur after a few hours exposure to a very dry atmosphere and can disappear as quickly on return to more humid conditions. If the dryness is intense the skin can become chapped and cracked, and if the basal layer of growing cells is torn, then the skin fissures will be slow to heal. These changes are illustrated in Figure 1-4 (Brundrett, 1990).

Experiments using small skin sites on the forearms of 250 people showed that normal skin did not release or absorb moisture to/from the air at relative humidities from 75-82% (Buettener, 1959). A field survey (Gaul and Underwood,1952) stated that skin problems occured when the outdoor dew point was below -7°C, which is equivalent to 15%RH at 20°C. The results of experiments conducted by McIntyer and Griffiths (1975) indicated occupants' perception of skin moisture was related to air temperature and relative humidity. Optimal temperature and humidity were shown to be 23°C and 70%RH.

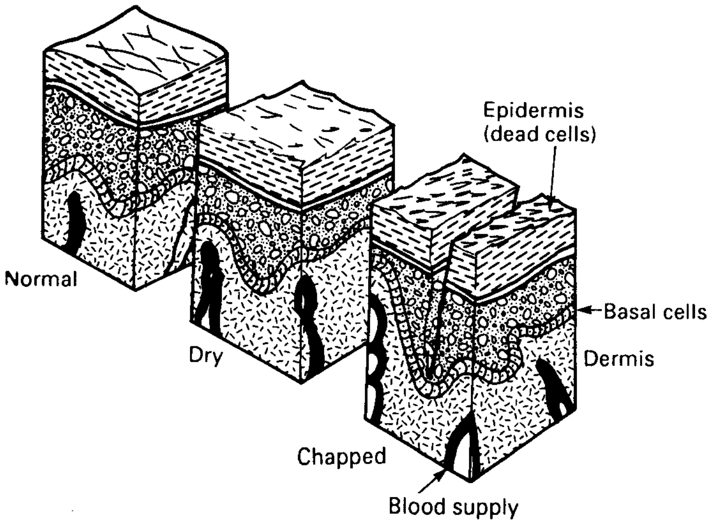


Figure 1-4. Progressive effects of dry skin condition (Brundrett, 1990)

1.3.2.4 Virus

Relative humidity in the air is a very important factor for most microorganisms and affects rate of infection of illness. Some viruses activate at high humidity and others at low humidity. Figure 1-5 shows the relationship between the survivability of the influenza virus and environmental relative humidity obtained in the experiments conducted by Harper (1963). Viability of the virus decayed quickly in air with relative humidity above 50%, and 99.9% of them died in 10 hours time. On the other hand, more than 50% of the viruses remained viable after 10 hours, and 10-20% of them after 24 hours at 35%RH and 20%RH.

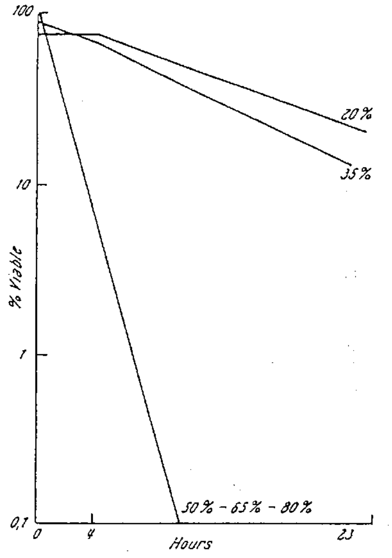


Figure 1-5. Viable decay of airborne influenza virus (Harper, 1963)

Ikeda et al. (2003) made some in-vitro experiments on the infectivity of the influenza virus. It was concluded that influenza virus was inactivate during a 5-hour exposure to 50%RH condition, and only a little was dormant during exposure to a below 20%RH environment. The infectivity of the influenza virus at 40%RH is ten times less than at 30%RH. However, the limiting criteria of virus infectivity has not been clear.

Some medical practitioners associate dry throat conditions with the onset of a cough or cold. Usuta (2000) states that no scientific evidence has been found that humidifying air results in airborne viruses losing their ability to be contagious. There is no suggestion that accretion of moisture to particles including viruses and humidifying the air prevents upper respiratory airways to dry and be immunized against infection.

Most previous studies and experiments on the effects of humidity on virus viability were carried out on the plate or in environments without ventilation. In actual buildings and houses, viruses might be removed by ventilation. Optimal humidity levels for reducing all kinds of virus indoor liveability can not be shown. Further discussion is required about removing viruses, bacteria and pollutants with ventilation.

1.3.2.5 Mould and Mites

Mites and mould are activated under high humidity conditions. While the optimal environment for mites is recognized as 25.0 °C and 80%RH, the limits at which the mites would not develop or multiply are not so clearly known. General guidelines suggest that mites will not multiply below 15°C, nor above 35.0°C at 75%RH (Brundrett, 1990).

Mould is a form of fungus which readily grows on damp materials and creates a characteristic unpleasant smell, and may eventually destroy the materials on which it grows. The general conclusion is that all outside air is heavily contaminated throughout the year with many kinds of mould spores. In one study, over 70 species were identified, although only 9 species provided 90% of the spores collected. Spore concentrations are lowest in winter, but rarely drop below a few hundred spores per cubic metre of air. In summer it is typically 15,000 spores/m^3 but can be much higher on occasion. Indoor airborne spore concentrations are typically one-fifth of those outdoors (Richards, 1956 and Nilsby, 1949). However, there is an order of magnitude difference in spore concentration between dry and damp houses, and there is a distinct change in the type of mould.

Fungi and house dust mites cause allergic rhinitis and asthma. Sundell (1994) pointed out that reduced humidity is known to have a positive effect on preventing condensation and mould growth as well as on reducing mite populations.

1.3.2.6 Fabric

All fabrics take up moisture as the ambient humidity rises. The amount of moisture is determined by the relative humidity, not the water vapour pressure, and only slightly affected by temperature. Organic fibres such as wool, cotton and linen absorb large amounts of moisture, particularly at high relative humidity. Artificial fibres usually absorb much less (Urquhart, 1960). The feeling of dampness in a fabric is also influenced by its surface properties, but for each material it is clearly linked to the moisture content. Dampness also affects the compressibility of clothing, as many fibres lose their natural springiness in moist conditions. Compressed clothing is not good as thermal insulator (Hall and Polte, 1956).

1.3.2.7 Electrostatic shocks

Under low humidity conditions, people may experience electrostatic shocks when they walk and touch objects such as doorknobs and cabinets. Brundrette (1990) reported electrostatic shocks rarely occurred in above 40%RH environments. Even under conditions with below 40%RH, in practice, electrostatic shocks can not possibly bother occupants, although safety criteria for avoiding them was recognized to be above 60%RH. On the other hand, occupants often experience electrostatic shocks at 20%RH. It is possible to avoid electrostatic shocks by selecting appropriate materials and treatment of surfaces. One carefully recorded survey shows the kind of complaint record of electrostatic shocks in a large open-plan office as presented in Figure 1-6 (Anon, 1975).

Tanabe (1996) made subjective experiments and reported that standing up from the modern office type of chair caused the highest voltage for the human body in office spaces.

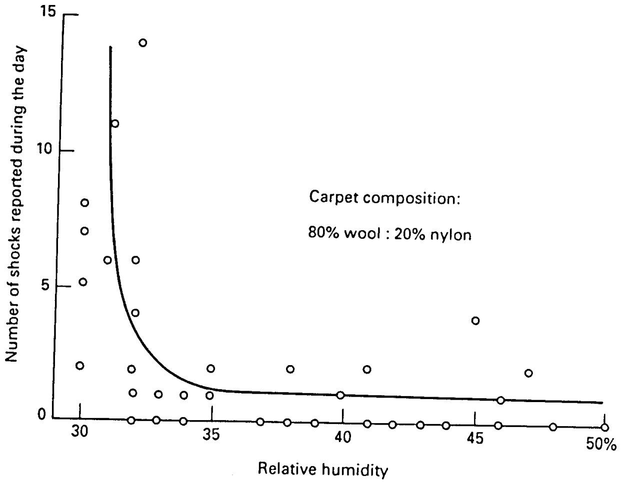


Figure 1-6. Complaint record of electrostatic shocks (Anon, 1975)

1.3.3 Contact Lenses (CL)

Contact lens wearers may be affected strongly by the humidity in the air because they are wearing contact lenses directly on their corneas.

Currently, 4 types of CL are available: conventional soft contact lenses (conventional SCL), disposable contact lenses (DSCL), conventional hard contact lenses (conventional HCL), and rigid gas permeable lenses (RGP-CL). DSCL is one kind of soft contact lens (SCL), and RGP-CL is one type of hard contact lens (HCL). In this study, RGP-CL and conventional HCL were classified as the “HCL-group”. DSCL and conventional SCL were put into the “SCL-group”. The characteristics of four kinds of CL are shown in Table 1-5 (Japan Ophthalmologists Association). Compared with glasses, CL has some merits: 1) Small optical demerit, 2) Good reflection on the retina, 3) Good for correction of anisometropia, 4) Good for correction of astigmatism (only HCL), 5) Convenience during exercise, 6) High accuracy of correction, 7) No effect on his/her appearance. On the other hand, their demerits are pointed out: 1) Difficult and complex method for maintenance, 2) Possibility of cornea damage (Nakayasu, 1998).

Table 1-5. Characteristic of four kinds of CL (from http://www.gankaikai.or.jp)

	HCL-group		SCL-group	
	Conventional HCL	RGP-CL	Conventional SCL	DSCL
Optics	Excellent	Excellent	Good	Good
Feeling	Not bad	Good	Excellent	Excellent
Damage to cornea	Moderate	Not damageable	Damageable	Not damageable
Pollution of lenses	Non-polluting	Little polluting	Polluting	Non-polluting
Service life	Long	Slightly short	Short	Short
Maintenance	Easy	Easy	Complex	Easy

Investigation of the CL market in the year of 2000 (SUCCEED, 2000) reported that 12,460,000 Japanese people used CL in daily life, which is equivalent to 9.9% of Japanese total population, and up to 10.4% of the Japanese population above 5 years old. Sixty-three point three percent of CL-wearers were females and 36.7% males. According to the data on the age of CL purchase, 46.1% of all consumers of CL were people aged from 15 – 24, and 32.8% ranged in age from 25-34. Thus, people aged 15 to 34 occupied 78% of all CL purchases.

HCL or RGP-CL were used by 26.8% of wearers, SCL by 38.3% and DSCL by 34.9% (in 2000). The number of SCL and DSCL wearers has been increasing recently, although 50.3% of CL-wearers used to use HCL or RGP-CL in 1996. More young people tend to use SCL and DSCL, on the other hand, more HCL wearers are reported from an older bracket group.

In the United States of America, the number of CL-wearers was 7.8% of all population. About 14% of CL-wearers used HCL, but most of them used DSCL or SCL (Mummert, 2001). It was reported in 1995 that less than 2% of Australian population were CL wearers, and of that number 80% were users of SCL (Hamano, 1995).

Yoshitoshi et al.(1996) conducted a survey of air line flight attendants who wear CLs to determine the effects that the environment in aircraft have on CL usage. The results of surveying 105 flight attendants including 72 HCL-wearers, 24 SCL-wearers and 12 DSCL-wearers showed 12 CL-wearers (11.4%) complained of strong discomfort. Their main symptoms were reported as sensations of dryness, eye redness and eye irritation. They concluded that low humidity conditions in the aircraft cabins caused the discomforts reported by CL-wearers and that more attention should be paid to those who wear CLs during flight.

Laviana et al.(1988) exposed 24 SCL-wearers to 10%RH and 30%RH at 23.9°C air temperature for 10 hours with a SCL in one eye. Only SCL were examined in this study, and further study about HCL is required.

The usage of HVAC systems, PCs and contact lenses has caused the problem of dry eye syndrome which has been getting more serious in office spaces recently. The “Help! Dry Eye network” which was organized by medical doctors to publicize dry eye syndrome, analysed the results of a survey conducted using 1025 office workers in 2001 and 2000 (Yokoi et al.). It was reported that 31.2% of workers (320 workers) were diagnosed as having dry eye syndrome. In particular, 40.7% of contact lens wearers (120 CL-wearers) were found to be suffering from dry eye syndrome.

Given that there are more and more CL-wearers every year, and that, according to the research cited above, CL are popular among the young, “dry eye syndrome” will likely grow as a problem in the future. As young wearers of CL mature and enter into the business world, it can be predicted that more complaints of dry eye syndrome will occur.

1.3.4 Effects of Factors Indoors on Human Productivity

Since office work requires workers to concentrate hard, many studies have been conducted recently about the effects of various different factors indoors on human performance.

Otto et al. (1993) exposed subjects to high VOCs concentration. Subjective performance did not decrease, although significant differences were obtained from participants when evaluating odour intensity, acceptability and irritation.

Gohara et al. (2001) conducted subjective experiments under varying conditions with different ventilation rates. They evaluated perceived air quality and appropriate tasks for evaluating subjects' performances.

Wargocki et al. (1999) showed that the percentage of the dissatisfied increased, and their productivity decreased in a polluted environment. This was the result of subjective experiments on the effects of indoor air quality on the subjective performance. In these experiments, a 20-year old carpet was used as the pollution source.

Wyon (1998) studied the relationship between the school children having breakfast and their performance in class. He also examined the effects of the bedclothes on their performance.

Witterseh et al.(1999) made subjective experiments on the relationship between noise and workers' productivity, using actual office noises. Moderate level of noise helped subjective performance increase during an addition task. Subjective performance was significantly lowered under noisy conditions when they worked on the creative thinking.

Fisk et al.(1997) estimated potential annual savings and productivity gained of 6 to 19 billion dollars by reducing respiratory disease, $ 1 billion to $ 4 billion from reduced allergies and asthma, $ 10 billion to $ 20 billion from reduced sick building syndrome symptoms, and $12 billion to $125 billion from direct improvements in worker performance that are unrelated to health. In office space, as cost for workers is greater than that for building construction and maintenances including HVAC systems, improvements in their health, comfort, and performance due to improved indoor air quality would bring benefits.

1.4 OUTLINE OF RESEARCH

The outline of this study is diagrammed in Figure 1-7.

In Chapter 1, “General Introduction”, the objective of this research is given. Background information and related researches are reviewed.

In Chapter 2, “Eye Comfort of Subjects Wearing Contact Lenses at Low Humidity During the Summer Season”, subjective experiments were carried out to investigate the dryness of eyes caused by the different types of contact lenses under low humidity in summer. A total of 37 subjects, 10 with soft contact lenses, 7 with hard contact lenses, 10 with glasses and 10 with naked eyes, were exposed for 3 hours in a climate chamber at Waseda University, Japan. Four humidity conditions, 30%RH, 40%RH, 50%RH and 70%RH with constant SET* were set. Subjects rated their sensations every 10 minutes during the exposure and skin moisture and break up time were recorded.

In Chapter 3, “Thermal Comfort and Productivity under Humidity Conditions with Different Indoor Air Quality Levels in Summer and Winter”, the effects of low humidity and indoor chemical pollutants, formaldehyde, are evaluated from the results of subjective experiments. Experiments were conducted in the climate chamber at Waseda University, Japan in summer and winter with the same procedure in order to investigate the seasonal differences of human responses. A total of 6 conditions with constant SET* were set: 3 humidity conditions (30%RH, 50%RH and 70%RH) × 2 indoor air quality levels (clean condition and polluted condition). An air cleaner was installed under the clean conditions and medium density fibreboards were set in place under the polluted conditions. For each season, 18 subjects were exposed for 3 hours performing 2 kinds of simulated office work: Addition task and Text Typing. Their sensation votes, objective test results and performance were examined in both seasons. Furthermore, subjective fatigue was tested in winter.

In Chapter 4, “Effects of Relative Humidity and Absolute Humidity on Subjective Comfort and Productivity”, the difference of the relative humidity effects and absolute humidity effects on subjective comfort and performance is shown. Sixteen subjects stayed in a climate chamber under a total of 6 conditions at constant SET*. Subjects performed simulated office work during the 3-hour exposure. Subjects reported their sensations, fatigue and subjective self-estimated performance after each task. Their skin moisture, break up time and oral mucous moisture were measured. Their performance and fatigue were examined.

In Chapter 5, “ Limiting Criteria for Human Exposure to Extremely Low Humidity”, the results of subjective votes, medical tests of eyes, nose and skin, and performance, obtained from the experiments under extremely low humidity, are described. Subjective experiments were carried out at International Centre for Indoor Environment and Energy, Technical University of Denmark. Thirty subjects performed simulated office work for 5 hours in climate chambers under 4 humidity conditions (5%RH, 15%RH, 25%RH and 35%RH) at 22°C of clean air. The other 30 subjects were exposed to polluted air with the same absolute humidity as 22°C/15%RH. Subjects were divided into sub groups, -normal, sensitive and contact lens-, and the differences in their responses were examined.

In Chapter 6, “Humidity and Air Temperature in Aircraft Cabins”, the results of measurements of humidity and air temperature in air cabins during flights are reported. In order to measure the air humidity at low air pressure, 3 kinds of polymer film electronic hygrometers were calibrated by using the saturated salt solution method in a sealed desiccator.

In Chapter 7, “Conclusive Summary”, results of each chapter are summarized.

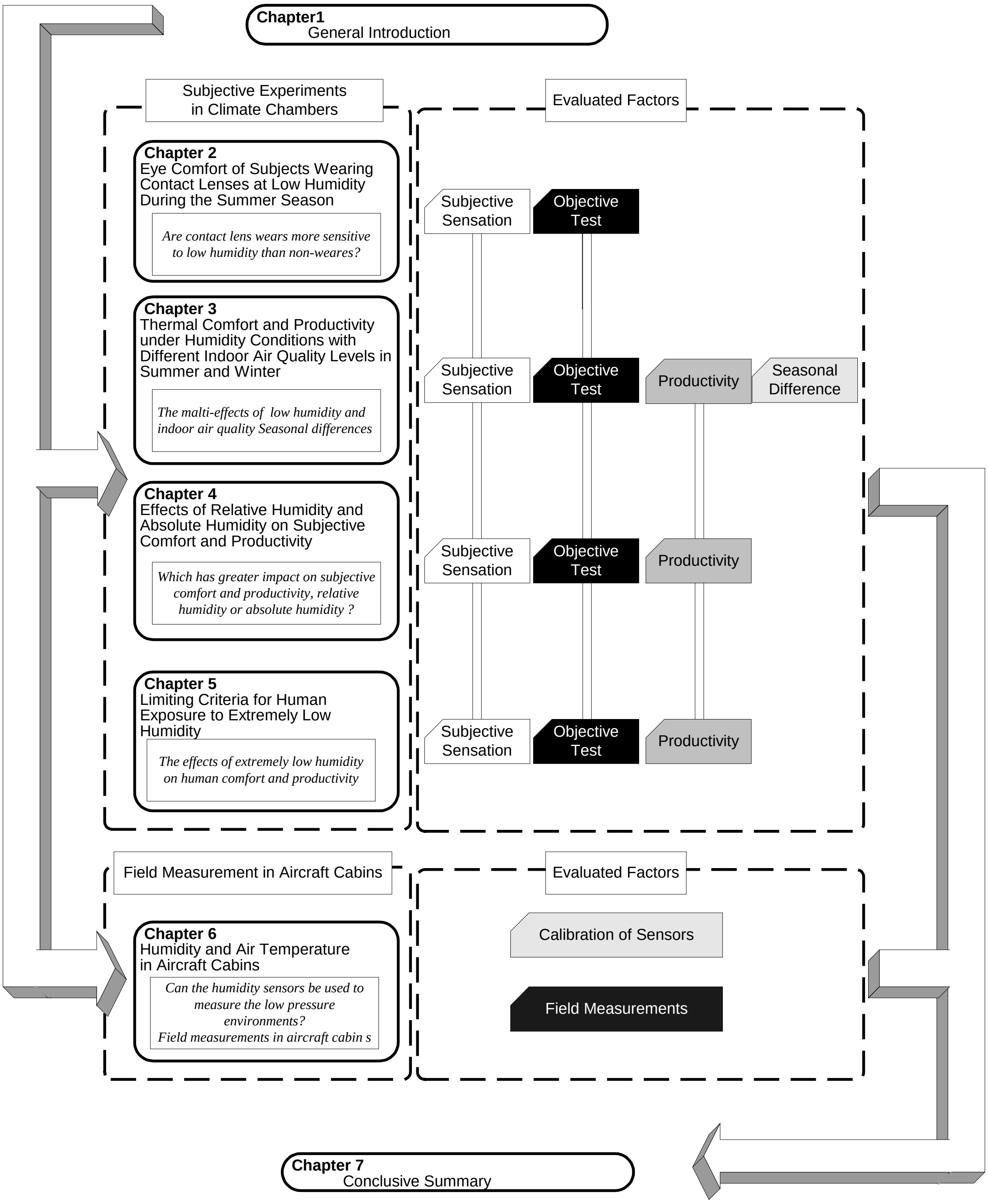


Figure 1-7. Outline of this study

CHAPTER 2

EYE COMFORT OF SUBJECTS WEARING CONTACT LENSES AT LOW HUMIDITY DURING THE SUMMER SEASON

Chapter 2

EYE COMFORT OF SUBJECTS WEARING CONTACT LENSES AT LOW HUMIDITY DURING THE SUMMER SEASON

2.1 INTRODUCTION

Due to the usage of HVAC system, computers and contact lenses, the problem of dry eye syndrome has been getting more serious in office spaces recently. It is generally said that contact lens wearers might be more sensitive to low humidity than non-wearers. It is because contact lenses are used on their cornea.

People mainly use 4 kinds of contact lenses; conventional soft contact lenses, conventional hard contact lenses, rigid gas permeable contact lenses and disposable contact lenses. In this chapter, eye comfort/discomfort caused by different types of contact lenses under low humidity conditions are studied.

2.2 EXPERIMENTAL DESIGN

In order to clarify the effects of low humidity caused by the use of different types of contact lenses, subjective experiments were carried out.

2.2.1 Climate Chamber

Subjective experiments were carried out during the summer season, 2000 in a climate chamber at Waseda University, Tokyo, Japan. The dimensions of the chamber were 3600 mm wide × 2700 mm deep×2600 mm high. Ceiling plenum and floor plenum were installed in the chamber.

Ceiling-supply or floor-supply can be set with the dampers. The maximum ventilation rate was 130 m^3/h. Sensible heat load designed under 19°C were 166 W from occupants and 430 W from computers or other instruments. An air handling unit (AHU) and a fan coil unit (FCU) were equipped. Air temperature could be controlled from 19°C to 30°C with accuracy of ± 1°C. Air humidity could be controlled between 40 and 60%RH with accuracy of ± 5% under the environment with 8.5g/kg of absolute humidity. Supply air of FCU could be controlled between 11 and 20°C for cooling (temperature difference between room air temperature and supply air ≤10°C) and between 25°C and 40°C for heating (temperature difference between room air temperature and supply air ≤10°C).

Ice storage system was also installed to establish low humidity in summer.

The ceiling-supply was adopted for this study. Air was exhausted through the floor plenum. The ice storage system was used for low humidity condition.

The HVAC system of the chamber is shown in Figure 2-1 and plan of the chamber in Figure 2-2.

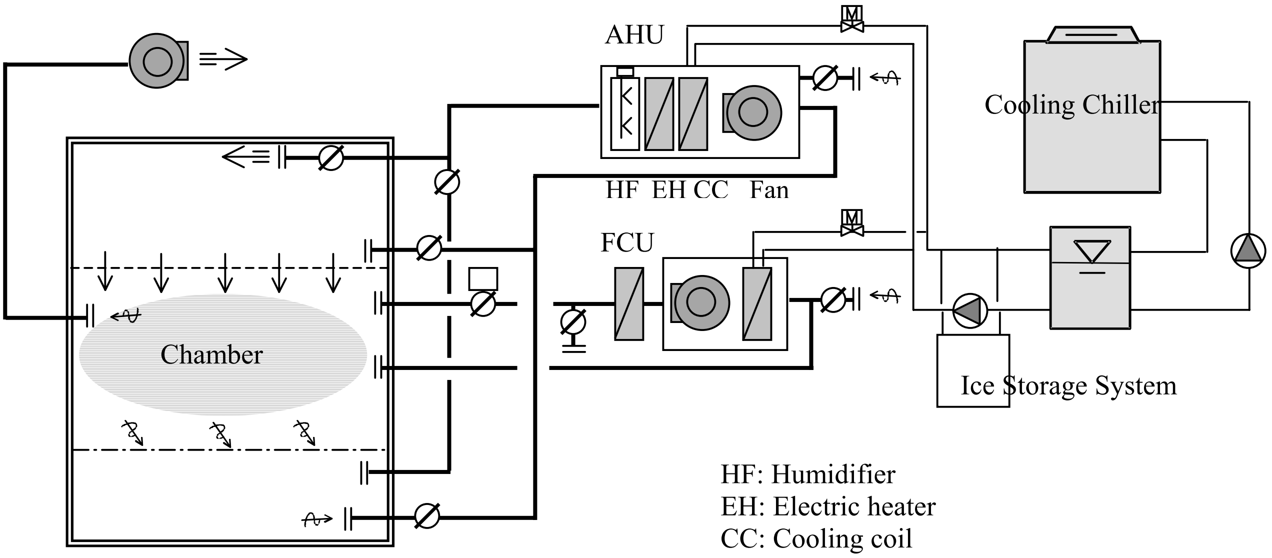


Figure 2-1. The HVAC system of the climate chamber

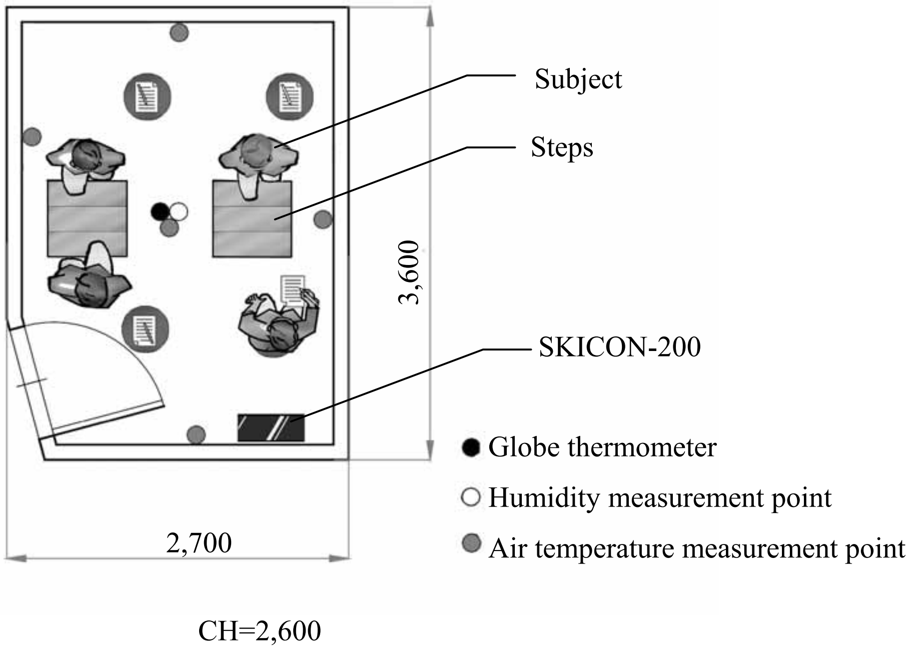


Figure 2-2. The plan of the climate chamber

2.2.2 Experimental Condition

Subjects wore clothing ensembles which consisted of a long-sleeve shirt, trousers and socks (Cotton 100%). All subjects wore their own underwear. The clo value was estimated to be 0.6 clo. To keep their metabolic rate at 1.2met, subjects were asked to go up and down 13-15 steps every 10 minutes during the experimental sessions. The number of their steps were calculated with the method proposed by Center for Environmental Design Research, University of California Berkeley (Arens et al., 1993).

The comfort condition with 25.0°C of air temperature, 50%RH of air humidity, still air, mean radiant temperature = air temperature, which is in the comfort zone as prescribed in ASHRAE Standard 55-92 and also the design criterion for the office space during the summer season, is set as standard. SET* is 25.2 °C under the standard condition. It is estimated for all conditions that air velocity is stii (<0.15m/s), mean radiant temperature is equivalent to air temperature, the clo value is 0.6 clo and metabolic rate is 1.2met. Four levels of relative humidity were set, namely 30%RH which is below the lower humidity limit showen in "Law for Maintenance of Sanitation in Buildings", 40%RH which is the lower humidity limit shown in it, 50%RH which is the standard condition and 70%RH which is the upper humidity limit shown in it. In all conditions, SET* was kept constant at 25.2°C by controlling air temperature.

Experimental conditions, measurement results of the thermal environment in the chamber during experiments and SET* calculated with measurement data are shown in Table 2-1. Under all conditions, SET* were in the range of 25.2°C ± 0.4°C.

The thermal environment in the anteroom was controlled in order to keep air temperature at about 25.0 °C, although detailed measurements were not conducted.

Table 2-1. Environmental conditions and measurement result Mean (Standard Deviation)

	Environmental Conditions						Measurement results			
	Air Temperature [°C]	Relative Humidity [%RH]	Air Velocity [m/s]	Clothing [clo]	Metabolic Rate [met]	SET* [°C]	Air Temperature [°C]	Globe Temperature [°C]	Relative Humidity [%RH]	SET* [°C]
1	24.6	70	<0.15	0.6	1.2	25.2	24.1 (0.31)	24.5 (0.35)	71 (1.5)	25.4 (0.40)
2	25.0	50					24.8 (0.44)	25.3 (0.52)	52 (1.2)	25.6 (0.47)
3	25.2	40					24.7 (0.22)	25.1 (0.21)	42 (1.3)	25.1 (0.19)
4	25.4	30					24.9 (0.28)	25.3 (0.33)	34 (0.9)	25.1 (0.29)

2.2.3 Subjects

A total of 4 groups, which were “HCL(hard contact lens)-group”, “SCL(soft contact lens)-group”, “Glasses-group” and “Naked eye-group”, were formed. Subjects with contact lenses were divided into 2 groups, which were the “SCL-group” consisted of conventional soft contact lens (conventional SCL) and disposable contact lens (DSCL) wearers and the “HCL-group” of conventional hard contact lens (conventional HCL) and rigid gas permeable contact lens (RGP-CL) wearers. All subjects in the “HCL-group” wore RGP-CL in this experiment.

A total of 37 Japanese college-aged subjects, namely 5 males and 5 females in the naked eye group, 2 males and 5 females in the HCL-group, 5 males and 5 females in the SCL-group and 5 males and 5 females in the glasses group, were exposed for 180 minutes. All subjects participated in all conditions. All subjects were volunteers, who were paid for participating in the experiments. Considering their circadian rhythm, all subjects took part in the experiments at the same time of the day. Physical characteristics of subjects are listed in Table2-2.

Table 2-2. Physical characteristics of subjects Mean (Standard Deviation)

Sex	Number	Eye Condition		Age [year]	Height [cm]	Weight [kg]	Body Surface Area [m^2]* 1)	Rohrer Index [-]*2)
Male	17	SCL	5	22.5 (2.6)	172.4 (5.1)	59.6 (3.3)	1.72 (0.06)	116.8 (11.86)
		HCL	2					
		Glasses	5					
		Naked eyes	5					
Female	20	SCL	5	22.5 (4.6)	159.1 (4.1)	50.0 (4.2)	1.50 (0.07)	124.4 (11.70)
		HCL	5					
		Glasses	5					
		Naked eyes	5					
All	37	SCL	10	22.5 (3.1)	164.7 (8.1)	54.1 (6.2)	1.60 (0.12)	121.2 (12.53)
		HCL	7					
		Glasses	10					
		Naked eyes	10					

*1) Takahira’s equation: $A=0.007246W^{0.425}\times H^{0.725}$

*2) Rohrer Index = $W/H^3\times10^7$

A=Body Surface Area [m2], W=Body Weight[kg], H=Height[cm]

2.2.4 Experimental Procedure

The experimental procedure is shown in Figure 2-3. Figure 2-4 shows the subjects during the experiment.

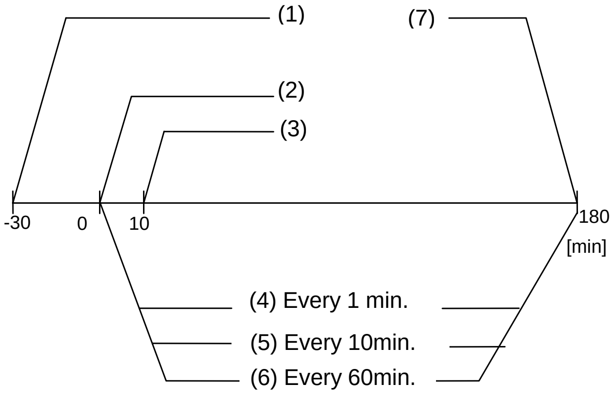
The subjects changed their clothing, entered the chamber and the first measurements of break up time (BUT) and skin moisture were done during 30 minutes before the experiments. When the subjects first started going up and down the steps, the experiment started. Each subject was asked to walk up and down 13-15 steps every 10 minutes during the experimental sessions, which simulated light office work (Arens et al., 1993). The number of steps was calculated from the physical characteristics of each subject. During the intermittent periods, the subjects were kept at sedentary activity. They were allowed to read books or talk with each other. However, they were not allowed to do computer work through the experimental time in order not to decrease/increase their blinking. Mean activity during the experiment was estimated to be 1.2 met.

Air temperature, relative humidity and globe temperature were monitored every minute. Air velocity was recorded before and after each experiment.

During the experiments, skin temperature was measured every minute, and body weight and armpit temperature were also logged before and after each experiment. Every 60 minutes, break-up time of eyes (BUT) and the skin moisture of the left forearm and left hand were recorded. BUT was proposed by Wyon (1987) that subjects measured the time from one blink to next blink with stopwatches.

Every 10 minutes, subjects recorded their sensations. The voting sheets consisted of general sensations including thermal sensation, comfort sensation, thermal acceptability, humidity sensation, eye dryness and eye comfort. The scales for subjective rating are mentioned in Section 2.3.

Table 2-3 lists the measurement items and instruments.



(1) Coming-in, Change Clothes, Weight, Questionnaires, Armpit Temperature
(2) Start of the Experiment, Skin Moisture, BUT, Activity (1st)
(3) Vote (1st), Activity (2nd)
(4) Environmental and Physiological Measurement
(5) Activity, Vote
(6) BUT, Skin Moisture
(7) End of the Experiment, Armpit Temperature, Change Clothes, Weight

Figure 2-3. Experimental procedure

Figure 2-4. Subjects during the experiment

Table 2-3. Measurement items

	Measurement Items	Interval	Instrument	Height (above floor)
Environmental Measurements	Air Temperature	1 min.	C-C thermocouples (φ0.32 mm)	0, 0.1, 0.6, 1.1, 1.7, 2.3 m
	Air Humidity	1 min.	Thermo recorder RS-11 (ESPEC)	0.6, 1.1 m
	Air Velocity	Before and after each experiments	Climomaster (KANOMAX)	0.6 m
	Globe Temperature	1 min.	Globe temparature	0.6 m
Objective Measurements	Skin Temperature	1 min.	C-C thermocouples (φ0.32 mm)	
	Skin Moisture	60min	SKICON-200 (IBS)	
	BUT	60min	Stopwatch	
Subjective Measurement	Subjective Rating	10min	Rating sheet	

2.3 RESULTS AND DISCUSSION

2.3.1 Thermal Comfort

The subjects marked their general thermal sensations on the questionnaire every 10 minutes during the exposure as psychological responses to the thermal environment. Votes during the last 60 minutes of the exposure period were used for further analyses assuming to be obtained at steady state. The rating scales of general sensations including thermal sensation, comfort sensation and thermal acceptability are shown in Figure 2-5.

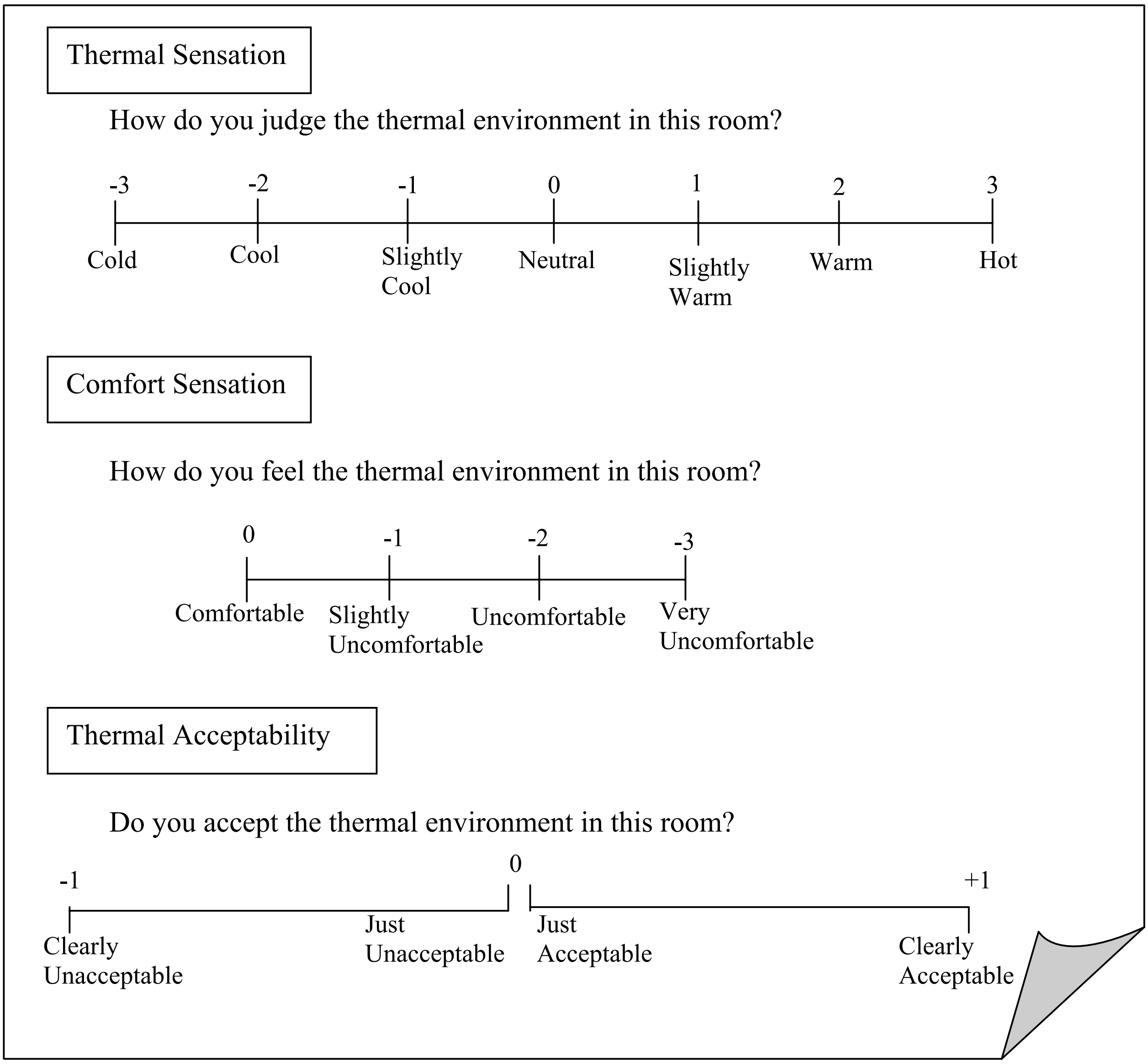


Figure 2-5. Rating scales

Table 2-4 shows the mean values and standard deviations of general sensations rated by each group of subjects under steady state.

The average values of thermal sensation, comfort sensation, thermal acceptability reported by all subjective groups under all conditions were scattered between –0.8 and +0.3, above –0.6, above +0.6 respectively. The subjects in the HCL-group reported to be cooler than other groups. It was because the number of females was more than males in the HCL-group, although the other groups consisted of the same number of males and females.

According to the results of general sensations, it was concluded that no group complained more of thermal environment than other groups. Therefore, it was found that the effects of humidity on the occupants' general sensations were modest under thermally neutral conditions.

Subjects' skin temperature might affect their thermal comfort. In this experiment, skin temperatures on their chest and back were measured every minute. Skin temperature of both parts changed with exposure time, with the same tendency. Table 2-5 shows the average values and standard deviation of skin temperature on their left chest for each group under steady state. All results were scattered between 33.9 and 34.5°C. The effects of environmental humidity on their skin temperature were moderate. By increasing humidity, the heat load is also increased. This can be canceled by decreasing air temperature under constant SET* conditions. No group showed higher/ lower skin temperature than any other group.

Table 2-4. General sensations under steady state Mean (Standard Deviation)

	Group	30%RH	40%RH	50%RH	70%RH
Thermal Sensation	SCL	-0.1 (0.49)	+0.1 (0.63)	0.0 (0.76)	-0.4 (0.56)
	HCL	-0.4 (0.89)	-0.3 (0.78)	-0.3 (0.76)	-0.8 (0.92)
	Glasses	-0.1 (0.59)	-0.3 (0.67)	+0.1 (0.64)	-0.3 (0.59)
	Naked eyes	+0.2 (0.52)	-0.1 (0.61)	+0.3 (0.68)	-0.3 (0.45)
Comfort Sensation	SCL	-0.3 (0.28)	-0.3 (0.34)	-0.5 (0.36)	-0.2 (0.18)
	HCL	-0.4 (0.39)	-0.2 (0.21)	-0.3 (0.30)	-0.2 (0.29)
	Glasses	-0.6 (0.56)	-0.5 (0.52)	-0.5 (0.66)	-0.4 (0.45)
	Naked eye	-0.4 (0.27)	-0.3 (0.32)	-0.4 (0.36)	-0.3 (0.24)
Thermal Acceptability	SCL	+0.9 (0.09)	+0.9 (0.15)	+0.7 (0.34)	+0.9 (0.11)
	HCL	+0.7 (0.37)	+0.9 (0.15)	+0.8 (0.15)	+0.9 (0.13)
	Glasses	+0.6 (0.51)	+0.6 (0.52)	+0.7 (0.44)	+0.7 (0.30)
	Naked eye	+0.7 (0.40)	+0.8 (0.33)	+0.7 (0.34)	+0.8 (0.32)

Table 2-5. Skin temperature on left chest Mean (Standard Deviation)

	Group	30%RH	40%RH	50%RH	70%RH
Skin Temperature [°C]	SCL	34.5 (0.51)	34.5 (0.70)	34.2 (0.71)	34.2 (0.58)
	HCL	34.3 (0.91)	33.9 (0.23)	34.1 (1.18)	34.0 (0.81)
	Glasses	34.0 (0.65)	34.0 (0.50)	34.3 (0.92)	34.2 (0.87)
	Naked eye	34.0 (0.74)	33.9 (0.69)	34.4 (0.57)	34.3 (0.55)

2.3.2 General Humidity Sensation

Subjects assessed their general humidity sensation every 10 minutes. The scale for rating the humidity sensation is shown in Figure 2-6. Votes during the last 60 minutes of the exposure period were used for further analyses assuming it to be in a steady state.

Figure 2-7 shows the general humidity sensation rated by each group. The error bar displays the standard deviation. Friedman non-parametric analysis did not reveal the significant differences among 4 humidity conditions (p=0.841). In pair-wise comparisons between each subjective group for each humidity condition using Mann-Whitney U test, no significant difference was observed.

The effects of environmental humidity and subjects' wearing contact lenses on their general humidity sensation were only small in this experiment.

Skin moisture of subjects would affect their humidity sensation. Therefore, in this experiment their skin moisture was measured every 60 minutes on their left forearm with SKICON-200 (IBS Corp.). SKICON-200 adopts the high frequency impedance method (Tagami, 1984). Skin moisture of the subjects measured at the end of experiments for each condition is shown in Figure 2-8. Significant difference of skin moisture was found among humidity conditions with Friedman non-parametric analysis (p<0.01). Table 2-6 shows the p-value obtained in pair-wise comparison between humidity conditions by means of non-parametric Wilcoxon Matched-Pairs Signed Ranks Test. Significant differences (p<0.01) were obtained between humidity conditions but not between 30%RH and 40%RH. Skin moisture was significantly higher under the conditions with humidity above 50%RH, though the difference of skin moisture between 40%RH and 30%RH was small. In pair-wise comparisons between subjective groups for each humidity condition using Mann-Whitney U test, significant differences shown in Figure 2-8 were observed. However, no group showed higher/ lower skin moisture compared with other groups.

According to the results of skin moisture measurements and subjective rating of general humidity sensation, subjective skin moisture was affected by the environmental humidity. Skin moisture measured under the condition with humidity above 50%RH was significantly higher than below 40%RH. However, the subjective humidity sensation was not associated with their skin moisture under thermally neutral conditions set in this experiment.

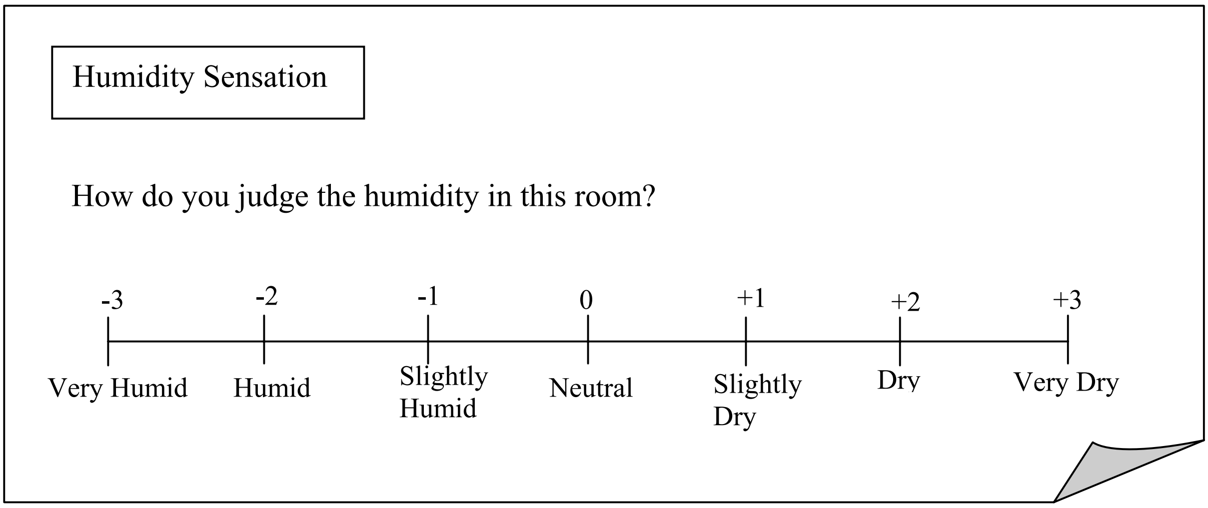


Figure 2-6. Scales for humidity sensation

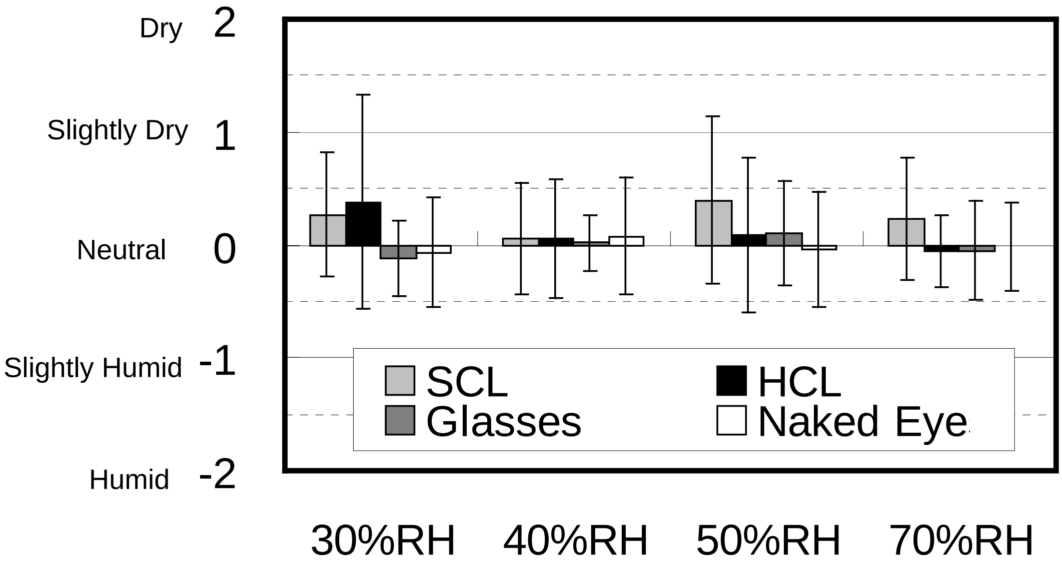


Figure 2-7. Humidity sensation rated at the end of exposure

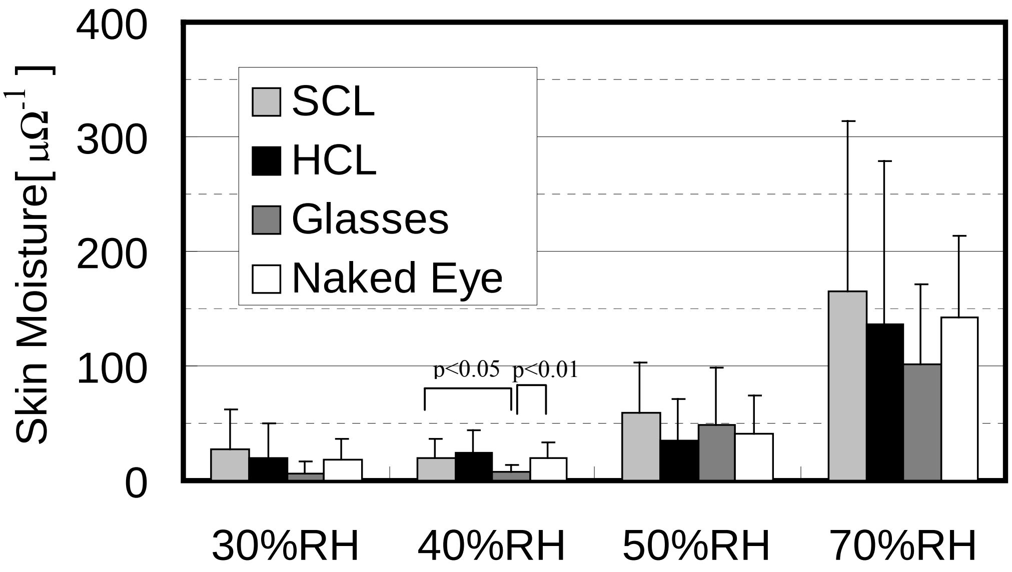


Figure 2-8. Skin moisture on left forearm measured at the end of exposure

Table 2-6. The levels of significant obtained in pair-wise comparison

Humidity condition				
30%RH	30%RH			
40%RH	N.S.	40%RH		
50%RH	$p<0.01$	$p<0.01$	50%RH	
70%RH	$p<0.01$	$p<0.01$	$p<0.01$	70%RH

2.3.3 Eye Comfort and Break up Time

The subjects assessed their dryness sensation and comfort sensation of their eyes every 10 minutes during the exposure. Eye dryness sensation was the response to the question how their eyes felt, and the same scale from –3(very humid) to +3(very dry) as for humidity sensation was used. Subjects answered whether their eyes felt comfortable or uncomfortable on the comfort sensation, rating it from –3(very uncomfortable) to 0(comfortable).

The sensation of eye dryness rated by all groups throughout the exposure time at 30%RH and the HCL-group and naked eye-group at 50%RH are shown in Figure 2-9. The condition of 50%RH represents the environment in summer in an office with a conventional HVAC systems and 30%RH represents a low humidity condition with a cold air distribution system. Votes of the subjects with naked eyes at 30%RH were not different from those at 50%RH. Eye dryness and eye discomfort perceived by the subjects with naked eyes was constant through the exposure period. On the other hand, subjects with HCL felt increasing eye dryness with longer exposure time.

The relationship between the eye dryness sensation and eye comfort sensation is shown in Figure 2-10. All values of each group of subjects under all conditions are plotted in this figure. Eye comfort tended to be lower under the condition where subjects' eyes felt dryer. The eye dryness reported by the subjects with naked eyes were scattered between –0.3 and +0.3 and eye comfort between –0.5 and 0. Eye dryness and eye discomfort votes of the subjects in the "Naked eye-group" were found to be smaller than those of subjects in other groups. On the other hand, the SCL-wearers and HCL-wearers complained more of their eyes being "dry" and "uncomfortable", compared with non-contact lens wearers ("Naked eye-group" and "Glasses-group").

The following regressions were obtained for each group:

HCL-group: $y=-0.684x-0.1102$ ($R^2=0.85$)
SCL-group: $y=-0.5806x-0.2444$($R^2=0.58$)
Glasses-group: $y=-0.3934x-0.3988$($R^2=0.45$)
Naked Eye-group: No regression
Where x = eye dryness, y = eye comfort.

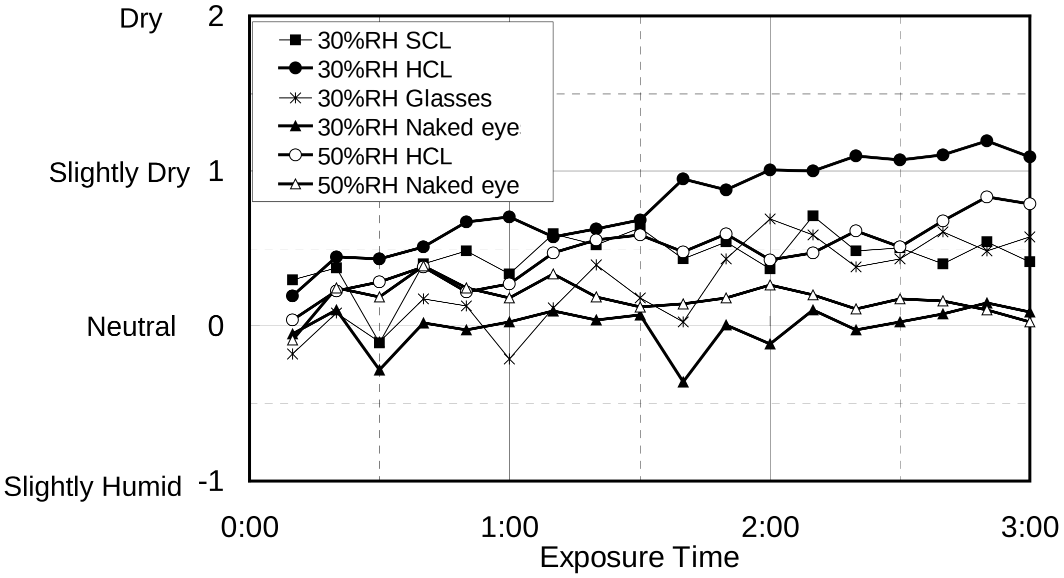


Figure 2-9. Change of eye dryness vote throughout the exposure time

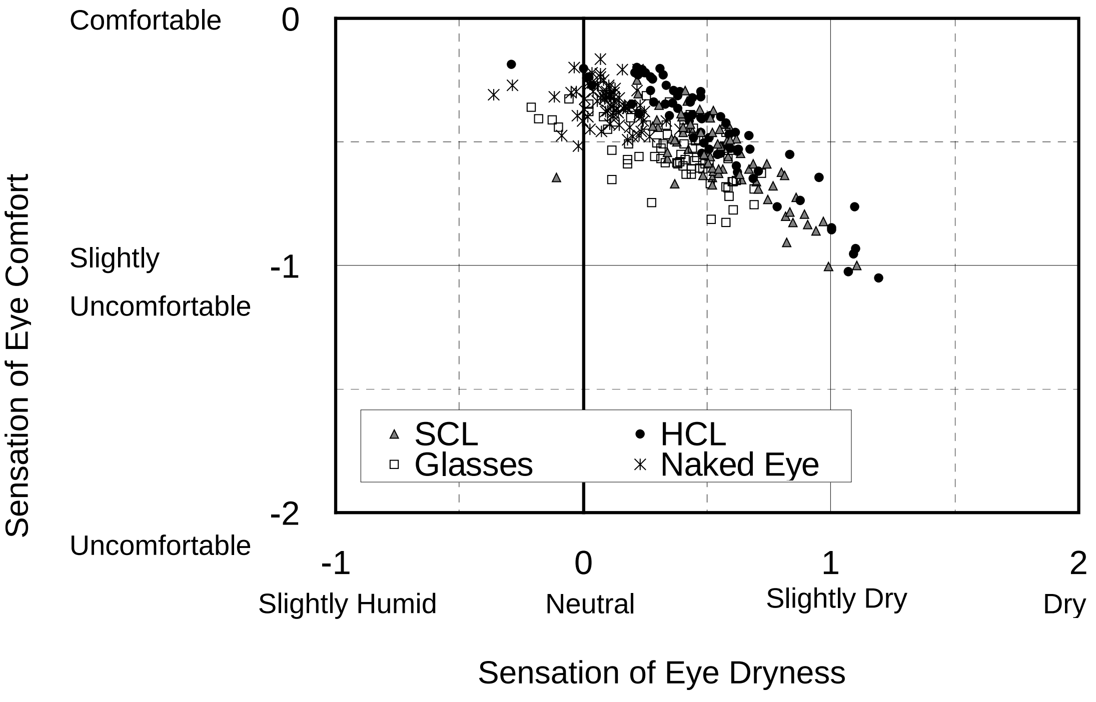


Figure 2-10. Eye dryness vs. eye comfort

These results demonstrated that SCL-wearers and HCL-wearers perceived their eyes to be more uncomfortable than non-wearers even when the increment of eye dryness was the same. There was a possibility that eye irritation and eye fatigue caused by the contact lenses affected their sensation of eye dryness.

Figure 2-11 shows the relationship between eye dryness and general humidity sensation rated by all subjects under all conditions. General humidity sensation was not associated with the sensation of eye dryness. Sensation of eye dryness was stronger than the general dryness sensation. Some subjects reported that their whole felt humid, although quite few reported that their eyes felt humid. It is concluded that the subjective perception of eye dryness was much more found than the perception of humid eyes.

"Break up Time (BUT)" is one of the physiological reactions that might affect the subjective eye comfort. Wyon et al. (1987) made experiments in a climate chamber and a car cabin for the purpose of evaluating the sensitivity of their eyes to the draught. The methods of "Norn lacrimal river dilution test", "Lissamine green test", "Mucus ferning test", "Observed break-up time" and "Self-reported BUT" were used for their experiments. It is reported in the paper that self-reported BUT, a method requiring only a stop-watch, i.e. no microscope and no instillation of eye drops in the eye, is the only feasible method for continuous assessment of BUT during the exposure to the draught. Addition to this merit, "Self-reported BUT" was adopted in this experiment due to its simple measurement process.

During the exposure time, the subjects measured their break up time by themselves using a stopwatch every 60 minutes. BUT in each group, measured at the end of the exposure is shown in Figure 2-12. The error bars represent the standard deviations. The overall significant difference among the 4 humidity levels was not found by Friedman non-parametric analysis ($p<0.429$). However, the Mann-Whitney U test revealed that BUT of HCL-wearers tended to be shorter than subjects with naked eyes for all conditions (30%RH; $p=0.147$, 40%RH; $p=0.147$, 50%RH; $p=0.181$, 70%RH; $p=0.220$). It was compatible with the result reported by Niimi et al.(1992) that the people with contact lenses blinked more frequently than those without contact lenses. They also concluded in the paper that the reason of blinking being changed by wearing HCL had not yet been clarified. It might be a result of the reaction by the cornea.

According to the results of BUT measurements and subjective rating of the sensation of eye dryness and comfort, it was found that the condition of the subjects' eyes affected their BUT and eye comfort stronger than environmental humidity did under thermally neutral conditions with constant SET* in summer.

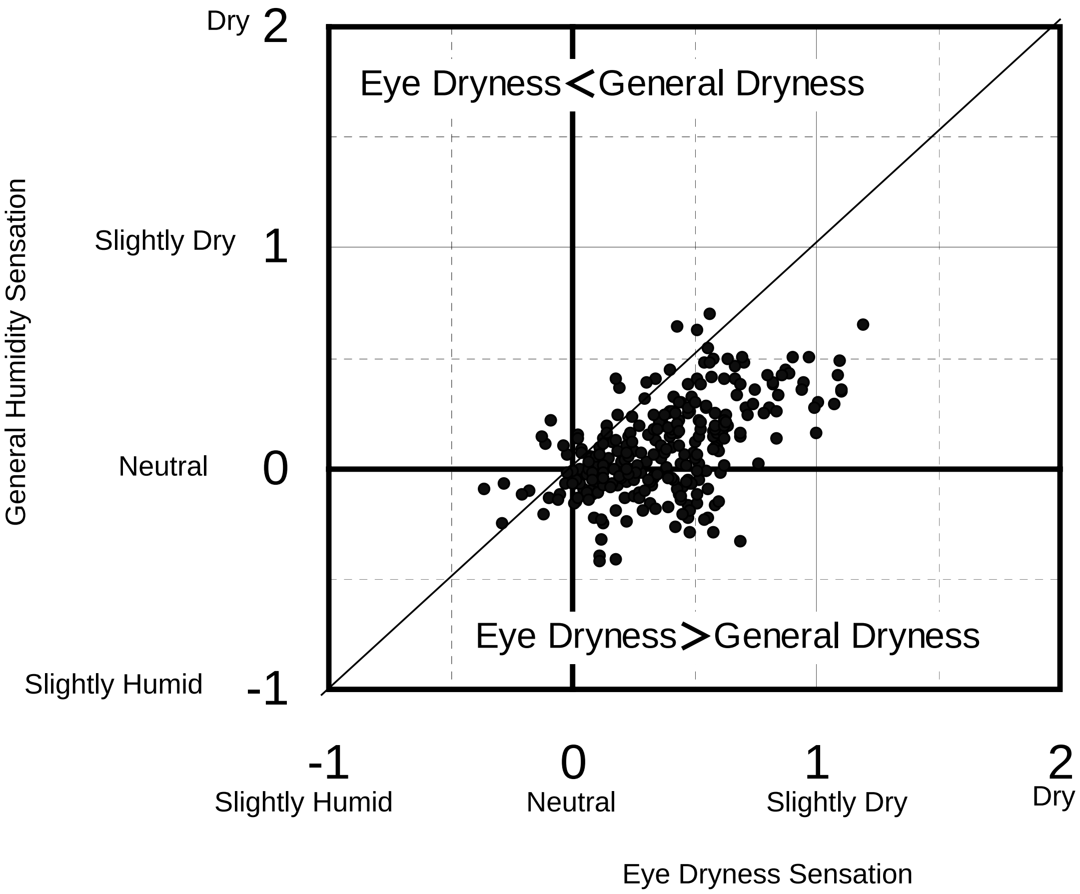


Figure 2-11. Eye dryness sensation vs. general humidity sensation

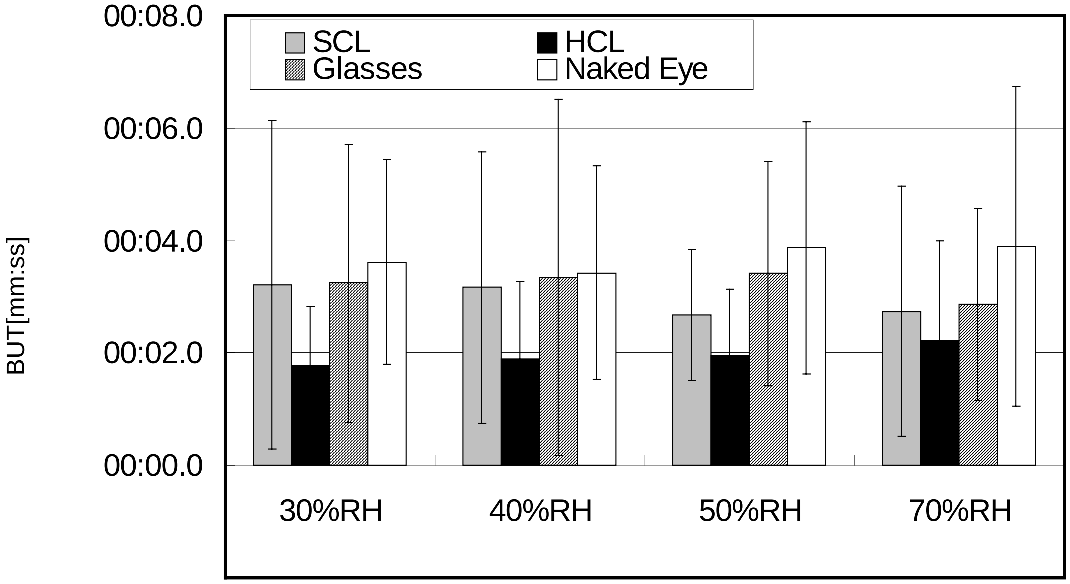


Figure 2-12. BUT measured at the end of the exposure

2.4 CONCLUSION

In order to clarify the effects of low humidity on wearers of different type of contact lenses, subjective experiments were carried out. Thirty-seven college-aged subjects were exposed for 180 minutes under the conditions with 25.2 °C of SET*. The following results were obtained.

1) The effects of humidity on the subjective general thermal comfort and skin temperature were modest under thermally neutral conditions with constant SET*.
2) Significant differences of general humidity sensation were not found either among the subjective groups or humidity conditions.
3) Skin moisture was high in conditions above 50%RH. Skin moisture was not associated with the general humidity sensation.
4) The contact lens wearers reported more eye discomfort caused by the increment of eye dryness than the non-contact lens wearers.
5) The eye dryness sensation was reported to be greater than the general dryness by all groups of subjects under all conditions.
6) It is concluded that the subjective perception of eye dryness was much more found than the perception of humid eyes.
7) Break up time of the hard contact lens wearers tended to be shorter than that of subjects with naked eyes. No significant difference was found among the humidity conditions.
8) The effect of wearing contact lenses on subjective eye comfort was found to be greater than that of environmental humidity.

CHAPTER 3

THERMAL COMFORT AND PRODUCTIVITY UNDER HUMIDITY CONDITIONS WITH DIFFERENT INDOOR AIR QUALITY LEVELS IN SUMMER AND WINTER

Chapter 3

THERMAL COMFORT AND PRODUCTIVITY UNDER HUMIDITY CONDITIONS WITH DIFFERENT INDOOR AIR QUALITY LEVELS IN SUMMER AND WINTER

3.1 INTRODUCTION

Air tightness, reduction of ventilation rate for saving energy consumption, and use of chemical materials cause a serious problem of high concentration of formaldehyde or VOCs (Volatile Organic Compounds) in many office buildings (Yanagi, 2001). Recent studies pointed out that occupants' sensation of dryness can indicate indoor chemical pollutants (Sundell, 1993). Indoor chemical pollutants irritate occupants' mucous membranes and they possibly perceive this irritation as dryness sensation caused by low humidity. Amano et al.(2000) reported that occupants' mucous membranes felt irritated and dry under the condition with high concentration of VOCs.

Subjective experiments were conducted during the summer season and the winter season in order to clarify the multiplied effects of humidity and indoor chemical pollutants on subjective comfort and productivity. Formaldehyde was selected as the indoor chemical pollutant. Concentration of formaldehyde is predicted 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 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 difference in subjects' reactions.

3.2 EXPERIMENTAL DESIGN

3.2.1 Experimental Conditions

Subjective experiments were carried out to clarify the effects of humidity and indoor chemical pollutants on subjective comfort and productivity. They were made in the climate chamber, at Waseda University, Tokyo, Japan in the summer of 2001 (from September to October) and winter of 2002 (from February to March). People adapt to a hot and humid climate in the summer and cold and dry climate in the winter in Japan. Comparing the results obtained in each experiment, it is possible to evaluate the seasonal differences in their reactions.

Eighteen college-aged subjects, 12 males and 6 females in summer and 9 males and 9 females in winter, were exposed for 180 minutes in a 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.

Experimental conditions are listed in Table 3-1.

Thermal environment:

The comfort condition with 25.0°C, 50%RH, still air, mean radiant temperature = air temperature, which was in the comfort zone prescribed by ASHRAE Standard 55-92 (1992), and design criterion in the office space during the summer season, was set as standard. SET* was 25.2 °C under this standard condition. Three levels of humidity condition, 30%RH, 50%RH and 70%RH were examined. In order for SET* to be constant for all conditions, air temperature was controlled. It was estimated for all conditions that air velocity was <0.15m/s; mean radiant temperature was equivalent to air temperature. 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 0.6clo. Subjects performed simulated office work during the 180-minute exposure and metabolic rate was estimated to be 1.2 met.

Air temperature, relative humidity and globe temperature in the chamber were monitored every minute. Air velocity was recorded before and after each exposure. Thermal environment measured during exposure and SET* are shown in Table 3-2.

SET* was a little higher than set point due to high air temperature in summer. In winter, relative humidity was measured 60%RH under the conditions which were intended to be 70%RH. However, SET* in winter was within 0.5 °C ± set point for each condition.

Indoor Air Quality:

Formaldehyde (HCHO) was selected as the indoor chemical pollutant to make different indoor quality levels. The Japanese Ministry of Health, Labour and Welfare (2002) prescribes 100 $\mu g/m^3$ as a guideline for formaldehyde concentration. This value is also stated in the "Building Standard Law of Japan (Ministry of Land, Infrastructure and Transport Government of Japan,1950)" and the "Law for Maintenance of Sanitation in Buildings (Ministry of Health, Labour and Welfare, Government of Japan, 1970)". Two indoor air quality levels were set for each humidity level. An air cleaner (Shinryo Eco Business Inc.) was used under the "clean conditions". MDF boards (Medium-density fibreboard) were used as the pollution source under the "polluted conditions". The total emission area of MDF boards was 64.8m^2, which was constant for all polluted conditions. The ventilation rate was controlled to be constant.

Concentration of formaldehyde was measured during exposure by using a DNPH-sampler (SUPELCO). A DNPH-sampler sampled for 4 hours for each exposure. Figure 3-1 shows the concentration of formaldehyde for each condition. Error bars in the figure represent standard deviations (S.D.). The S.D. under 50%RH/polluted condition in summer was not obtained. The concentrations of formaldehyde measured under clean conditions were significantly lower than under polluted conditions at the same humidity. In polluted air, the concentration of formaldehyde was the lowest under 30%RH condition, though it was high under high humidity conditions. Emission rate of formaldehyde increased under high humidity conditions because it is hydrophilic. Thus, a low humidity is able to reduce concentration of formaldehyde even in a building where emission sources exist.

Concentration of VOCs was measured using a sampler filled with Carbopak B and Carboxen 1000 (SUPELCO) and analysed with GC/MC. Concentration of VOCs for each condition is presented in Figure 3-1. Concentration of VOCs was much lower than 400 $\mu g/m^3$

for all conditions, which is within the guideline given by the Japanese Ministry of Health, Labour and Welfare (2002).

The concentrations of formaldehyde and VOCs set in this experiment were moderate and controlled to be around the guidelines of the Japanese Ministry of Health, Labour and Welfare.

The plan of the climate chamber and airflow through ducts are illustrated in Figure 3-2 and Figure 3-3. The climate chamber comprised of an air cleaner or MDF-boards, which was separated by a partition from the subjects so that they could not see them. The cleaned air by the air cleaner under clean conditions, and the polluted air of the MDF boards under polluted conditions was supplied into the room where subjects stayed by using the re-circulation system of the HVAC system of the chamber.

Ventilation rate was measured with the constant concentration method using the photoacoustic multi-gas monitor (B&K 1302, Bruel and Kjaer) and multipoint sampler and doser (B&K 1303, Bruel and Kjaer). Sulfur hexafluoride (SF_6) was used as the tracer gas. The ventilation rate was 49 m^3/h on average during experiments.

In addition to the 6 conditions mentioned above, a ‘pre condition’ with 25.0°C/50%RH was set to avoid subjects’ learning effects.

Table 3-1. 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				

Table 3-2. Thermal conditions measured during the experiments

	Summer				Winter			
	Air Temperature [°C]	Relative Humidity [%RH]	Globe Temperature [°C]	SET* [°C]	Air Temperature [°C]	Relative Humidity [%RH]	Globe Temperature [°C]	SET* [°C]
30c	25.9 (0.80)	32 (2.7)	26.1 (0.45)	25.8 (0.24)	25.1 (1.44)	29 (2.5)	25.1 (1.11)	25.0 (0.73)
50c	26.2 (0.90)	49 (2.1)	26.6 (0.82)	26.8 (0.76)	25.1 (0.95)	44 (1.7)	25.2 (0.81)	25.4 (0.48)
70c	25.6 (0.50)	63 (3.8)	25.9 (0.47)	26.8 (0.33)	24.8 (0.47)	60 (1.7)	25.0 (0.49)	25.7 (0.40)
30p	26.7 (0.86)	30 (2.3)	27.0 (0.80)	26.5 (0.70)	25.0 (1.68)	31 (2.1)	25.1 (1.38)	24.9 (0.94)
50p	26.6 (0.74)	50 (2.4)	26.9 (0.59)	27.2 (0.34)	25.4 (0.66)	43 (1.6)	25.4 (0.67)	25.6 (0.39)
70p	25.9 (1.01)	63 (2.3)	26.1 (0.64)	27.0 (0.69)	24.6 (0.76)	60 (2.6)	24.8 (0.51)	25.5 (0.41)

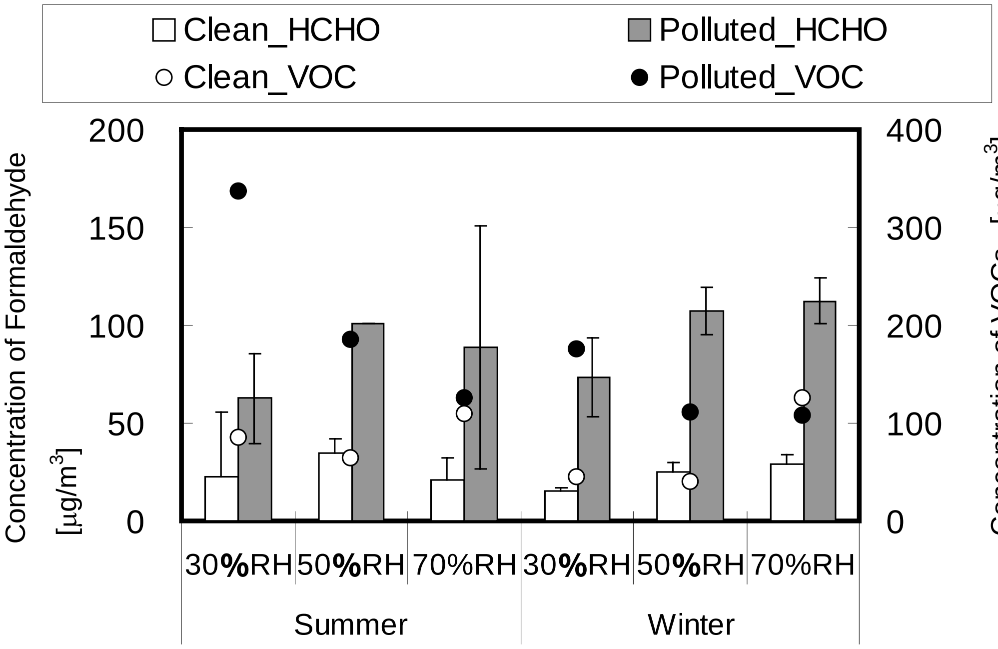


Figure 3-1. Concentration of formaldehyde and VOCs during the exposure

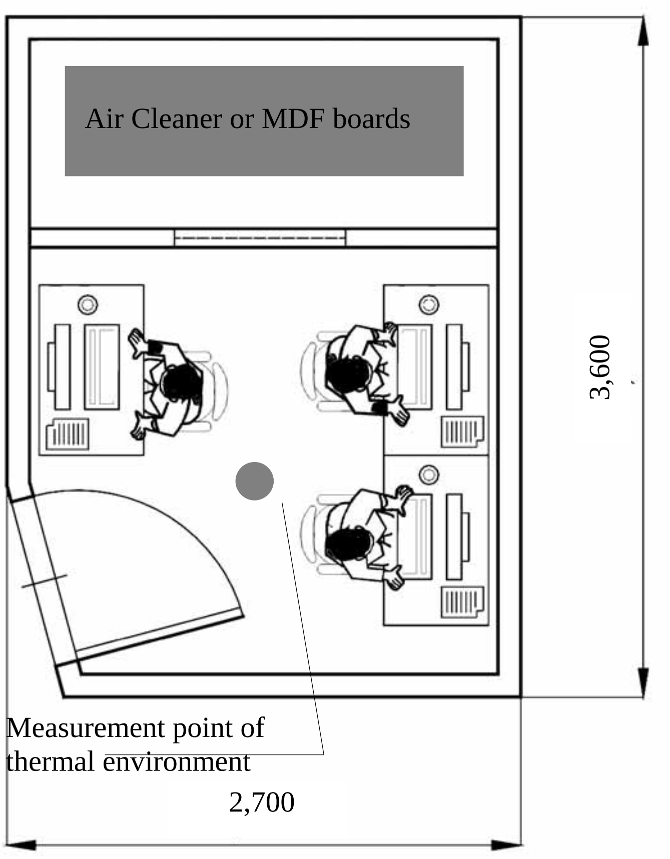


Figure 3-2. The plan of the chamber

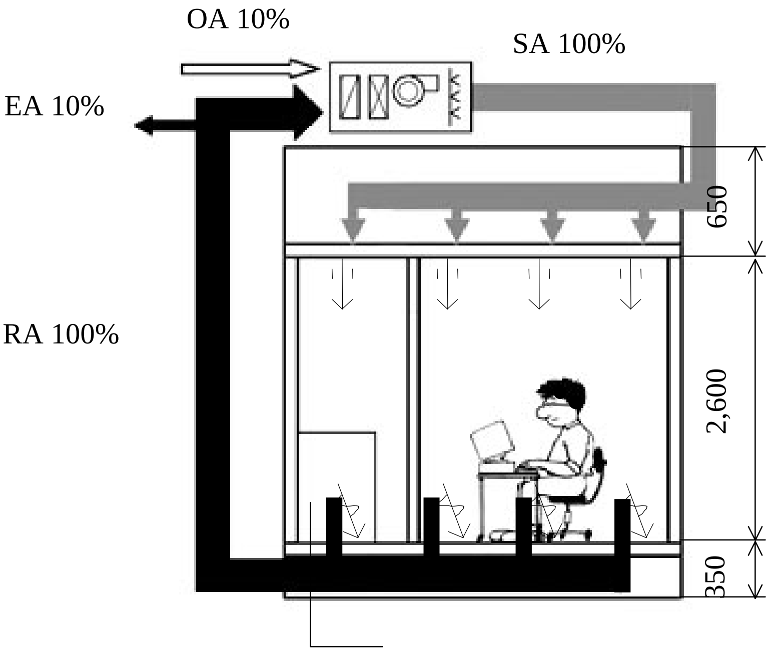


Figure 3-3. Airflow through the duct

3.2.2 Experimental Procedure

In both summer and winter, the experiments were carried out with the same procedure. Experimental procedure is shown in Figure 3-4.

After subjects were seated quietly in the anteroom for 30 minutes, they went out to rate perceived air quality of outdoor air. When subjects entered the chamber and rated their initial sensations, exposure time started. Subject performed 2 kinds of simulated office work, an ‘Addition Task’ and ‘Text Typing’ during the 180-minute exposure.

The ‘Addition task’ was a simple calculation task in which two 2-digit numbers were added together. Subjects answered questions shown on a computer screen. Subjects performed the 20-minute addition task twice.

Subjects typed English sentences from simple stories for 25 minutes for the ‘Text typing’ activity. Considering the characteristics of keyboard to input Japanese, stories written in English were used, although, in Capter5, Danish subjects input the texts written in Danish. Subjects typed them with 1-byte characters in order that the number of times they had pressed a key could be counted. English stories were changed every time the subjects participated in the experiment to avoid their learning effects. Three different texts were used when “Text Typing” was conducted during the exposure.

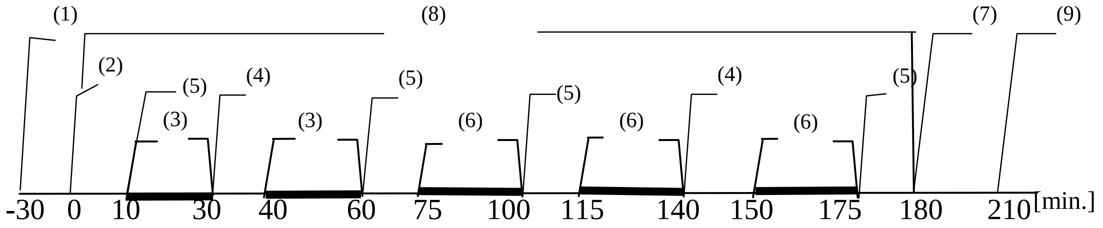
During ten-minute intervals between each task, subjects rated their sensations. In winter, subjects also reported their symptoms related to the fatigue.

Break-up time of eyes (BUT) and skin moisture on the 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. It was proposed by Wyon (1987).

Skin moisture was measured with SKICON-200 (IBS) (Tagami, 1984). SKICON-200 adopts the high frequency impedance method.

Note that for detailed information on these methods, see Chapter 2.

After a 180-minute exposure, subjects went out and rated their perceived air quality again. When they reentered the chamber and judged their perceived air quality, the experiment ended.



(1) Questionnaire, Seat quietly, Rating of perceived air quality outdoors
(2) Enter the chamber, Rating
(3) Addition Task
(4) Rating
(5) Rating, Skin moisture, BUT
(6) Text Typing
(7) Get out of the chamber, Rating of perceived air quality outdoors
(8) Measurement of thermal environment, IAQ and ventilation
(9) Re-enter the chamber, Rating

Figure 3-4. Experimental procedure

3.2.3 Rating Scale

Subjects rated their air quality acceptability, odour intensity and irritation of eye, nose and throat outdoors before and after the exposure. They rated during the exposure thermal sensation, comfort sensation, thermal acceptability, air quality acceptability, odour intensity, general humidity sensation, eye dryness and irritation of eye, nose and throat. Each scale is illustrated in Figure 3-5. The scales were given as visual analogue scales. Subjects were allowed to rate their sensation either just on the number or between the numbers on the scales.

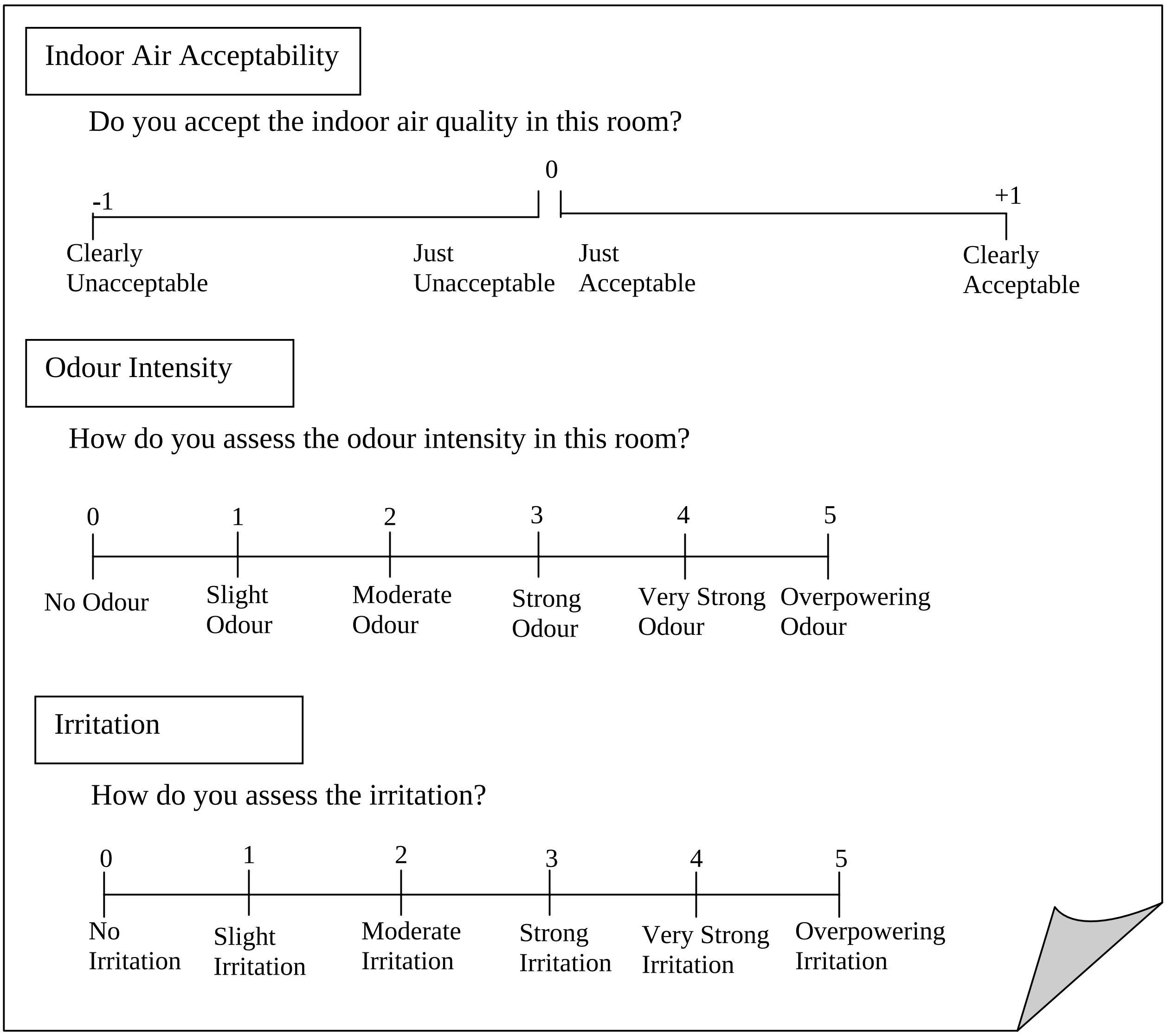
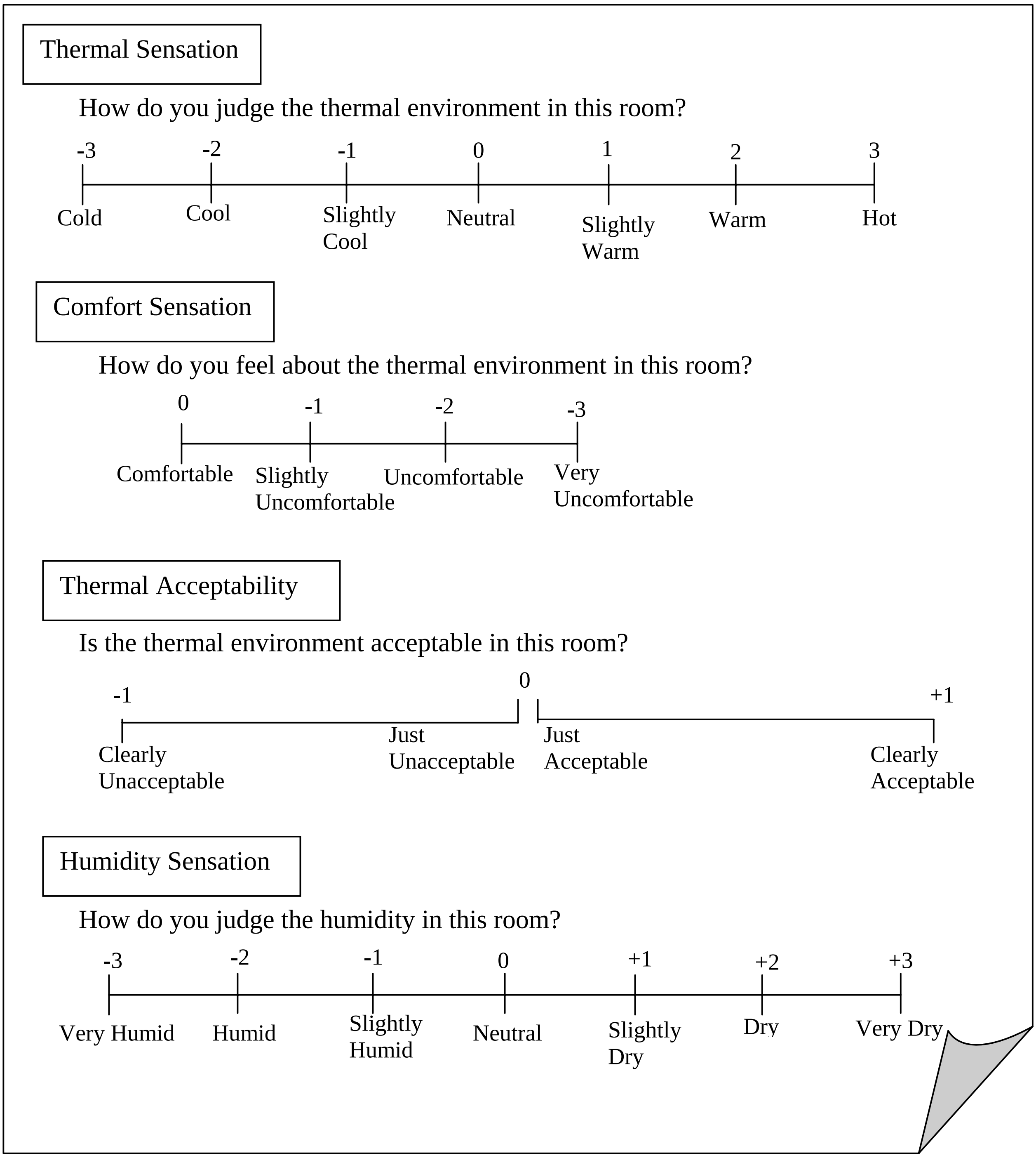


Figure 3-5 (1). Rating Scales



Thermal Sensation

How do you judge the thermal environment in this room?

-3 Cold
-2 Cool
-1 Slightly Cool
0 Neutral
1 Slightly Warm
2 Warm
3 Hot

Comfort Sensation

How do you feel about the thermal environment in this room?

0 Comfortable
-1 Slightly Uncomfortable
-2 Uncomfortable
-3 Very Uncomfortable

Thermal Acceptability

Is the thermal environment acceptable in this room?

-1 Clearly Unacceptable
Just Unacceptable
0
Just Acceptable
+1 Clearly Acceptable

Humidity Sensation

How do you judge the humidity in this room?

-3 Very Humid
-2 Humid
-1 Slightly Humid
0 Neutral
+1 Slightly Dry
+2 Dry
+3 Very Dry

Figure 3-5 (2). Rating Scales

3.2.4 Statistical Analysis

Data obtained in the experiments were analysed with the method of Non-parametric statistical analysis (Siegel, 1988). The Wilcoxon Matched-Pairs Signed Ranks test was adopted in order to balance between the clean condition and the polluted condition under the same humidity level. Friedman nonparametric analysis was used for comparison among 3 humidity conditions under the same indoor air quality level. Then, the Wilcoxon Matched-Pairs Signed Ranks test was administered between each condition as a post-hoc test.

The data obtained in summer was not compared with those in winter because a different group of people participated in each experiment.

The p-values mentioned in the next section represent the levels of significance.

3.3 SUBJECTIVE RATING

3.3.1 Thermal Comfort

Table 3-3 shows the general thermal comfort during the last 2 hours of exposure, assuming a steady state.

As shown in Table 3-2 SET* was higher than set point in summer. However, thermal sensation votes for all conditions are scattered between –0.5 and +0.4, which is in the comfort zone. For all conditions in both seasons, subjects rated their comfort sensation between –1.2 and 0, and thermal acceptability between +0.3 and +0.5. The differences between different values within thermal sensation, comfort sensation and thermal acceptability under summer and winter condition were small.

Accordingly, the effects of environmental humidity and indoor air quality on subjective thermal comfort were moderate under the thermally neutral conditions.

Table 3-3. Subjective general thermal comfort

	RH [%RH]	IAQ	Summer			Winter		
			Thermal Sensation	Comfort Sensation	Thermal Acceptability	Thermal Sensation	Comfort Sensation	Thermal Acceptability
30c	30	Clean	-0.5	-0.9	+0.5	+0.1	-0.9	+0.5
50c	50		+0.4	-0.1	+0.4	-0.1	-0.9	+0.4
70c	70		-0.2	-0.8	+0.5	+0.4	-0.9	+0.5
30p	30	Polluted	+0.2	-1.2	+0.4	+0.1	-1.1	+0.3
50p	50		-0.1	-0.9	+0.5	+0.1	-0.8	+0.5
70p	70		0.0	-0.9	+0.5	+0.1	-0.9	+0.4

3.3.2 Perceived Air Quality (Indoor Air Acceptability and Odour Intensity)

Air Quality Acceptability:

Though indoor air acceptability was rated a number of times, Figure 3-6 shows rating for when subjects first entered the chamber and when they left.

Votes of indoor air quality at the beginning of exposure were higher in clean air than in polluted air with the same humidity at 30%RH and 70%RH for both seasons. Acceptability was the highest under the 30%RH/clean condition at the beginning of exposure in both seasons. Friedman nonparametric analysis revealed that indoor air acceptability at low humidity in clean air was significantly higher than at high humidity in clean air in winter ($p<0.02$). This is in agreement with the result of Fang et al. (1998a, 1998b) who stated that decreasing the indoor air temperature and humidity improved the perceived air quality; the acceptability of air increased linearly with decreasing enthalpy of air. On the other hand, compared them in polluted environments, perception of air quality was lowest under 70%RH condition due to the high formaldehyde concentration. Environmental humidity and indoor air quality did not affect the perception of air at the end of exposure.

The Wilcoxon Matched-Pairs Signed Ranks test showed votes of acceptability at the end of 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 a 3-hour exposure.

No seasonal difference of air quality acceptability was found.

. **Odour intensity:**

Changes of odour intensity as a function of exposure time are presented in Figure3-7.

Subjects rated odour intensities higher under polluted conditions than under clean conditions in all humidity levels at the beginning of exposure in both seasons. This was because of higher formaldehyde concentration in polluted air. Odour intensity under 30%RH/clean conditions was lower than that of the other clean conditions when subjects entered the chamber in both seasons. In contrast, all values of odour intensity were at the same level at the end of exposure. The values of odour intensity got lower during exposure in summer and winter. This proved that subjects adapted to indoor air during the exposure under polluted condition.

However, when they reentered the chamber and rated the perceived air quality, their olfactory sense had already recovered because of their respiration outdoors.

According to the results mentioned above, concentration of formaldehyde has an impact on their perceived air quality in polluted air. Subjects perceive the air to be more acceptable under low humidity in clean air. Seasonal differences in perceived air quality are small.

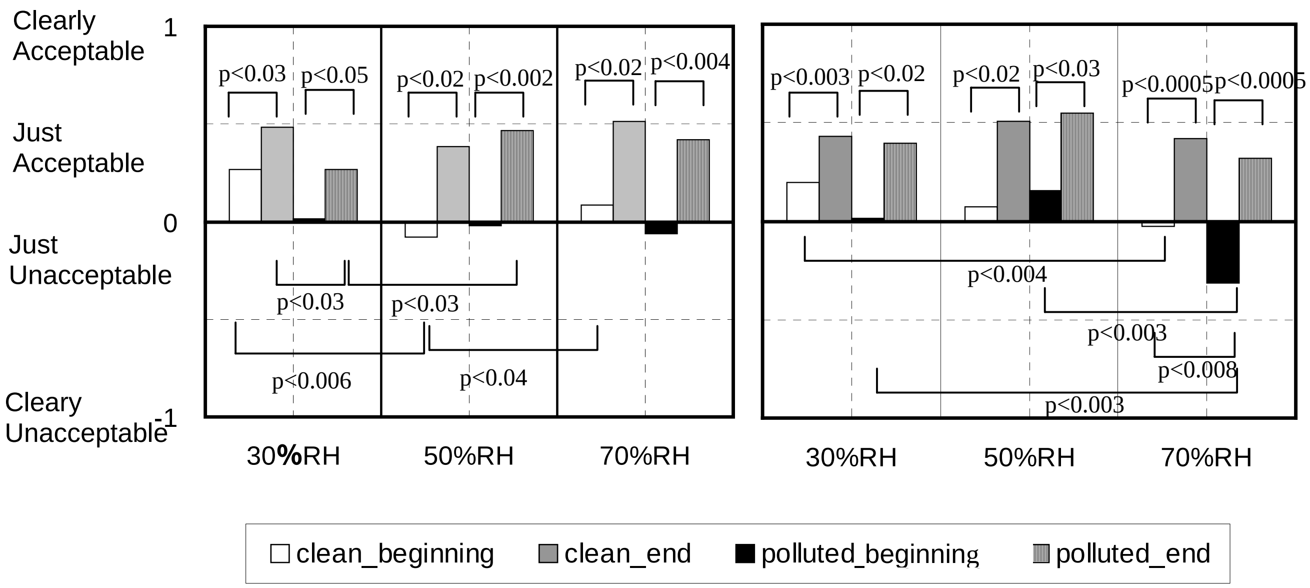


Figure 3-6. Indoor air acceptability (Left: summer, Right: winter)

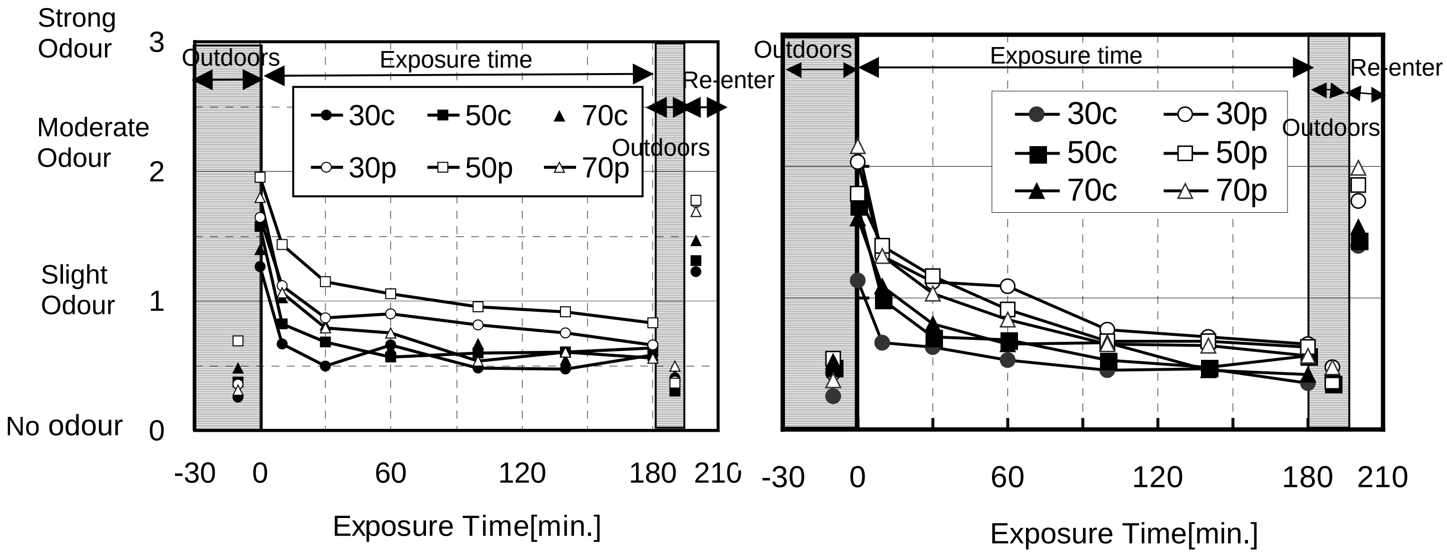


Figure 3-7. Odour intensity (Left: summer, Right: winter)

3.3.3 Humidity Sensation (General Humidity Sensation and Eye Dryness)

General humidity sensation:

Figure 3-8 presents general humidity sensation rated at the end of exposure in both seasons.

Subjects felt significantly dryer under low humidity condition (30%RH) than under other conditions with polluted air in winter ($p<0.003$), although the differences among conditions are small. The same tendencies were also observed under clean conditions in winter and polluted condition in summer, despite no statistically significant differences being found.

It proved that the impact of environmental humidity and indoor air quality on their general humidity sensation under various conditions were small in both seasons, although people tended to feel dryer under low humidity in winter.

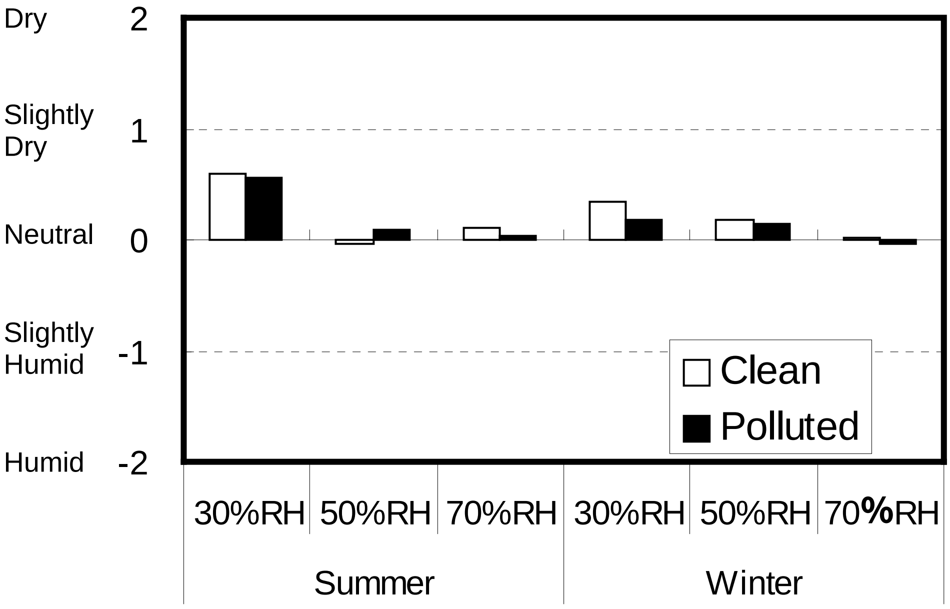


Figure 3-8. General humidity sensation rated at the end of exposure

Sensation of eye dryness:

The scales shown in Figure 3-5 were used for evaluating subjective eye dryness sensation. Sensation of eye dryness got stronger as the time passed for all conditions in both summer and winter. Although subjects performed the same tasks during exposure both in summer and winter, the average of eye dryness rated under all conditions at the beginning of exposure was 0.0 and +1.1 at the end of exposure in summer, and +0.3 at the beginning and +0.6 at the end in winter. Increment of eye dryness sensation during exposure time was smaller in winter than in summer. According to the weather records obtained by the Tokyo Meteorological Agency, the average of absolute humidity outdoors during the experiments in summer was about 9.7 g/kg which is equivalent to the amount of moisture at 25.0°C /50%RH. 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, the increase of eye dryness as exposure time passed in the winter was less due to higher absolute humidity in the climate chamber as compared to outdoor air under all conditions.

As shown in Figure 3-9, high environmental humidity caused lower subjective eye dryness after 180-minute exposure under the polluted condition in summer, and under the clean and polluted conditions in winter. Stronger eye dryness was found under the 50%RH/clean condition than under the other clean conditions in summer.

The differences among conditions were so small that no statistically significant overall difference was observed among 3 humidity levels, and between 2 indoor air quality levels.

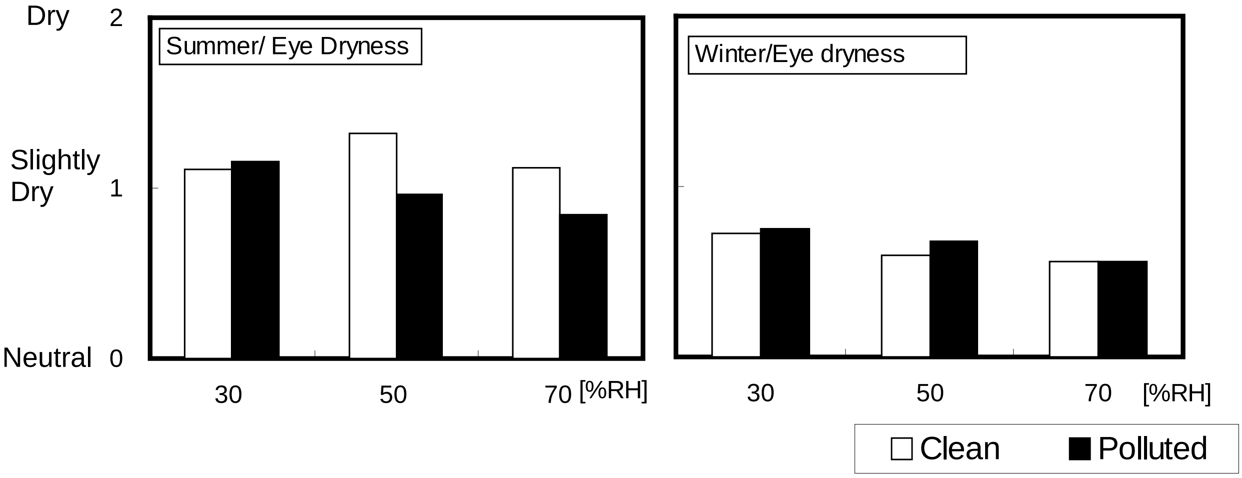


Figure 3-9. Sensation of eye dryness at the end of the exposure

3.3.4 Mucous Irritation

Subjects rated their irritation of eyes, nose and throat.

The eye irritation vote increased as exposure time passed. Subjects reported their nose irritation strongest at the beginning of exposure, and then their irritation got weaker as time passed. Throat irritation stayed at the same level throughout the exposure time, because subjects were allowed to drink water during the exposure. The ratings chosen for illustration in Figure 3-10 – 3-12 are the ones showing the greatest difference of rating between conditions.

As shown in Figure 3-10, the subjects complained their eye were more irritated under the polluted condition than the clean condition in winter, while the data obtained in summer conflicted with it. Statistically significant differences were not found either between the clean and the polluted condition, or among humidity conditions in both seasons. In winter, the irritation rating under 70%RH/clean condition was lower than under the other clean conditions, while it was higher under 70%RH/polluted condition than the other polluted conditions. It follows from this that formaldehyde in the air causes subjects' eye irritation in winter. However, the same result was not shown in summer.

As shown in Figure 3-11, the estimate of throat irritation at the end of exposure was higher under the polluted condition than under the clean condition for all humidity conditions, except for at 50%RH/clean condition in summer. Subjects tended to feel that their throat were more irritated under the low humidity condition with clean air in summer, although statistical analysis did not reveal any significant differences. On the other hand, in polluted air, the irritation was lowest under 50%RH, and no effect as a result of humidity and indoor air quality was observed. In winter, subjects complained of throat irritation more at high humidity in polluted air. Despite drinking water, their throat irritation ratings in polluted air were higher than in clean air. This was because formaldehyde irritated the mucosa of their throats.

Nose irritation under the polluted condition was higher than under the clean condition with the same humidity when subjects entered the chamber, as presented in Figure 3-12. In pair-wise comparison using the Wilcoxon Matched-Pairs Signed Ranks test, significant differences between the clean condition and polluted condition at the same humidity were obtained under 30%RH in summer ($p<0.04$), and at 70%RH in winter ($p<0.02$). Subjects felt their nose to be significantly more irritated under the high humidity condition with polluted air in winter ($p<0.002$), although the differences of votes among conditions were small in the summer.

The results of the experiments clearly demonstrated that high formaldehyde concentration due to high humidity made subjects' mucosa of eyes, noses and throats irritated in the winter. However, the effects of humidity and indoor air quality were not found clearly in summer.

Air quality acceptability and general dryness sensation were lower, and eye dryness and eye irritation were higher under 50%RH/clean condition in the summer compared with other conditions. Some other factors apart from formaldehyde and humidity might have affected subjective eye comfort and perceived air quality under this condition.

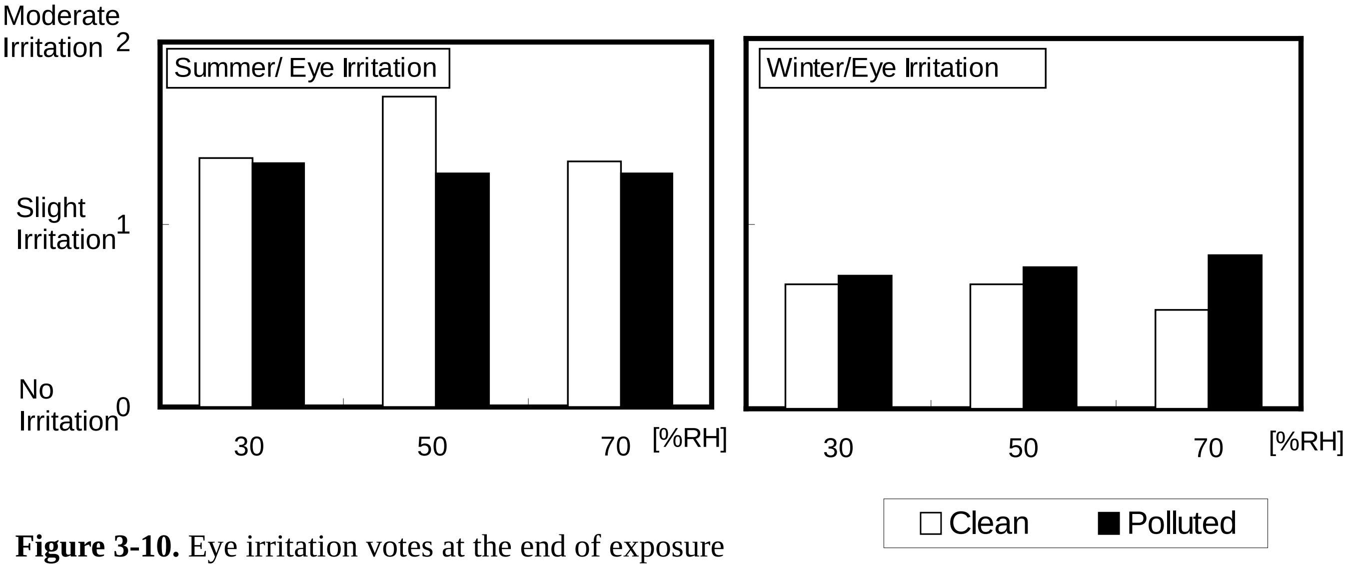


Figure 3-10. Eye irritation votes at the end of exposure

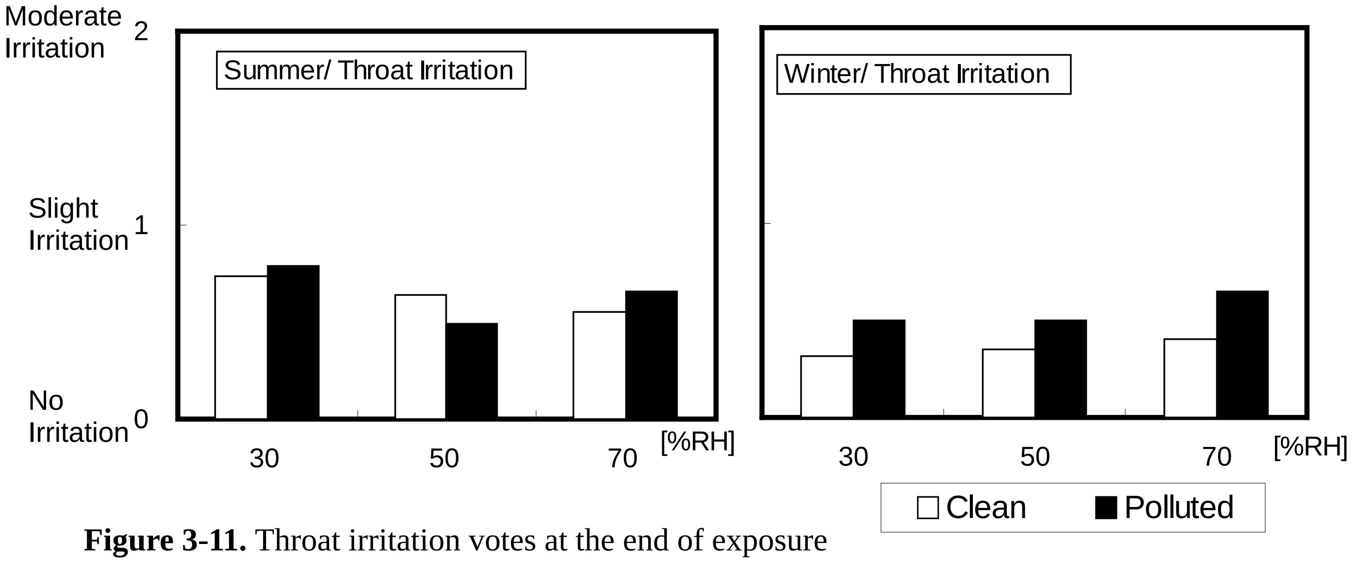


Figure 3-11. Throat irritation votes at the end of exposure

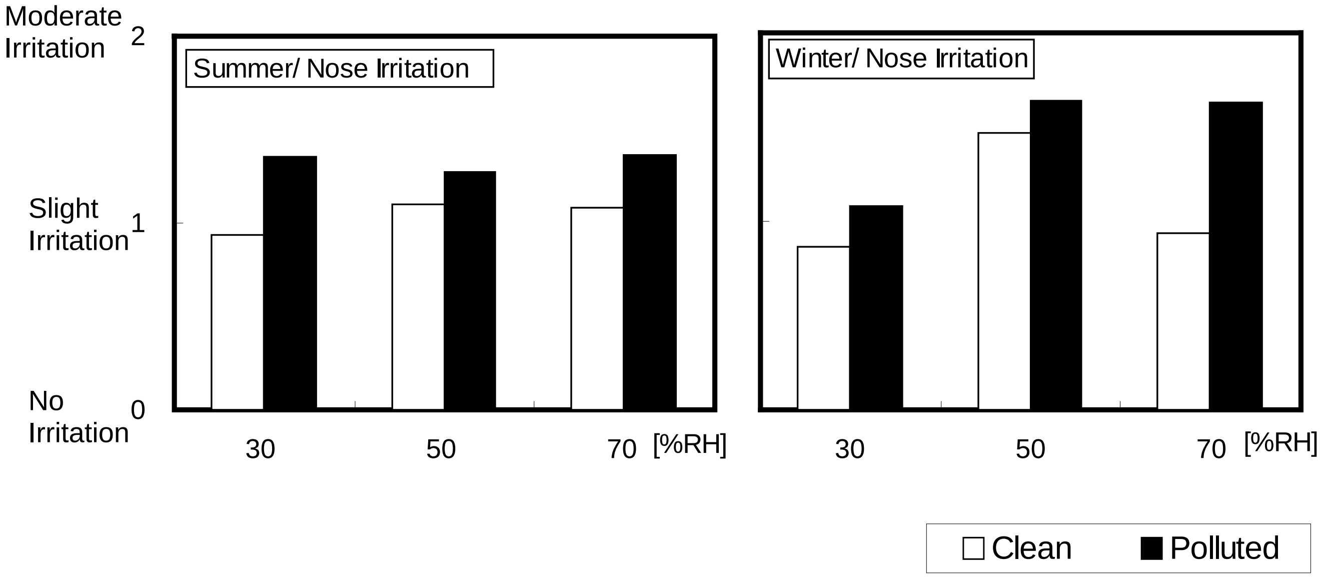


Figure 3-12. Nose irritation votes at the beginning of exposure

3.4 OBJECTIVE MEASUREMENT RESULTS

3.4.1 Skin Moisture

Subjects exposed their forearms to the environment during the experiment. The skin moisture of the left forearm measured at the end of exposure is shown in Figure 3-13.

The Friedman nonparametric analysis reported that, in both summer and winter, skin moisture was significantly higher in the high humidity environment than in the low humidity one ($p<0.01$).

The Wilcoxon Matched-Pairs Signed Ranks test revealed p-values presented in Table 3-4. Significant differences were obtained between the clean condition and polluted condition at 30%RH and 70%RH in summer and at 30%RH in winter. However, there was no significant difference under the other conditions. It is concluded that environmental humidity has stronger effects on subjects' skin moisture than indoor air quality.

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 that they adapted to the dry condition outdoors in winter.

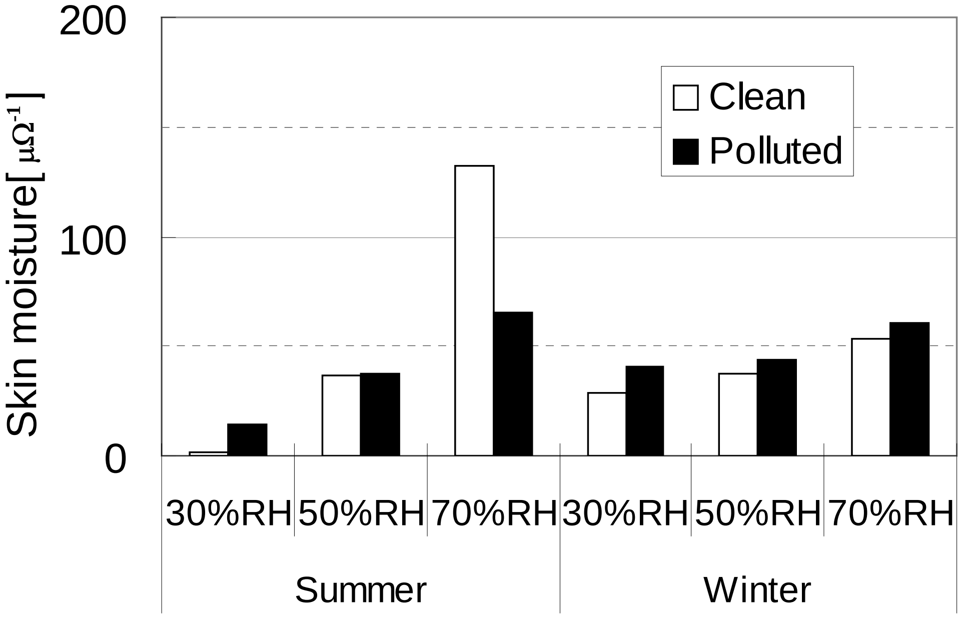


Figure 3-13. Skin moisture on the left forearm measured at the end of the exposure

Table 3-4. The p-values obtained with Wilcoxon Matched-Pairs Signed Ranks test

Summer

Condition						
30c	30c					
50c	p<0.001	50c				
70c	p<0.0007	p<0.004	70c			
30p	p<0.007	p<0.02	p<0.0006	30p		
50p	p<0.0007	N.S.	p<0.003	p<0.05	50p	
70p	p<0.002	N.S.	p<0.03	p<0.009	p<0.02	70p

Winter

Condition						
30c	30c					
50c	p<0.03	50c				
70c	p<0.0005	p<0.009	70c			
30p	p<0.05	N.S.	p<0.02	30p		
50p	p<0.02	N.S.	p<0.05	N.S.	50p	
70p	p<0.0003	p<0.0008	N.S.	p<0.01	p<0.003	70p

3.4.2 Break Up Time (BUT)

In both seasons, 3 soft contact lens (SCL) wearers, 1 hard contact lens (HCL) wearer, 6 people with glasses and 8 people without corrective lenses of any kind took part in the experiments.

Figure 3-14 presents the break up time (BUT) measured after a 3-hour exposure. Significant difference in BUT measured at the end of exposure was not obtained either between the clean and polluted conditions or among humidity levels.

Percentages of subjects whose BUT measured at the end of exposure was shorter than that at the beginning of exposure are listed in Table 3-5. More subjects’ BUT got shorter during the exposure under the polluted condition in both seasons.

It was concluded that formaldehyde irritated occupants’ eyes under polluted conditions, and a shorter BUT was observed. However, differences between conditions were small.

As a result of comparison between summer and winter, BUT measured in summer was longer than in winter for all conditions despite the participation of the same number of contact lens wearers and non-contact lens wearers. Furthermore, compared with the results obtained in the experiments in which 10 subjects with SCL, 7 with HCL, 10 with glasses and 10 with naked eyes were used (See Chapter 2), BUT measured in winter was shorter.

According to the weather records obtained by the Tokyo Meteorological Agency mentioned in Section 3.3.3, people’s eyes were exposed to air with low temperature and low humidity in winter. It is likely that short BUT prevents their eye from drying up.

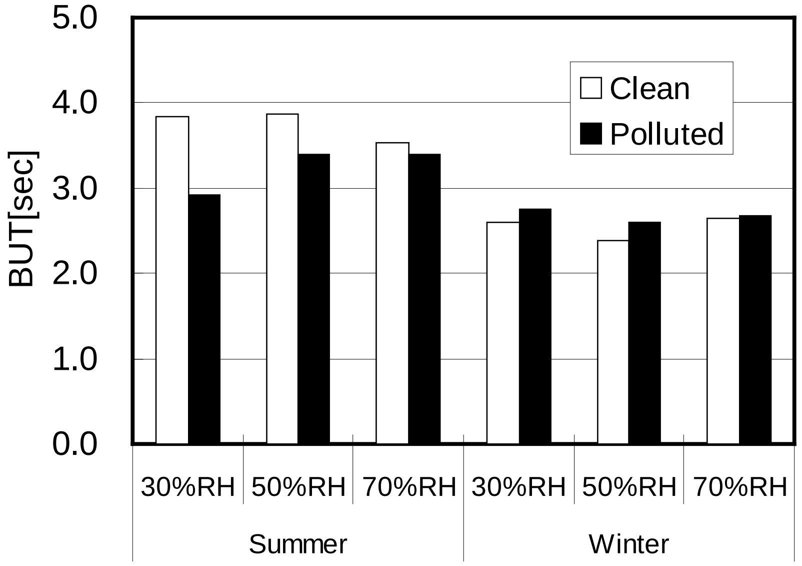


Figure 3-14. BUT measured after 180-minute exposure

Table 3-5. Percentage of subjects whose BUT got shorter during the exposure

	Summer			Winter		
	30%RH	50%RH	70%RH	30%RH	50%RH	70%RH
Clean	60%	56%	56%	50%	61%	50%
Polluted	71%	56%	63%	67%	72%	61%

3.5 TASK PERFORMANCE AND FATIGUE

3.5.1 Addition Task

The “correct answer speed of the addition task” indicates the number of correct answers a subject could input every minute. Making more mistakes would cause a lower correct answer speed, even though subjects input the answers quickly. Thus, the correct answer speed indicates not only their answering speed, but also their accuracy. It was used for evaluation of subjects’ performance in this section. Subjects performed the addition task twice during the exposure. In Figure 3-15 the average values of the correct answer speed of two addition tasks for each condition are plotted.

Compared under the same humidity condition, the correct speeds were faster in the clean conditions than in polluted conditions in both of summer and winter. However, no significant difference was observed with the Friedman nonparametric analysis, and the Wilcoxon Matched-Pairs Signed Ranks test both among humidity conditions and between the clean and polluted condition in this experiment. Wargocki et al. (1999) also concluded that subjects’ performance was higher in clean air than in polluted air.

In winter, their correct answer speeds tended to decrease at low humidity, although no significant difference was observed. On the other hand, in summer, slightly increment of the correct answer speed was given at low humidity.

3.5.2 Text Typing

Figure 3-16 shows the subjects' typing speed under each condition. Typing speed indicates the number of times keys are struck each minute during text typing task. This included spaces between words, commas and periods. Subjects performed 25-minute text typing three times during the exposure. The average value of subjects' typing speed during 3 text typing tasks is plotted in Figure 3-16.

Typing speed tended to decrease under the high humidity condition in clean air during the summer ($p<0.06$), although significant difference was not found in polluted air. In winter, typing speed was significantly higher under high humidity conditions both in clean and polluted air (Clean: $p<0.04$, Polluted: $p<0.03$). Despite of the high concentration of formaldehyde, typing speed increased under high humidity conditions in winter. It followed that the impact of environmental humidity on subjects' typing speed was greater than that of indoor air quality in winter.

Subjects input more text under clean conditions in winter than polluted conditions, though the difference was too small to find statistical difference. In summer, this tendency was not observed.

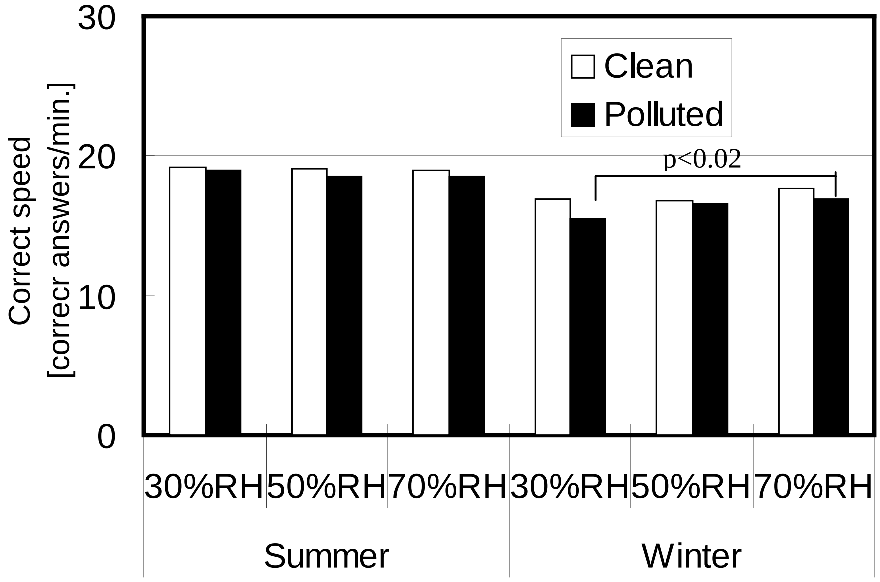


Figure 3-15. Correct speed of addition task [Correct answers/min.]

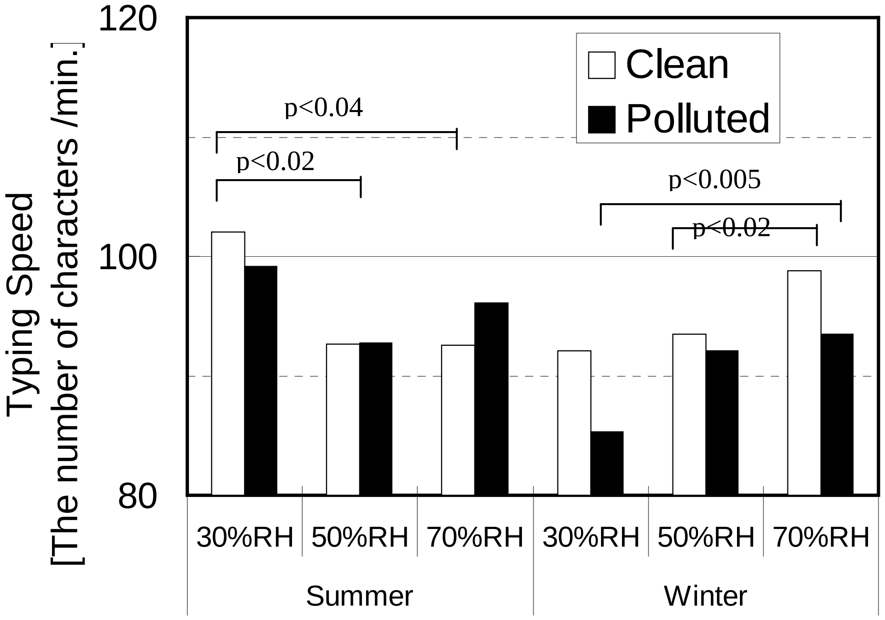


Figure 3-16. Typing Speed for text typing

3.5.3 Fatigue

Subjects were asked to assess their fatigue in addition to the subjective rating in winter. A questionnaire proposed by the “Working Group for Occupational Fatigue, Japan Society for Occupational Health” was used to evaluate their fatigue (Yoshitake, 1973). The questionnaire composes of 3 groups, category Ⅰ, category Ⅱ and category Ⅲ. “Category Ⅰ” indicates drowsiness and dullness in subjects, “Category Ⅱ” is about difficulty in concentration, and “Category Ⅲ” is to do with physical discomfort. Each category has 10 symptoms related to subjects’ fatigue as listed in Table3-6. Subjects marked “O” if they had the given symptoms, and marked “X” if they did not. Ratio of complaints was calculated for each category using the equation below:

$$Rate\ of\ complaints = \frac{Total\ number\ of\ complaints(= Total\ number\ of\ "O")}{(The\ number\ of\ symptoms)\times(Total\ number\ of\ subjects\ who\ used\ a\ questionnaire)}\times 100(\%)$$

Three patterns were suggested by comparing the rate of complaints for each category:

Ⅰ>Ⅲ>Ⅱ: Ⅰ-dominant
Ⅰ>Ⅱ>Ⅲ : Ⅱ-dominant
Ⅲ> Ⅰ>Ⅱ : Ⅲ-dominant

“Ⅰ-dominant” indicates a general pattern of fatigue, “Ⅱ-dominant” a typical pattern of fatigue for mental work or night work and “Ⅲ-dominant” a typical pattern of fatigue for physical work.

Table 3-7 presents the ratio of complaints of each category at the end of exposure. Subjects rated their general pattern of fatigue, Ⅰ>Ⅲ>Ⅱ, under all conditions except for the 30%RH/polluted condition. Higher humidity in clean air caused a lower ratio of complaints for categories Ⅱ and Ⅲ. It is likely that people feel more tired at low humidity in winter. In pair-wise comparison between the clean condition and polluted condition with the same humidity, it was observed that the ratio of complaints for category Ⅱ was higher under the polluted conditions. This proves the possibility of difficulty in concentrating when they were in polluted air. This may be related to the fact that performance of subjects, for example correct answer speed on the addition task and typing speed during text typing, was lower under the polluted conditions than under the clean conditions.

For this experiment, evaluation of subjects' fatigue was conducted only in the winter of 2002. Thus, the seasonal difference of subjective fatigue was not discussed.

Table 3-6. Three categories and a total of 30 symptoms related to fatigue

	Category Ⅰ Drowsiness and dullness	**Category Ⅱ** Difficulty in concentrating	**Category Ⅲ** Physical Discomfort
1	Feel heavy in the head	Feel difficult in thinking	Have a headache
2	Get tired through the whole body	Become weary of talking	Feel stiff in the shoulders
3	Get tired in the legs	Become nervous	Feel a pain in the back
4	Take a yawn	Unable to concentrate	Feel difficulty in breathing
5	Feel the brain hot or muddled	Unable to take interest in things	Feel thirsty
6	Become drowsy	Become apt to forget things	Have a husky voice
7	Feel eye strain	Lack in self-confidence	Have dizziness
8	Become rigid or clumsy in motion	Anxious about things	Have a spasm on the eyelids
9	Feel unsteady while standing	Unable to straighten up in a posture	Have a tremor in the limbs
10	Want to lie down	Lack patience	Feel ill

Table 3-7. Rate of complaints [%]

	RH[%RH]	IAQ	Category Ⅰ	CategoryⅡ	CategoryⅢ
30c	30	Clean	26.7	13.3	16.1
50c	50		21.7	12.8	12.8
70c	70		23.9	7.2	11.1
30p	30	Polluted	23.5	15.9	10.0
50p	50		22.4	17.1	17.6
70p	70		23.9	13.3	15.1

3.6 CONCLUSION

Subjective experiments were conducted with 3 humidity levels and 2 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 to evaluate the seasonal difference of the subjects' reactions.

1) Lower concentration of formaldehyde was observed under a low humidity condition than under a high humidity condition. This was the case even when the same amount of pollution sources existed.
2) The effects of environmental humidity and concentration of formaldehyde on subjective thermal comfort were small under thermally neutral conditions both in summer and winter.
3) Subjects rated the acceptability of air lower at the beginning of the exposure in the environments polluted with formaldehyde. On the other hand, lower humidity caused subjects to rate air quality higher in clean air.
4) Mucous irritation of the eyes, nose and throat due to formaldehyde was found in winter, though not in summer.
5) Environmental humidity had greater effects on skin moisture than indoor air quality. High skin moisture was obtained in the high humidity environment.
6) Subjects complained of having difficulty concentrating under polluted conditions. Moreover, their performance was found to be lower.
7) Seasonal differences in subjective responses were found for eye dryness, BUT and skin moisture. Changes in eye dryness throughout the exposure time were smaller in winter. Smaller differences in skin moisture between conditions were found in winter than in summer. BUT observed in winter was shorter than in summer.
8) Subjects' performance was affected more by environmental humidity than indoor air quality in winter; performance was found to be higher under high humidity conditions. On the other hand, correct answer speed slightly increased in a low humidity environment in summer.

CHAPTER 4

EFFECTS OF RELATIVE HUMIDITY AND ABSOLUTE HUMIDITY ON SUBJECTIVE COMFORT AND PRODUCTIVITY

Chapter 4

EFFECTS OF RELATIVE HUMIDITY AND ABSOLUTE HUMIDITY ON SUBJECTIVE COMFORT AND PRODUCTIVITY

4.1 INTRODUCTION

There are 2 indices to express humidity in the air; relative humidity and absolute humidity. The lower humidity limits prescribed in ASHRAE Standard 62-2001(2001) and the Law for Maintenance of Sanitation in Buildings of Japan (Ministry of Health, Labour and Welfare, Government of Japan (1970)) are specified in relative humidity; the lower boundary given in ASHRAE Standard 55-92 (1992) is expressed in absolute humidity.

In many previous studies, either the effects of absolute humidity or relative humidity were evaluated. And also only factors, for instance mucous moisture, skin moisture and eye dryness, was evaluated. It has been not yet clear which index, if any, has a strong effect on human comfort and productivity, relative humidity or absolute humidity, under the conditions with constant SET* in summer.

Therefore, in this chapter, the effects of relative humidity and absolute humidity on occupants' physiological reactions, psychological reactions and performance under constant SET* conditions are reported.

4.2 EXPERIMENTAL DESIGN

4.2.1 Experimental Condition

In order to investigate the effects of relative humidity or absolute humidity, on occupants' comfort, health and productivity, subjective experiments were conducted in a climate chamber at Waseda University in Tokyo, Japan during the summer of 2002. The plan of the chamber is shown in Figure 4-1. For detailed information of the HVAC system of the chamber, see Chapter 2.

A total of 15 healthy college-aged volunteers participated in the experiments. They were divided into groups composed of four subjects for each experiment. Considering their circadian rhythm, all the subjects took part in the experiments at the same time of the day and on the same day of the week during the whole experiment. Subjects had no knowledge about the purpose of the experiments. They were paid for their participation. Their physical characteristics are given in Table 4-1.

The environmental conditions are shown in Table 4-2. The diagram of the experimental conditions is shown in Figure 4-2. The condition of [25.4 ^{o}C/30%RH/0.6 clo] was set as "standard condition". A total of six conditions of different relative humidity and absolute humidity conditions were utilized. Air temperature was adjusted so that SET* was kept constant at 25.2^{o}C. Metabolic rate of the simulated office work was estimated to be 1.2 met. Mean radiant temperature was estimated to be equal to air temperature. Air velocity was also set to be still. In order to avoid subjects' learning effects of the simulated office work, a practice session (pre condition) at SET*=25.2^{o}C/50%RH was conducted in addition to the six conditions. The experimental conditions were randomly assigned.

Measurements of air temperature, relative humidity and globe temperature were made every minute during the exposure. Air velocity was recorded before and after the exposure. Concentration of formaldehyde and toluene were measured before each exposure with gas detector tubes (Formaldehyde: Gas Detector Tube 91PL, GASTEC, Toluene: Gas Detector Tube 122P, GASTEC) to evaluate indoor air quality in the chamber.

Measured environmental conditions are also shown in Table 4-2. The actual humidity was a little different from the target value, due to the accuracy of environmental control of the chamber. However, SET* was between 24.9 ^oC and 26.2 ^oC, which was assumed to be comfortable. The names of experimental conditions in the sections of results and discussion will be presented by the actual measurement values. The average concentration of formaldehyde and toluene were lower than 100 $\mu g/m^3$ and 260 $\mu g/m^3$ respectively, defined as the upper limit of the guideline of Ministry of Health, Labour and Welfare in Japan (2002).

Two clothing conditions, which were estimated by ISO 9920 (1995) to be 0.6 clo, standard clothing at the office in summer, and 1.0clo, standard clothing at the office in winter, were set in order to make 6 different relative humidity levels and absolute humidity levels keeping SET* constant at 25.2 ^oC. The ensemble of 0.6 clo consisted of a long-sleeve shirt, trousers and socks. The ensemble of 1.0 clo consisted of a long-sleeve shirt, trousers, socks and jacket. The same clothing ensembles were prepared for both males and females. Subjects wore their own underwear.

The measurements using a thermal manikin proved the clothing ensembles estimated 0.6clo and 1.0clo to be 0.7clo and 1.0clo respectively.

Figure 4-3 shows the 2 kinds of clothing ensembles.

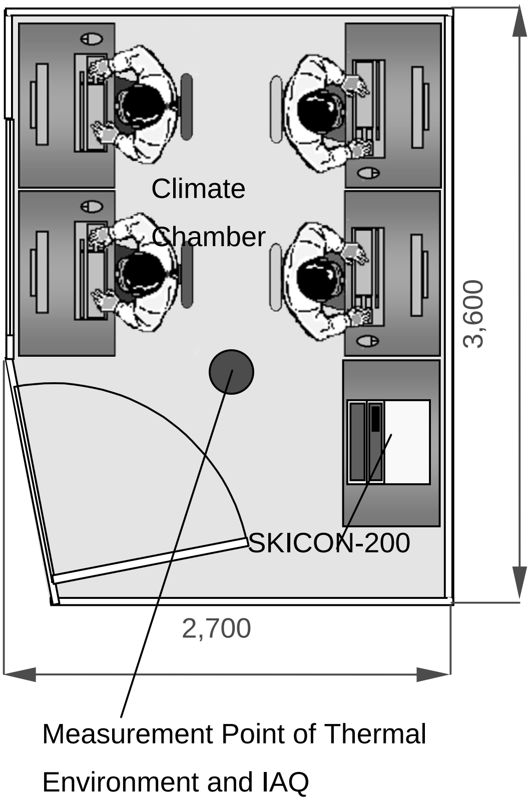


Figure 4-1. Plan of the climate chamber

Table 4-1. Physical characteristics of subjects Mean (Standard Deviation)

Sex	Number	Age [year]	Height [cm]	Weight [kg]	Body Surface Area [m^2]$^{*1)}$	Rohrer Index [-]$^{*2)}$
Male	8	20.4 (1.6)	171.0 (7.0)	60.8 (8.8)	1.72 (0.11)	122.73 (24.1)
Female	7	21.4 (2.0)	157.2 (5.7)	50.6 (4.7)	1.50 (0.08)	130.71 (16.5)
All	15	20.9 (1.8)	164.6 (9.4)	56.0 (8.8)	1.62 (0.15)	126.45 (20.6)

*1) Takahira’s equation: $A=0.007246W^{0.425}\times H^{0.725}$
*2) Rohrer Index = $W/H^3\times 10^7$
A=Body Surface Area [m^2], W=Body Weight[kg], H=Height[cm]

Table 4-2. Environmental conditions Mean (Standard Deviation)

	Target Value						Measured value						
	Relative Humidity [%RH]	Absolute Humidity [g/kg]	Clo Value[clo]	Air Temperature [°C]	Air Velocity [m/s]	SET* [°C]	Relative Humidity [%RH]	Absolute Humidity [g/kg]	Clo Value[clo]	Air Temperature [°C]	MRT[°C]	Air Velocity [m/s]	SET* [°C]
1	30	6.1	0.6	25.4	<0.15	25.2	37 (3.4)	7.2 (0.34)	0.7	25.0 (1.32)	25.4 (0.56)	0.10 (0.06)	25.9 (0.46)
2	37		1.0	22.1			45 (4.7)	7.0 (0.55)	1.0	21.3 (1.37)	21.9 (0.57)	0.11 (0.06)	25.1 (0.46)
3		7.5	0.6	25.3			41 (4.7)	8.2 (0.48)	0.7	25.0 (1.03)	25.5 (0.52)	0.08 (0.08)	26.1 (0.46)
4	45		1.0	21.9			48 (3.8)	7.5 (0.42)	1.0	21.0 (1.37)	21.7 (0.60)	0.12 (0.06)	24.9 (0.58)
5		9.0	0.6	25.1			48 (2.7)	9.3 (0.22)	0.7	24.9 (1.07)	25.3 (0.33)	0.12 (0.07)	26.2 (0.27)
6	55		1.0	21.7			55 (3.8)	8.6 (0.24)	1.0	21.1 (1.17)	21.9 (0.61)	0.13 (0.08)	25.2 (0.49)

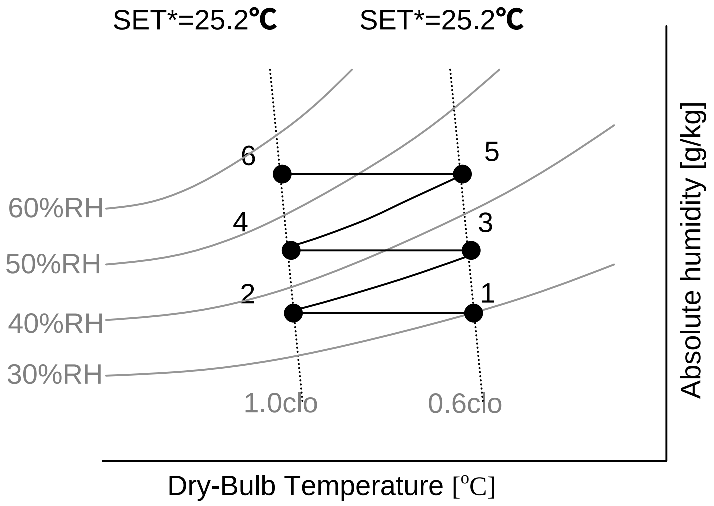


Figure 4-2. Diagram for environmental conditions

Figure 4-3. Two kinds of clothing ensemble (Left: 0.7clo, Right:1.0clo)

4.2.2 Experimental Procedure

The experimental procedure is shown in Figure 4-4.

After subjects were seated quietly in the anteroom for 30 minutes, they rated their acceptability of air outdoors. Subjects drank a glass of water (about 200 ml) to keep their oral mucous moisture at the same level. The exposure time started when subjects entered the chamber and rated their first impression.

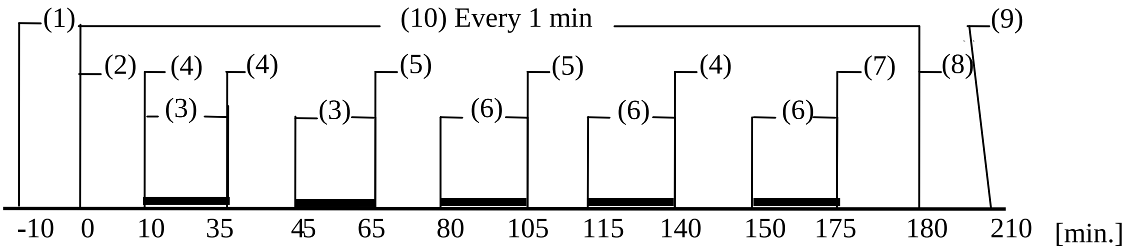
Subjects performed simulated office work – 20 minutes of “Addition Tasks”, repeated twice and 25 minutes of “Text Typing”, repeated three times during the exposure. The ‘Addition Task’ was a simple calculation task in which two 2-digit numbers were added together. Subjects answered questions shown on the computer screen. Subjects typed English sentences from simple stories for 25 minutes for the ‘Text Typing’. Considering the characteristics of the keyboard to input Japanese, stories written in English were used. Subjects typed them with 1-byte characters in that the number of times they had pressed keys could be counted. English stories were changed every time to avoid their learning effects.

During the 10-minute interval between each task, subjects rated their sensations, symptoms of fatigue and subjective evaluation of their performance on questionnaires. Subjects measured their break up time (BUT) by using a stopwatch 4 times during exposure. “Break up Time (BUT)” is one of the physiological reactions that might affect subjective eye comfort. Wyon et al. (1987) proposed the “Self-reported-BUT” method. For detailed information about it, see Chapter 2.

Measurement of the subjects’ skin moisture on their left forearm was also made with SKICON-200 (IBS) 4 times. SKICON-200 adopts the high frequency impedance method (Tagami, 1984). At the end of the exposure, oral mucous moisture was recorded. The diagnoses of Sjögren’s Syndrome was used for measurements of oral mucous moisture (Japanese Medical Society for Sjögren’s Syndrome, 2000). At the beginning and at the end of each experiment, subjects went outside to rate their perceived air quality. Then, they re-entered the chamber and assessed the perceived air quality again.

Air temperature, relative humidity, air velocity, globe temperature and concentration of formaldehyde and toluene in the chamber were recorded during the exposure. Measurement results of these are described in section 4.2.1.

Figure 4-5 presents the subjects performing the tasks wearing the ensemble of 0.6clo.



(1) Coming-in Chamber, Change Clothes, Weight, Questionnaires, Rating outdoors
(2) Start of the Experiment, Rating, Skin Moisture, BUT
(3) Addition Task
(4) Subjective vote
(5) Rating, Skin Moisture, BUT
(6) Text Typing
(7) Rating, Skin Moisture, BUT, Oral mucous moisture
(8) Stepping-out Chamber, Weight, Change Clothes, Rating
(9) Reenter, Questionnaires, End of the Experiment
(10) Environmental Measurements (Temperature, Humidity, Globe Temperature), Skin Temperature, water vapour pressure under clothing

Figure 4-4. Experimental procedure

Figure 4-5. Subjects performing simulated office work during the exposure time

4.2.3 Rating Scale

Subjects assessed their air quality acceptability outdoors before and after the exposure. They rated thermal sensation, comfort sensation, thermal acceptability, air quality acceptability, general humidity sensation, eye dryness and irritation of eye during the exposure. Rating scales are illustrated in Figure 4-6. They were given as visual analogue scales. Subjects were allowed to record their sensation at any point on the scale.

To investigate their feelings of fatigue, subjects filled in the “Evaluation Sheets of Subjective Symptoms of Fatigue” which is used in the field of labour and ergonomics science suggested by “Working Group for Occupational Fatigue, Japan Society for Occupational Health” (Yoshitake, 1973). As listed in Table 4-3, it consists of 30 symptoms which are divided into 3 categories of 10 items. The category-I consists of questions of “drowsiness and dullness”, category-II “difficulty in concentration” and category-III “physical symptoms”. Subjects marked “O” if they had the symptom and marked “X” if they did not. The ratio of complaints was calculated for each category using the equation below:

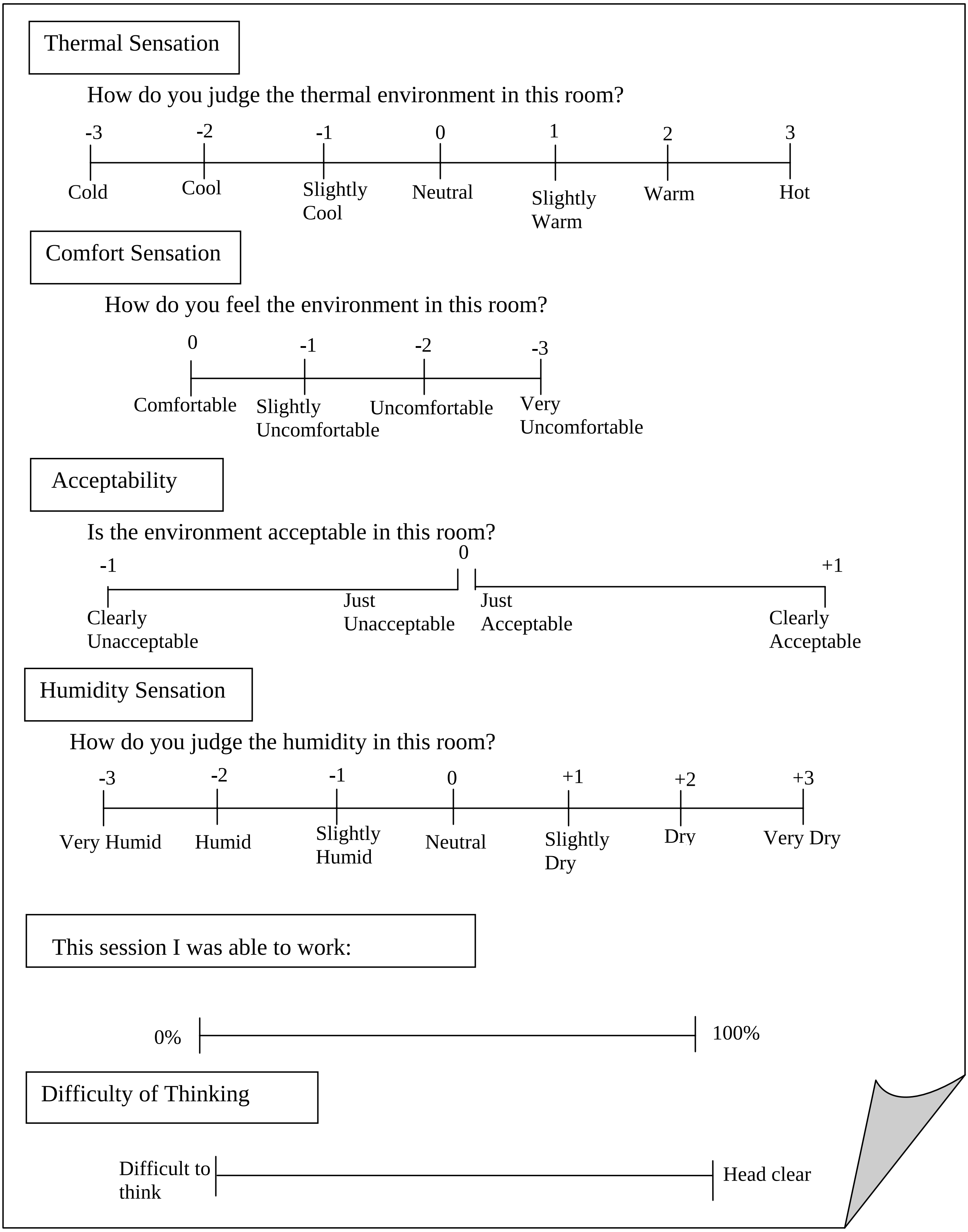
$$Rate\ \ of\ \ complaints = \frac{Total\ \ number\ \ of\ \ compl\mathrm{aints}(= Total\ \ number\ \ of\ \ "O")}{(The\ \ number\ \ of\ \ symptoms)\times(Total\ \ number\ \ of\ \ subjects\ \ who\ \ used\ \ a\ \ questionnaire)}\times 100(\%)$$

Three patterns are suggested, from the compared ratio of complaints for each category:

Ⅰ>Ⅲ>Ⅱ: Ⅰ-dominant
Ⅰ>Ⅱ>Ⅲ : Ⅱ-dominant
Ⅲ> Ⅰ>Ⅱ : Ⅲ-dominant

“Ⅰ-dominant” indicates general pattern of fatigue, “Ⅱ-dominant” typical pattern of fatigue for mental work or night work and “Ⅲ-dominant” typical pattern of fatigue for physical work.

Subjects also judged their performance using scales given in Figure4-6. This data was used to investigate the effects of humidity on their productivity.



Thermal Sensation

How do you judge the thermal environment in this room?

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Comfort Sensation

How do you feel the environment in this room?

0	-1	-2	-3
Comfortable	Slightly Uncomfortable	Uncomfortable	Very Uncomfortable

Acceptability

Is the environment acceptable in this room?

-1	0	0	+1
Clearly Unacceptable	Just Unacceptable	Just Acceptable	Clearly Acceptable

Humidity Sensation

How do you judge the humidity in this room?

-3	-2	-1	0	+1	+2	+3
Very Humid	Humid	Slightly Humid	Neutral	Slightly Dry	Dry	Very Dry

This session I was able to work:

0% —— 100%

Difficulty of Thinking

Difficult to think —— Head clear

Figure 4-6. Rating Scales

Table 4-3. Evaluation sheets of subjective symptoms of fatigue

	Category Ⅰ Drowsiness and dullness	**Category Ⅱ** Difficulty in concentrating	**Category Ⅲ** Physical Discomfort
1	Feel heavy in the head	Feel difficult in thinking	Have a headache
2	Get tired through the whole body	Become weary of talking	Feel stiff in the shoulders
3	Get tired in the legs	Become nervous	Feel a pain in the back
4	Take a yawn	Unable to concentrate	Feel difficulty in breathing
5	Feel the brain hot or muddled	Unable to take interest in things	Feel thirsty
6	Become drowsy	Become apt to forget things	Have a husky voice
7	Feel eye strain	Lack in self-confidence	Have dizziness
8	Become rigid or clumsy in motion	Anxious about things	Have a spasm on the eyelids
9	Feel unsteady while standing	Unable to straighten up in a posture	Have a tremor in the limbs
10	Want to lie down	Lack patience	Feel ill

4.2.4 Statistical Analysis

Data obtained in the experiments were analysed Non-parametric statistical analysis method (Siegel and Castellan, 1988). Friedman nonparametric analysis was used for comparison among the 6 conditions. And then, the Wilcoxon Matched-Pairs Signed Ranks test was administered between each condition as a post-hoc test.

The data of the objective and subjective test was correlated with relative humidity and absolute humidity to evaluate the impact of relative humidity and absolute humidity on subjective responses.

The p-values mentioned in the following section represent the levels of significance.

4.3 SUBJECTIVE RATING

4.3.1 Thermal Comfort

Subjects recorded their general thermal sensation, comfort sensation and thermal acceptability using scales illustrated in Figure 4-6. Table 4-4 gives the general thermal comfort rating during the last 2 hours of the exposure assuming to be obtained under a steady state. Subjects wore the clothing ensemble of 1.0 clo under the 3 conditions coloured with grey in Table 4-4. Under these 3 conditions, they felt cooler than under the 3 conditions with 0.7clo. It was because SET* under the 3 conditions with 1.0clo was actually lower than under the other 3 conditions with 0.7 clo. Comparing them among the 3 conditions with the same clo value, the difference of subjective thermal sensation was small.

As a consequence, the effects of relative humidity and absolute humidity on subjective thermal sensation, comfort sensation and thermal acceptability were moderate under the thermally neutral conditions.

Table 4-4. General thermal comfort

No.	Condition [Relative Humidity/Absolute humidity]	Thermal Sensation	Comfort Sensation	Thermal Acceptability
1	[37%RH/ 7.2 g/kg]	-0.3	-0.7	+0.5
2	[45%RH/ 7.0 g/kg]	-1.1	-1.0	+0.4
3	[41%RH/ 8.2 g/kg]	-0.2	-0.6	+0.6
4	[48%RH/ 7.5 g/kg]	-1.4	-1.2	+0.0
5	[48%RH/ 9.3 g/kg]	0.0	-0.7	+0.6
6	[55%RH/ 8.6 g/kg]	-1.4	-1.1	+0.3

4.3.2 Assessment of Humidity

Scales shown in Figure 4-6 were used for assessment of their humidity sensation and humidity comfort sensation.

Figure 4-7 presents mean general humidity sensation votes at the end of the 180-minute exposure as a function of relative humidity and absolute humidity. Freidman non-parametric analysis revealed that subjects perceived air in the chamber to be significantly dryer under low humidity conditions ($p<0.01$). Significant differences obtained with the Wilcoxon Matched-Pairs Signed Ranks test between the 2 different conditions are also shown in Figure 4-7. It was clearly observed that the general dryness sensation was raised by the decline of absolute humidity, compared with that of the function of relative humidity.

No significant difference was found among humidity comfort sensation votes reported by subjects at the end of the exposure as shown in Figure 4-8. However, according to the correlation coefficient, subjects felt less comfortable at low absolute humidity ($R^2=0.73$). On the other hand, relative humidity had little effect on the humidity comfort sensation.

For these reasons, subjective assessment of humidity was affected by absolute humidity more than relative humidity.

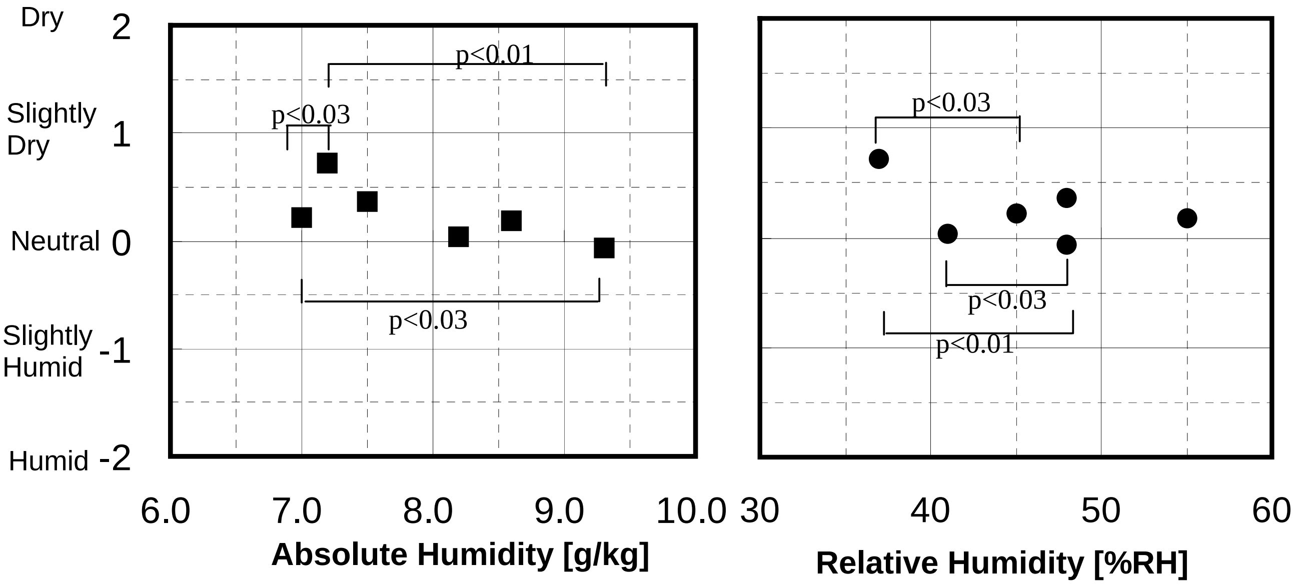


Figure 4-7. General humidity sensation as the function of absolute humidity and relative humidity

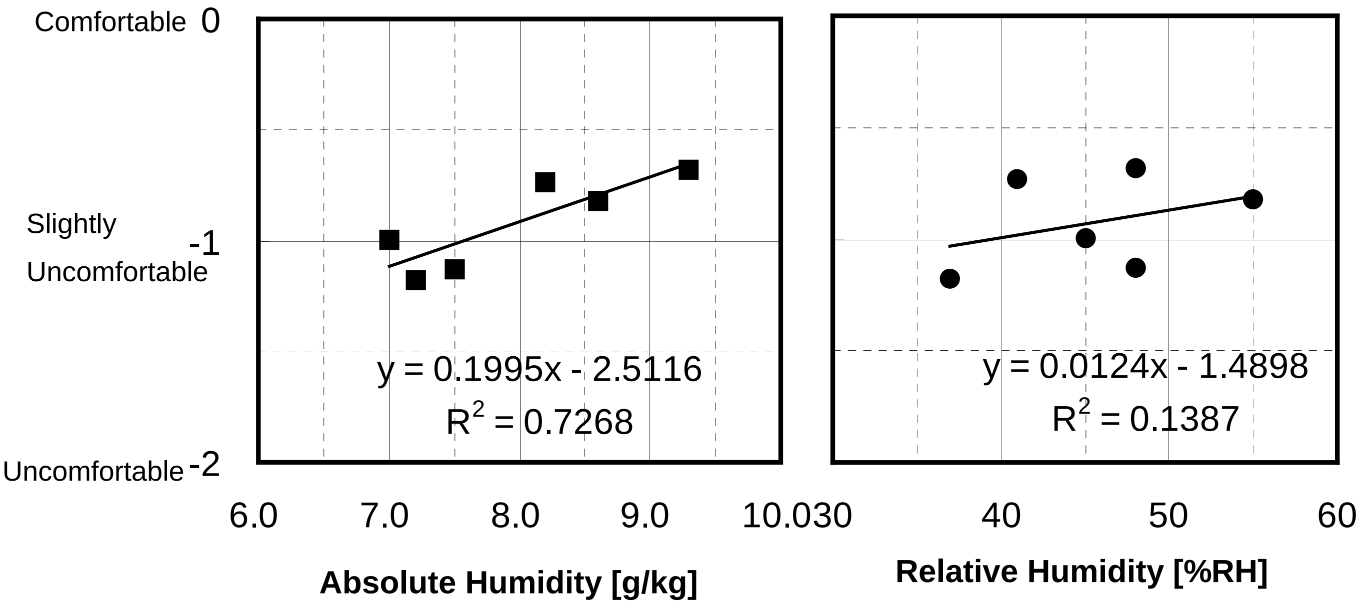


Figure 4-8. General humidity comfort sensation as the function of absolute humidity and relative humidity

4.3.3 Humidity Sensation and Comfort Sensation of Eye, Nose and Mouth

Humidity sensation and comfort sensation of eye, nose, and mouth were rated using scales illustrated in Figure 4-6.

Figure 4-9 presents the mean humidity sensation vote of subjects' eyes at the end of the 180-minute exposure as a function of relative humidity and absolute humidity. Freidman non-parametric analysis revealed no significant difference among the 6 conditions. No high coefficient of correlation between humidity conditions and subjective eye dryness was found.

The eye comfort sensation vote at the end of the exposure as the function of absolute humidity and relative humidity was plotted in Figure 4-10. High correlation between eye comfort votes and absolute humidity was found (R^2=0.93), while it was not found between eye comfort votes and relative humidity (R^2=0.21). Subjects tended to feel more comfortable under the high absolute humidity conditions. Eye comfort was strongly affected by absolute humidity and it could be expressed as the function of absolute humidity. However, the same tendency was not obtained for the relationship between eye comfort and relative humidity.

There was no correlation between the eye dryness and eye comfort sensation under the conditions set for this experiment.

Figure 4-11 gives the mean humidity sensation of the nose votes at the end of the 180-minute exposure as a function of relative humidity and absolute humidity. Freidman non-parametric analysis revealed no overall significant difference among the 6 conditions. No correlation between humidity conditions and subjective nose dryness was found.

Mean nose comfort sensation votes reported by all subjects when the exposure time ended were plotted in Figure 4-12. High correlation between the nose comfort sensation and absolute humidity was found (R^2=0.84). Nose comfort declined with decreased absolute humidity, while no effects of relative humidity on the nose comfort sensation was found.

There was no significant difference among the mouth dryness sensation rated by subjects at the end of the exposure under the 6 conditions. As shown in Figure 4-13, absolute humidity had a stronger correlation (R^2=0.64) with the mouth dryness sensation than relative humidity.

Subjects rated their mouth to be more comfortable under the condition with high absolute humidity as shown in Figure 4-14. A significant difference was not found among the votes of the mouth comfort sensation after the 180-minute exposure under the 6 conditions. Higher correlation was observed between mouth comfort and absolute humidity than relative humidity.

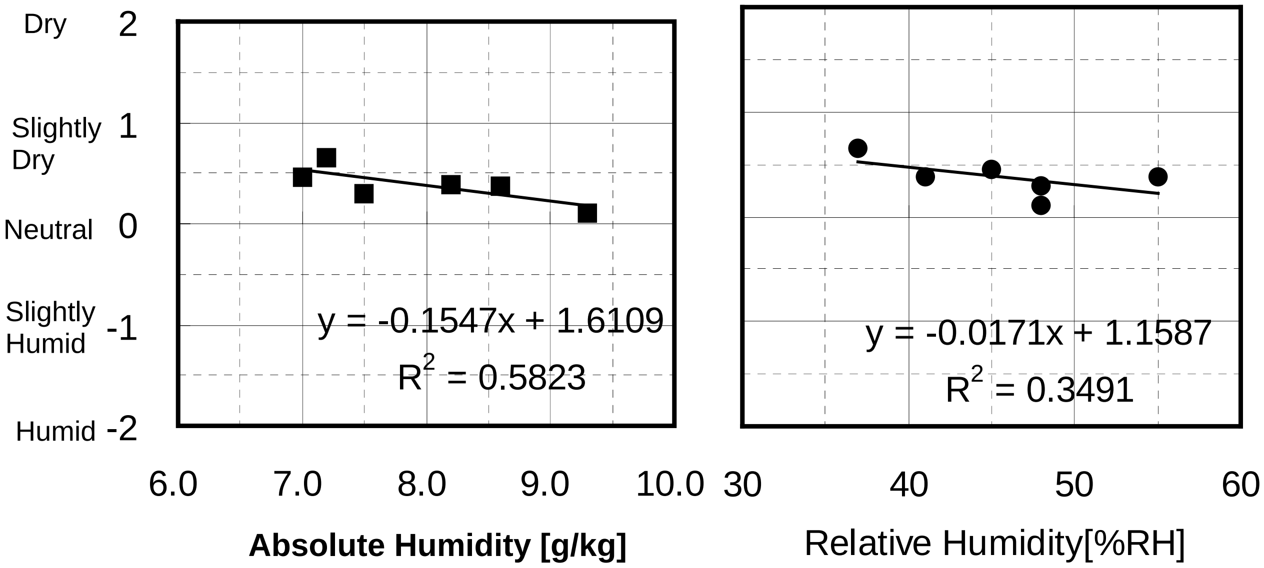


Figure 4-9. Humidity sensation of eyes as the function of absolute humidity and relative humidity

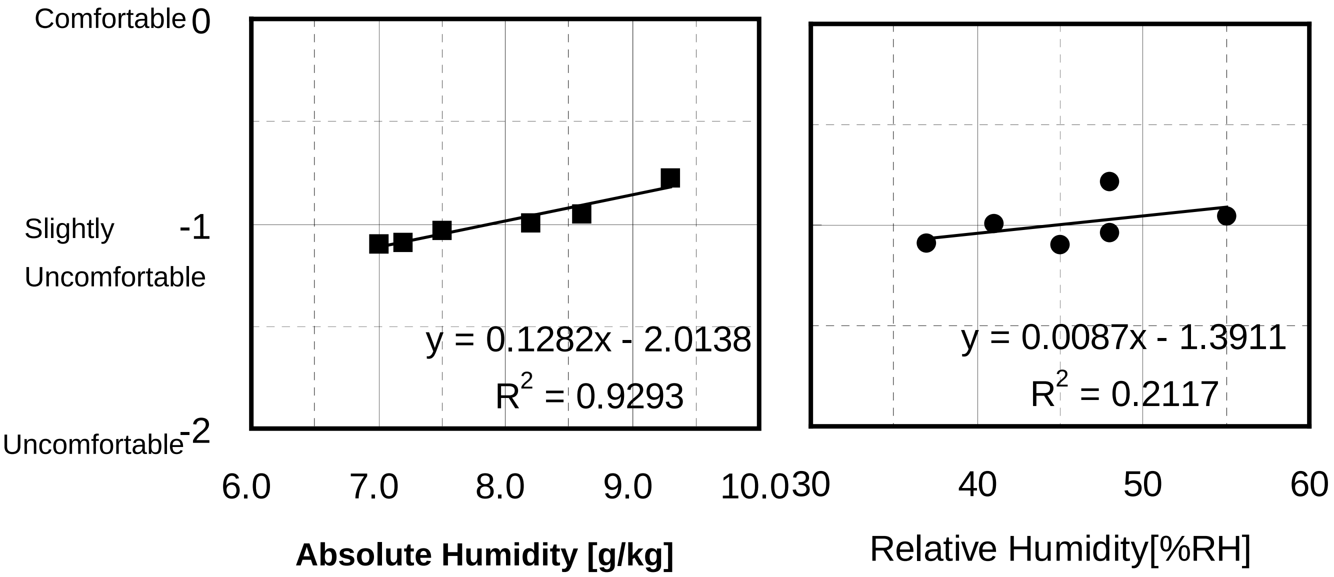


Figure 4-10. Comfort sensation of eye as the function of absolute humidity and relative humidity

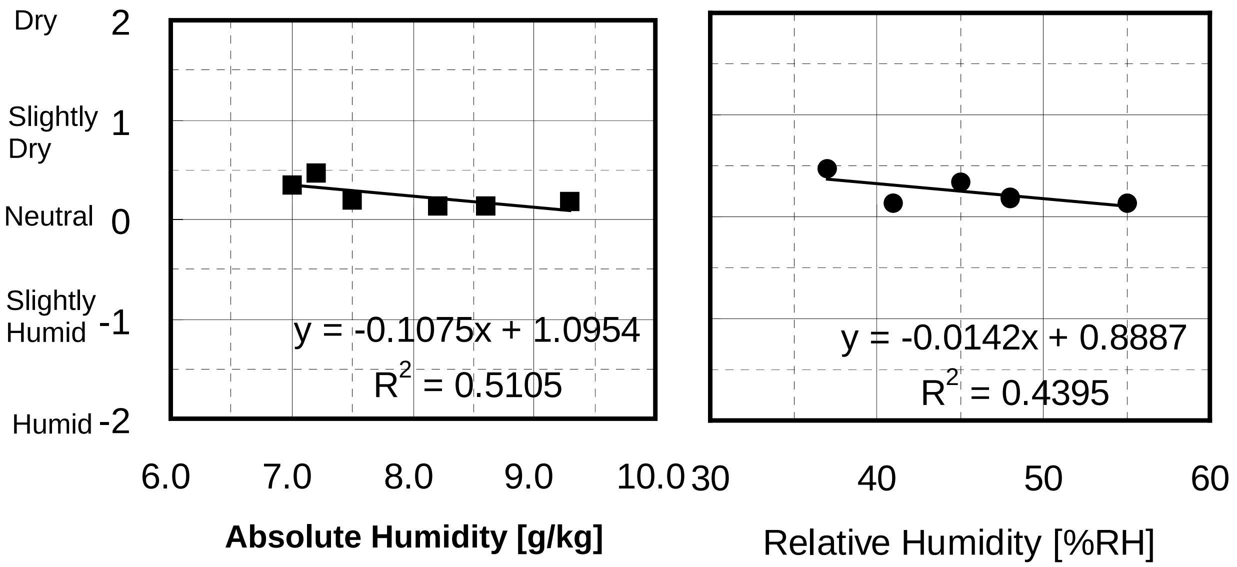


Figure 4-11. Humidity sensation of nose as the function of absolute humidity and relative humidity

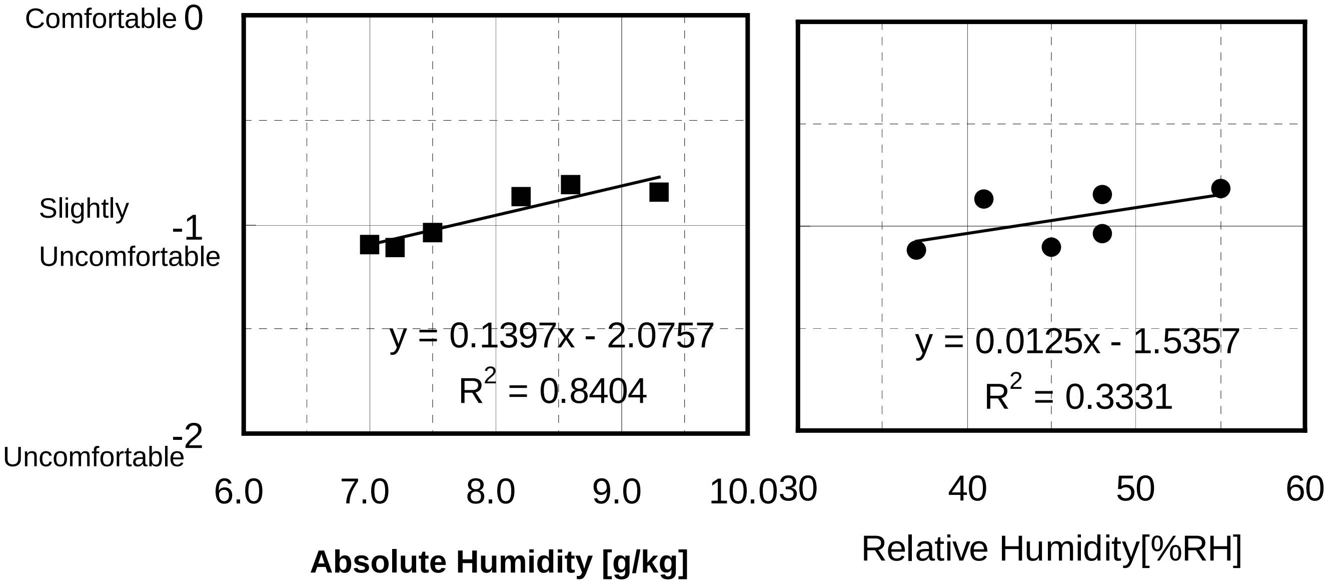


Figure 4-12. Comfort sensation of nose as the function of absolute humidity and relative humidity

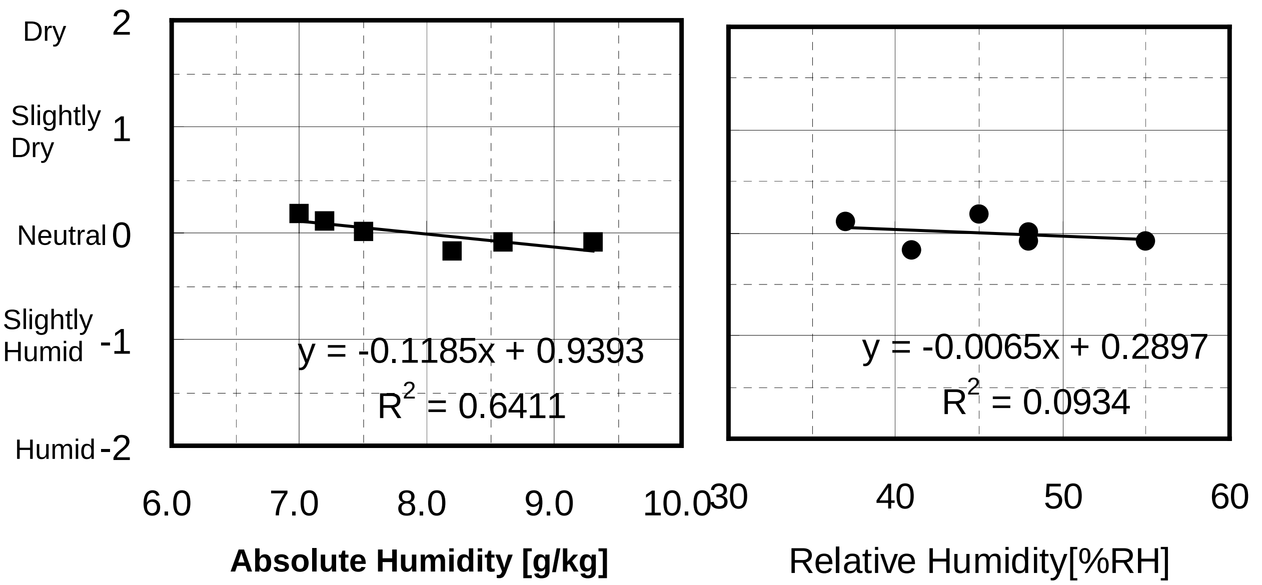


Figure 4-13. Humidity sensation of mouth as the function of absolute humidity and relative humidity

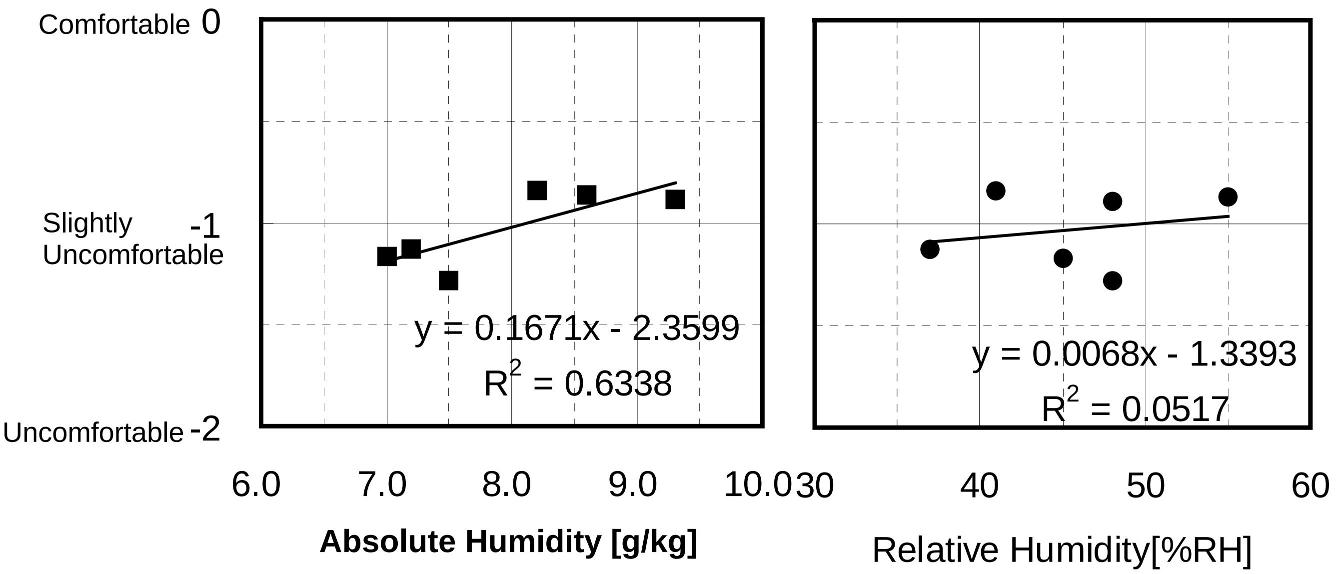


Figure 4-14. Comfort sensation of mouth as the function of absolute humidity and relative humidity

4.3.4 Air Quality Acceptability

The scale illustrated in Figure 4-6 was used for investigating the indoor air acceptability.

Acceptability of the air on entering the chamber was presented in Figure 4-15 as the function of relative humidity and absolute humidity. There was little difference of perceived indoor air quality under all the relative humidity or absolute humidity conditions. There were also fewer ranges of votes during the exposure. The prominent difference between every relative humidity and absolute humidity condition was not found by using neither Friedman non-parametric analysis nor the Wilcoxon Matched-Pair Signed Rank test.

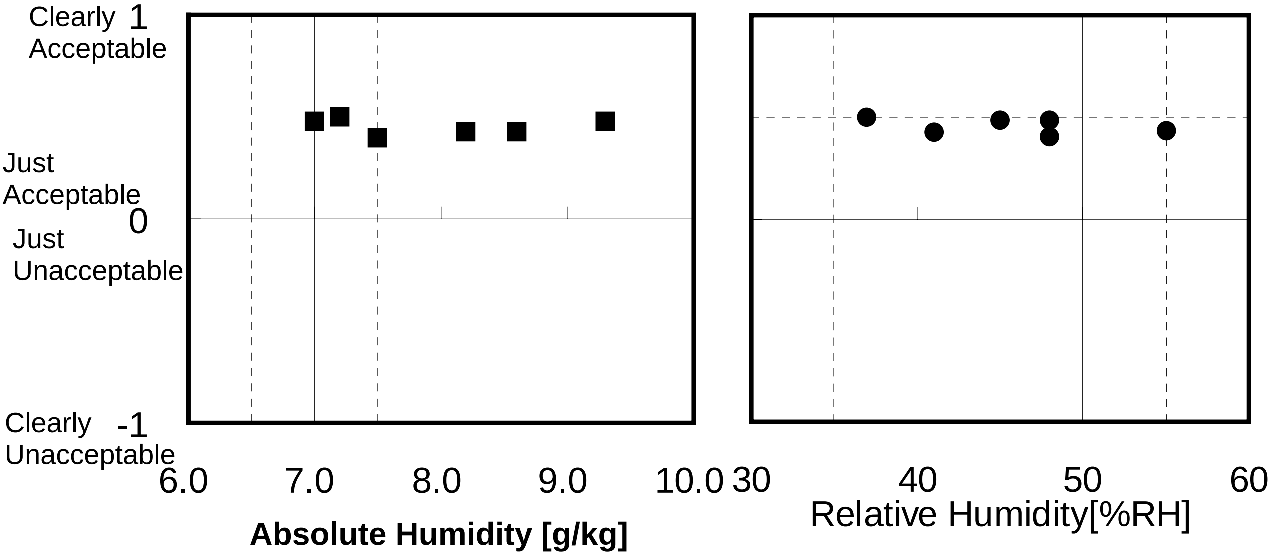


Figure 4-15. Acceptability of the air on entering the chamber as the function of absolute humidity and relative humidity

4.4 OBJECTIVE MEASUREMENT RESULTS

4.4.1 Skin Moisture

During the exposure, the skin moisture on the left forearm was measured using SKICON-200 (IBS) 4 times. The subjects were asked to keep exposing their left forearms to the environment in the chamber. Skin moisture on the left forearm measured at the end of exposure is shown as the function of relative humidity and absolute humidity in Figure 4-16. Friedman non-parametric analysis revealed a significant difference among the conditions ($p<0.04$). It could be concluded that skin moisture on the forearm was significantly higher under high humidity conditions than low humidity conditions. The significant differences obtained in the pair-wise comparison of conditions using the Wilcoxon Matched-Pair Signed Rank test are also given in Figure 4-16. Significant differences between the 2 conditions with high absolute humidity, [48%RH/9.3g/kg] and [55%RH/8.6g/kg], and the other 4 conditions were found.

The skin moisture on the left forearm obtained in the experiments conducted in the summers of 2000 and 2001 were added to these results, as shown in Figure 4-17. The skin moisture was also measured with SKICON-200 in 2000 and 2001. All measurements were made under the conditions with 25.2 °C of SET*, and relative humidity between 30%RH and 70%RH. Change of skin moisture on the left forearm was found to be curved with change of humidity.

Further study and measurements would be required to investigate the difference of the relative humidity effect and absolute humidity effect on the skin moisture.

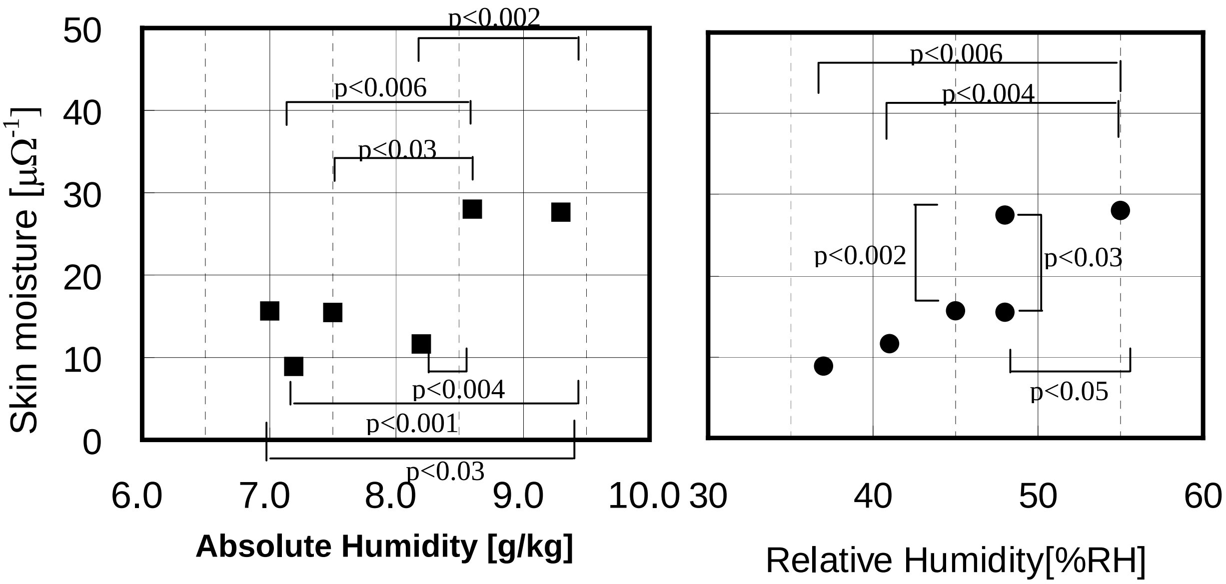


Figure 4-16. Skin moisture measured at the end of exposure in 2002 as the function of relative humidity and absolute humidity

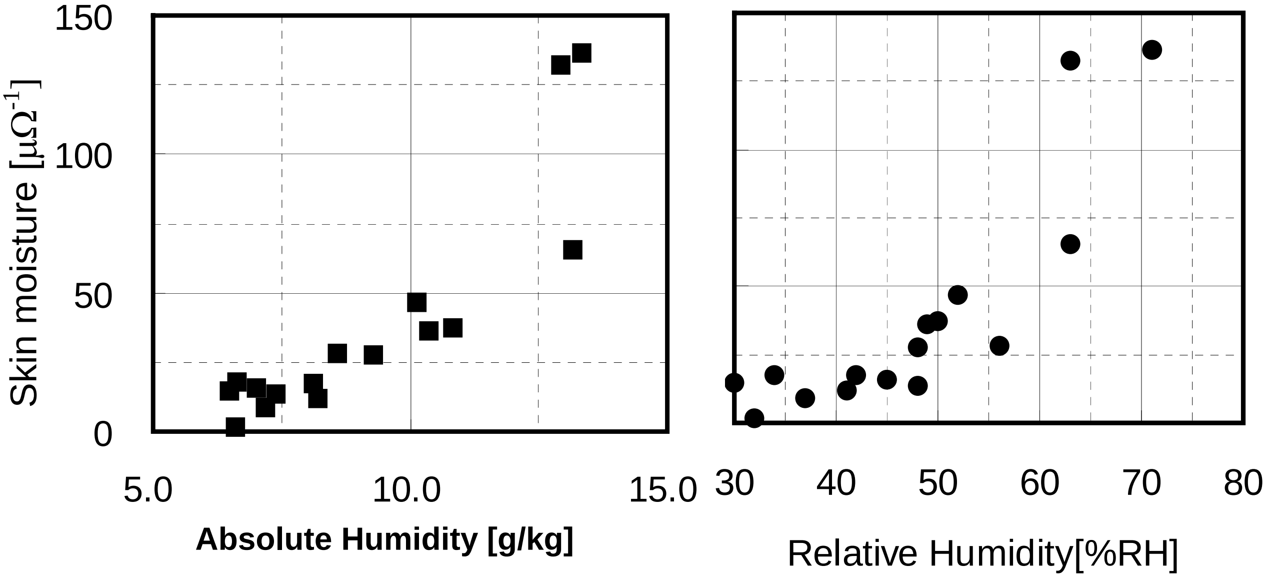


Figure 4-17. Pooled data of skin moisture measured under 25.2 °C of SET* in the summer of 2000, 2001 and 2002 as the function of relative humidity and absolute humidity

4.4.2 Oral Mucous Moisture

Oral mucous moisture may affect the subjective mouth comfort sensation. In this experiment, oral mucous moisture was measured using the Saxon test, which is one of the diagnoses of Sjögren’s Syndrome(Japanese Medical Society for Sjögren’s Syndrome, 2000). Subjects drank a glass of water, 200ml, in order to keep their oral mucous moisture at the same level just before the exposure started. At the end of the exposure, subjects were asked to chew a piece of gauze at a rhythm of 1 time/sec for two minutes. Then, the weight of gauze was measured with an accurate electrical balance. The weight difference of gauze between before and after their chewing was considered to be the weight of their oral mucous moisture.

Mean weights of the oral mucous moisture under different conditions are shown in Figure 4-18. Friedman non-parametric analysis revealed a significant difference among 6 humidity conditions ($p<0.05$). The P-values obtained with the Wilcoxon Matched-Pair Signed Rank test were shown in this figure. Oral mucous moisture under the [45%RH/7.0g/kg] conditions was significantly lower than those under other conditions. However, the difference of the relative humidity effect and absolute humidity effect on oral mucous moisture was not found. Further study would be needed.

In section 4.3.3, it is described that the comfort sensation of the mouth was affected by absolute humidity. Taken in the light of both results, there is no direct correlation between subjective mouth comfort and their oral mucous moisture.

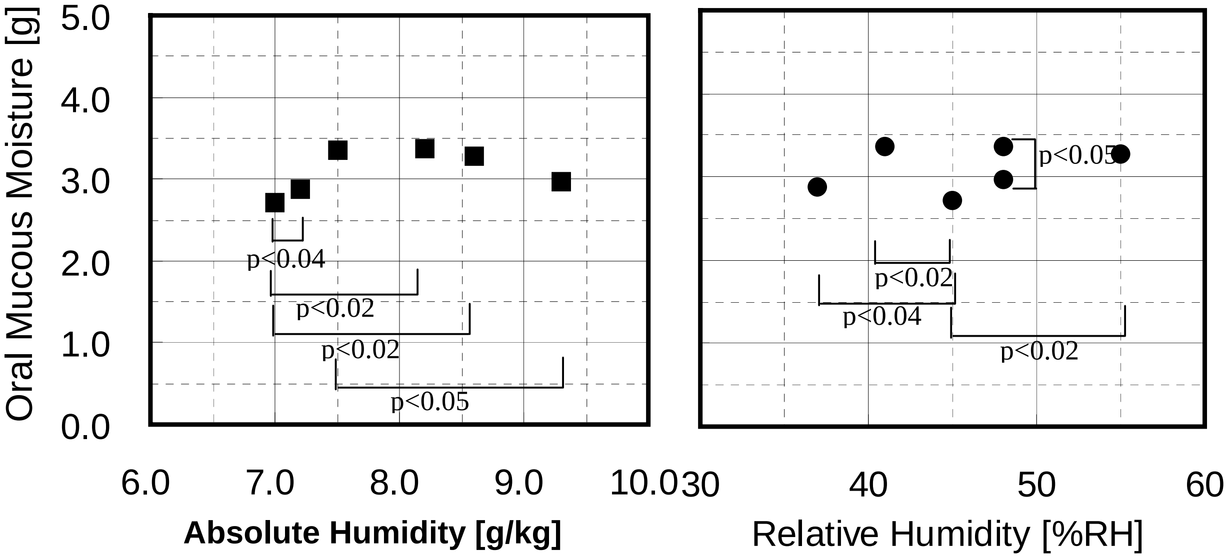


Figure 4-18. Oral mucous moisture

4.4.3 Break up Time

Break up time (BUT) was the time between one blink and another. Subjects measured their BUT by using a stopwatch several times for each exposure. The mean value of these measurements was used as their BUT at that time.

BUT of the subjects did not change significantly throughout the exposure time. Figure 4-19 gives the BUT measured at the end of exposure. Friedman non-parametric analysis did not show significant difference among the conditions. The ratio of the people, whose BUT measured at the end of the exposure was shorter than at the beginning, was almost the same under all conditions. The difference in the effects of relative humidity and absolute humidity on BUT was not found either.

It is shown in section 4.3.3 that subjects tended to perceive their eyes to be more uncomfortable under the conditions with low absolute humidity. Taking these results into consideration, there is no correlation between BUT and the subjective eye comfort sensation.

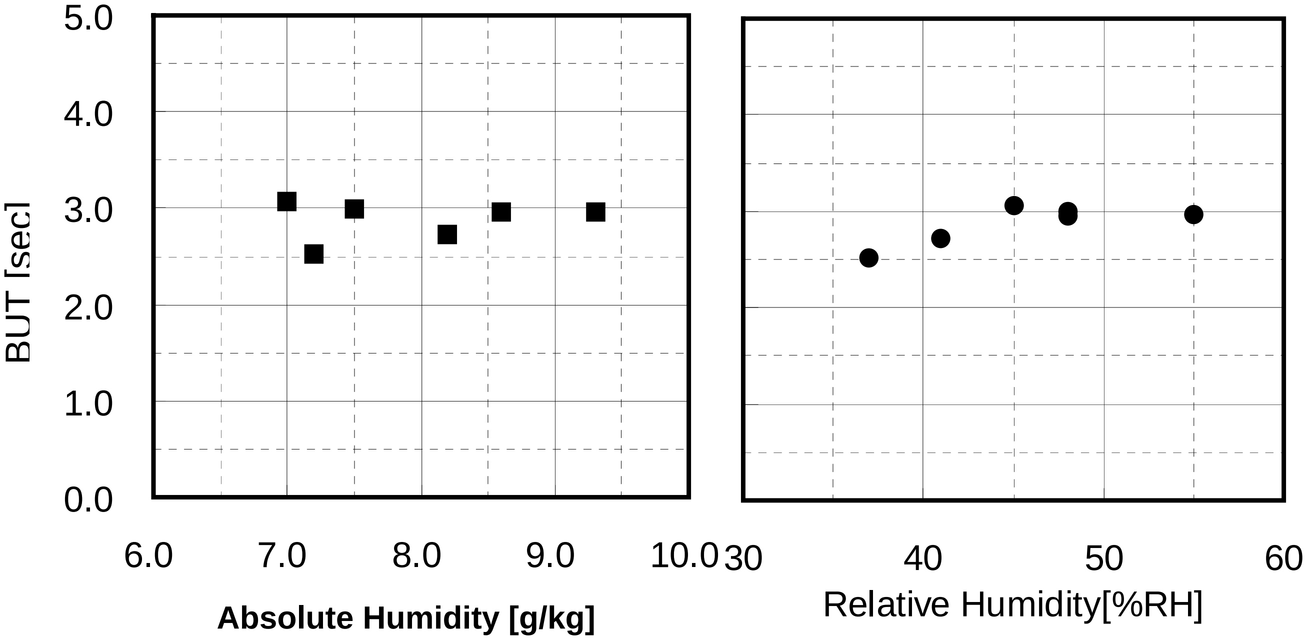


Figure 4-19. BUT measured at the end of the exposure

4.5 TASK PERFORMANCE AND FATIGUE

4.5.1 Addition Task

The correct answer speed of the addition task indicates the number of correct answers the subject input every minute. Making more mistakes would cause lower correct answer speed, even though subjects input the answers quickly. Correct answer speed indicates not only subjects' answering speed but also their accuracy. Thus, it is used for the evaluation of subjects' performance in this experiment. Subjects performed the addition task twice during the exposure. In Figure 4-20 the mean values of the correct answer speed of two addition tasks for each condition were plotted. No significant difference was obtained under all the humidity conditions by using Friedman non-parametric analysis. The difference of effects of relative humidity and absolute humidity were not found. The effects of relative humidity and absolute humidity on subjects' performance of the addition task were moderate under the conditions within the narrow range of humidity, 37%RH-55%RH/ 7.0 g/kg-9.3 g/kg.

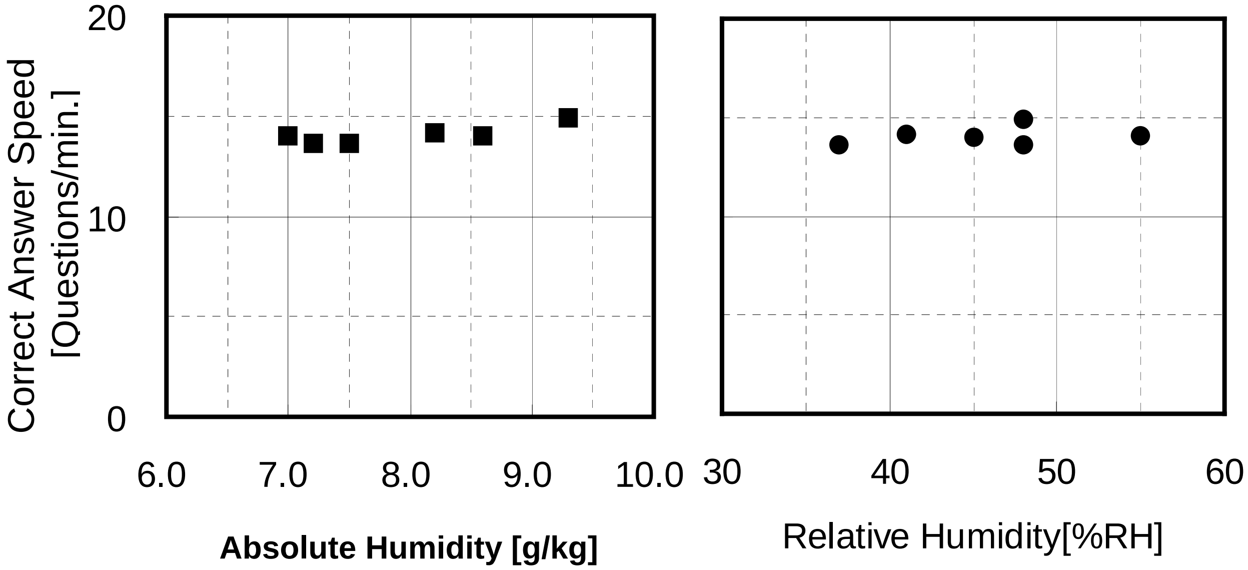


Figure 4-20. The correct answer speed of the two addition tasks under different conditions as the function of absolute humidity and relative humidity

4.5.2 Text Typing

Figure 4-21 gives the text typing speed, which indicates the number of characters input every minute by the subject. It included the spaces between words, commas and periods. The mean value of the typing speed of 3 “Text Typing” activities for each condition was plotted in this figure. Friedman non-parametric analysis did not give significant difference among the conditions. The difference of the relative humidity effect and absolute humidity effect was not shown under the condition made for this experiment.

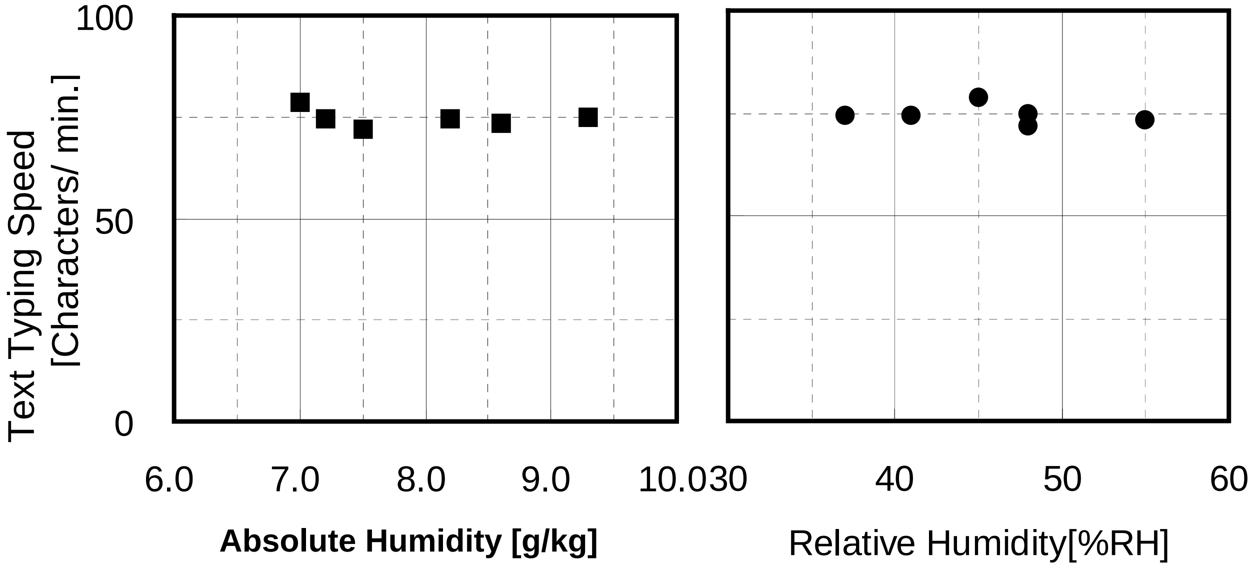


Figure 4-21. The mean values of the typing speed under different conditions as the function of absolute humidity and relative humidity

4.5.3 Fatigue

Table 4-5 shows the rate of complaints for each category reported by the subjects after a 180-minute exposure. Under all conditions, the pattern of fatigue was found to be Ⅰ>Ⅲ>Ⅱ: Ⅰ-dominant, which indicates the general pattern of fatigue.

Figure 4-22 presents the total rate of complaints of all the subjects at the beginning and at the end of the exposure. At the beginning of the exposure, little difference was observed between the ratio of complaints among the 6 conditions. The effects of relative humidity and absolute humidity on the subjective feeling of fatigue were nonexistent when exposure time started. Subjects complained more of the symptoms of fatigue at the end of the exposure than at the beginning of the exposure, while rate of complaints at the end of the exposure were at the same level as those at the beginning under the conditions of [55%RH/8.6g/kg]. High correlation was found between the rate of complaints at the end of the exposure and relative humidity in the air (R^2=0.80). An increase of relative humidity in the air caused a decrease in the rate of complaints reported after the 180-minute exposure. However, a high correlation was not observed between the rate of complaints and absolute humidity.

Table 4-5. Rate of complaints for each group reported at the end of the exposure

No.	Condition [Relative Humidity/Absolute Humidity]	Category Ⅰ[%] Drowsiness and dullness	Category Ⅱ[%] Difficulty in concentration	Category Ⅲ[%] Physical discomfort
1	[37%RH/ 7.2 g/kg]	30.7	15.0	16.4
2	[45%RH/ 7.0 g/kg]	20.8	9.3	18.7
3	[41%RH/ 8.2 g/kg]	23.3	10.7	12.0
4	[48%RH/ 7.5 g/kg]	23.6	10.0	12.7
5	[48%RH/ 9.3 g/kg]	27.3	8.7	12.0
6	[55%RH/ 8.6 g/kg]	15.3	6.7	6.8

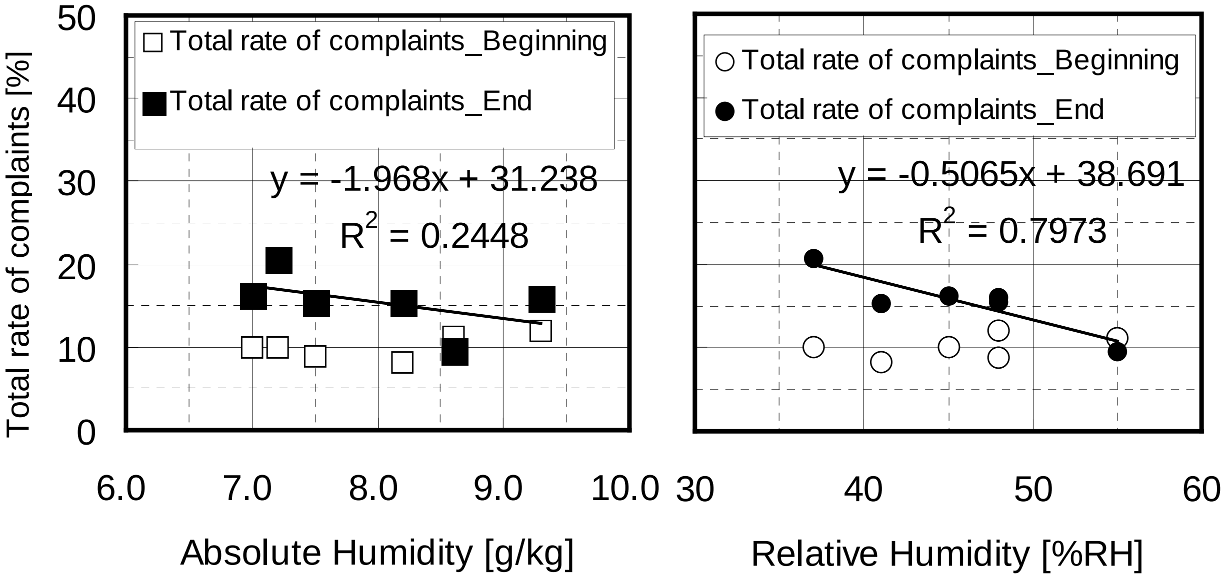


Figure 4-22. Total rate of complaints as the function of absolute humidity and relative humidity

4.5.4 Self-Estimated Performance

Each subject was asked to assess his or her subjective performance after each task, so that his or her effort needed to complete the tasks was investigated.

Each subject answered the question how much he or she was able to work. The subjective rating as the function of the exposure time is presented in Figure 4-23. Subjects reported a lower sense of achievement after the first task (the first addition task) under all conditions. In the pair-wise comparison of the sense of achievement between before and after the first task, using the Wilcoxon Matched-Pairs Signed Ranks test, it was found that the subjective vote after the first task tended to be lower than before it, under 5 conditions except for [55%RH/8.6g/kg] ($p<0.1$). On the other hand, Friedman non-parametric analysis did not give a significant difference among the 6 conditions as for the subjective votes reported at the end of the exposure. They were at the same level under all conditions.

Figure 4-24 presents the difficulty of thinking rated by the subjects before and after the first task (Addition Task). The mean value of votes of all subjects was plotted in this figure. Quantification of the subjective rating was done, giving the value of “100” to “Head clear” and “0” to “difficult to think”. The pair-wise comparison of votes at the beginning and end of the exposure with the Wilcoxon Matched-Pairs Signed Ranks test revealed that, under the 3 conditions with high absolute humidity, subjects complained of difficulty of thinking significantly more after the first task than before it. Votes of difficulty of thinking after the 180-minute exposure are plotted in Figure 4-25 as the function of relative humidity and absolute humidity. Friedman non-parametric analysis showed that subjective difficulty of thinking was significantly raised by the decline of relative humidity in the air ($p<0.05$). The significant differences between the conditions obtained with the Wilcoxon Matched-Pairs Signed Ranks are shown in Figure 4-25.

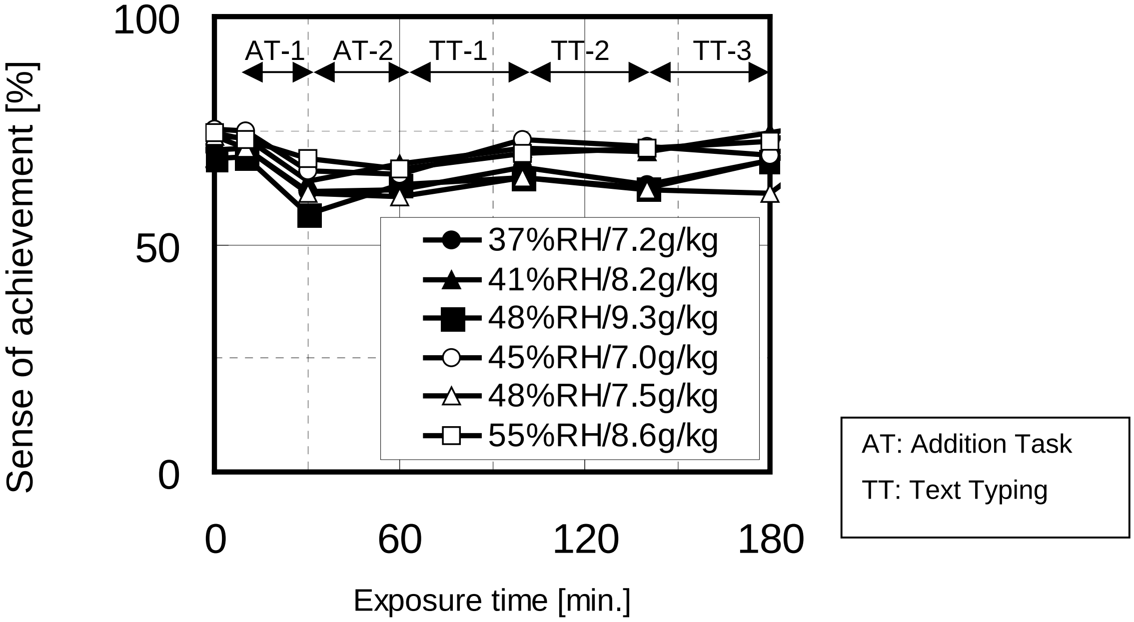


Figure 4-23. Change of the sense of achievement as the exposure time passed

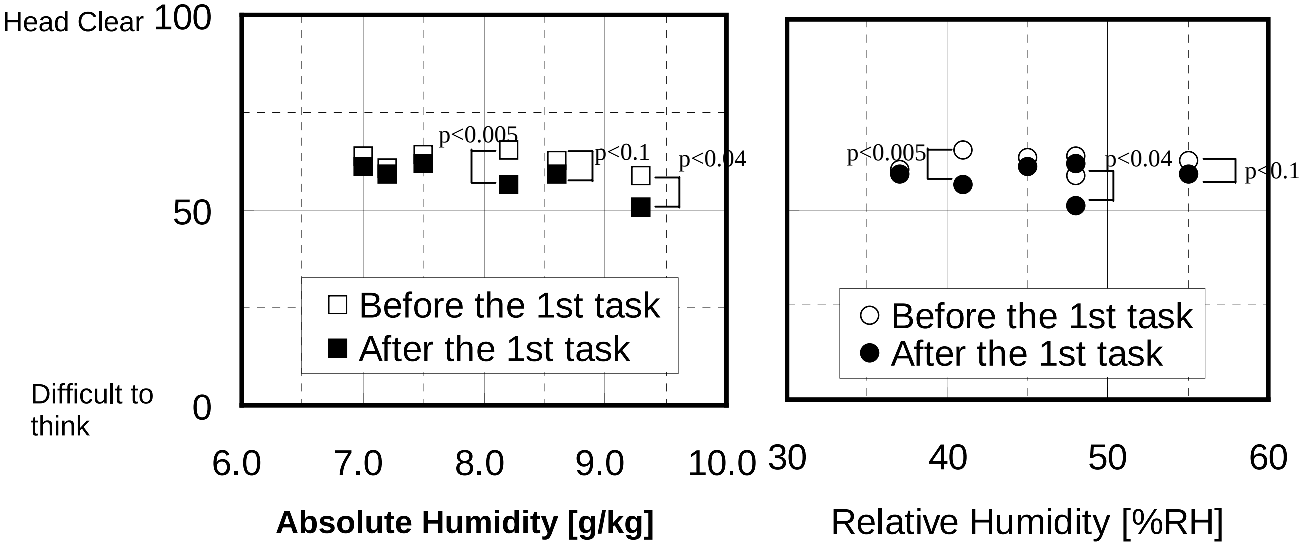


Figure 4-24. Difficulty of thinking rated before and after the 1st task

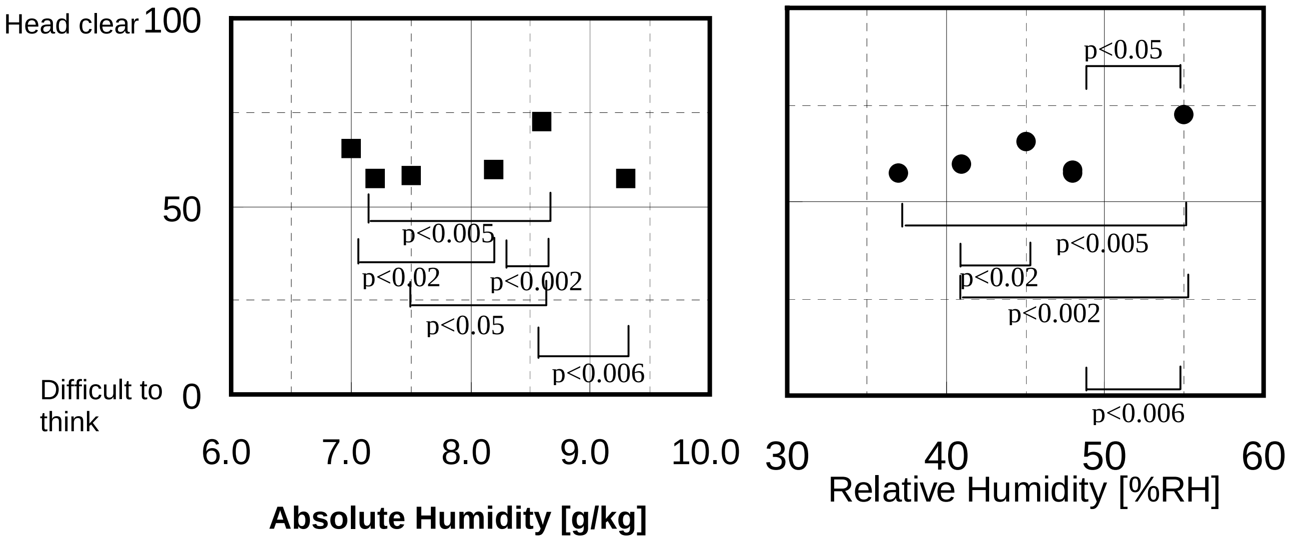


Figure 4-25. Difficulty of thinking rated at the end of exposure

4.6 CONCLUSION

To investigate the different effects of absolute humidity and relative humidity in the air under the condition with constant SET*, subjective experiments were conducted in the summer season.

1) Subjective general dryness sensation got higher under low absolute humidity conditions.
2) High correlation between absolute humidity and general humidity sensation, eye comfort and nose comfort were found, although the differences of vote under different conditions were small.
3) The differences of the effects of relative humidity and absolute humidity on their acceptability of air were not shown.
4) Increasing humidity caused higher skin moisture. However, further study is needed to clarify the difference of the relative humidity effect and absolute humidity effect.
5) Break up time was measured at the same level under all conditions.
6) Oral mucous moisture under the condition of [45%RH /7.0g/kg] was significantly lower than that under the other conditions.
7) Subjective performance did not change with the difference of conditions.
8) The type of subjective fatigue was “general fatigue”. Subjects complained less at high relative humidity.
9) As for the subjective difficulty of thinking, subject tended to report that it was difficult to think under the condition with high absolute humidity after the first task. On the other hand, at the end of the exposure, their complaints were found to be lower with the increase of relative humidity.

CHAPTER 5

LIMITING CRITERIA FOR HUMAN EXPOSURE TO EXTREMELY LOW HUMIDITY

Chapter 5

LIMITING CRITERIA FOR HUMAN EXPOSURE TO EXTREMELY LOW HUMIDITY

5.1 INTRODUCTION

The lowest humidity conditions in the subjective experiments mentioned in Chapters 2, 3, and 4 are 30%RH at 25.2ºC of air temperature, simulating the office spaces in the summer season in Japan. In this chapter, experimental conditions are extended to “extremely low humidity” such as below 10% at 22.0ºC. Human comfort, health and productivity were examined under conditions where relative humidity was below 35% in both clean and polluted air.

The experiments were carried out at the International Centre for Indoor Environment and Energy, Technical University of Denmark, from April to June of 2001.

5.2 EXPERIMENTAL DESIGN

5.2.1 Experimental Conditions

In order to be able to separate temperature effects from the effects of low humidity in the relevant zone of the psychrometric chart, the design listed in Table 5-1 included four levels of humidity, 5, 15, 25 and 35%RH, at a constant air temperature of 22ºC with clean air, and three levels of air temperature from 18- 26ºC, at a constant moisture content of 2.4 g/kg, together with a repeat of the 22ºC, 35%RH condition, in normally polluted air.

The clean air conditions were established by using a high ventilation rate (30 L/s per person) with no added pollution source. A high ventilation rate is needed in order to remove the moisture produced by the subjects and to establish the extremely low humidity condition (5% at 22ºC). Recirculation air was not used, in order to avoid confounding with any possible effects that might be introduced by a dehumidifier, such as transfer of pollutants.

The normally polluted conditions were maintained with a lower ventilation rate (4 L/s per person) and by means of added pollution sources that are typical of the office environment. These were a quantity of carpet that had been used for 20 years in a problem building and thus had absorbed airborne pollution, and linoleum, in each case sufficient to cover the floor of the chamber. Table 5-1 shows that it was possible to compare the two air quality conditions at 22ºC, 15% RH, and at 22ºC, 35% RH.

Thus eight different environmental conditions (six hygro-thermal conditions and two levels of air pollution) were studied. The experiment was designed to investigate not only the negative effect of low humidity on dryness symptoms but also the positive effect of low humidity on perceived air quality. The experimental design makes it possible to test whether the following effects would occur:

- The intrinsic effect of low humidity on physiological reactions and dryness symptoms at four levels of relative humidity (5, 15, 25 and 35%RH) under low-polluting conditions with a moderate level of air temperature (22ºC) can be investigated. Since the air pollution is so low (high level of ventilation rate at 30 L/s per person, without additional pollution sources) it is assumed that there was negligible air pollution.

- The effect of low humidity on physiological reactions and dryness symptoms at two levels of relative humidity (15 and 35%RH) under polluted conditions with a moderate level of air temperature (22ºC). Since the air was moderately polluted by adding pollution sources and by decreasing the ventilation rate to 4 L/s per person, the effect of low humidity, combined with that of air pollution, can be investigated.

- The effect of air pollution on physiological reactions and dryness symptoms at two levels of humidity (15 and 35%RH) and the interaction effect between low humidity and air pollution can be investigated.

- The effect of air temperature on physiological reactions and dryness symptoms can be investigated at three levels of air temperature (18, 22, 26ºC) with constant (low) moisture content.

Table 5-1. Environmental conditions

		Air Temperature		
		18ºC	22ºC	26ºC
Absolute Humidity	0.8g/kg (5%RH at 22ºC)		L	
	2.4g/kg (15%RH at 22ºC)	H	L, H	H
	4.1g/kg (25%RH at 22ºC)		L	
	5.7g/kg (35%RH at 22ºC)		L, H	

H: High level of air pollution (Low ventilation rate of 4L/s per person + pollution source)
L: Low level of air pollution (High ventilation rate of 30L/s per person without pollution source)

5.2.2 Climate Chambers

The subjective experiments took place in three of the new climate chambers at the International Centre for Indoor Environment and Energy, Technical University of Denmark. The dimensions of the chambers are 5.4 m wide, 4.2 m deep, and 2.5 m high. The three chambers can be controlled individually and independently. The temperature can be controlled between 15ºC and 40ºC with an accuracy of +/-0.25ºC, and the humidity can be controlled between 30% and 70% with an accuracy of +/-3% RH.

To establish the driest condition to be tested in this experiment, additional desiccant dehumidifiers were installed in two of the chambers to further decrease humidity to 5%RH at 22ºC. A small pollution chamber can be included in the air supply system of each of the three climate chambers, or by-passed. In this small room, it is possible to either install a high efficiency air filter to further clean the supply air, or to replace the filter with samples of building materials, to introduce a certain level of air pollution simulating the pollutants from indoor air. In two of the chambers, where subjects were exposed, the air exchange rate can be controlled between 12 L/s and 180 L/s; $1\ h^{-1} < n < 10\ h^{-1}$ and in the last one of three chambers, where medical tests were conducted, it can be controlled between 24 L/s and 340 L/s; $2\ h^{-1} < n < 20\ h^{-1}$. The background noise level in the chambers is less than 35 dB(A).

To establish the extremely dry conditions required for this study, additional high-performance desiccant rotary dehumidifiers were installed to dehumidify the outdoor air. Since rotary dehumidifiers can absorb air pollutants while absorbing moisture from the air, there was no recirculation of the air that had passed through the climate chamber. The moisture production from the subjects was removed by supplying dehumidified outdoor air, thus avoiding any effect of the dehumidifier. For the high humidity conditions (e.g. 35%RH/22ºC), a humidifier was used to control the humidity. A small amount of moisture was introduced as required by a well-maintained steam humidifier, using only distilled water.

5.2.3 Chamber Set-Up and Physical Measurements

Three workstations were installed in each of two chambers so that six subjects could be exposed at the same time. Each workstation was equipped with a PC.

To measure the temperature, humidity and air quality, temperature and humidity sensors and air sampling tubes were installed at the center of each chamber. The temperature and humidity were measured using Vaisala (HMP141) humidity and temperature transmitters and logged by an Agilent 4397A data logger every minute. The air sampling tubes were connected to a 12-channel gas analyzer (B&K 1302, B&K 1303) to monitor and record the concentration of CO_2 and TVOC every five minutes during the experiment. Outdoor air temperature and humidity and CO_2 concentrations were also measured. Air velocities were measured using an indoor climate analyzer (B&K 1213). The air velocity at each workstation was checked before the experiment at heights of 0.1m, 0.6m and 1.0m. The climate chambers have well-controlled ventilation and air distribution systems and the air movement during each five-hour experiment was known to be very constant.

The stability of air temperature and humidity measured inside the exposure chamber was +/-0.25ºC and +/-2% RH respectively. The size distribution of airborne dust and the concentration of ozone did not differ significantly between the conditions. Monthly average maximum outdoor temperatures (April-June 2001) were 9.1, 15.8 and 16.4ºC, while the monthly average outdoor relative humidity was 73, 63 and 71% during the experiments.

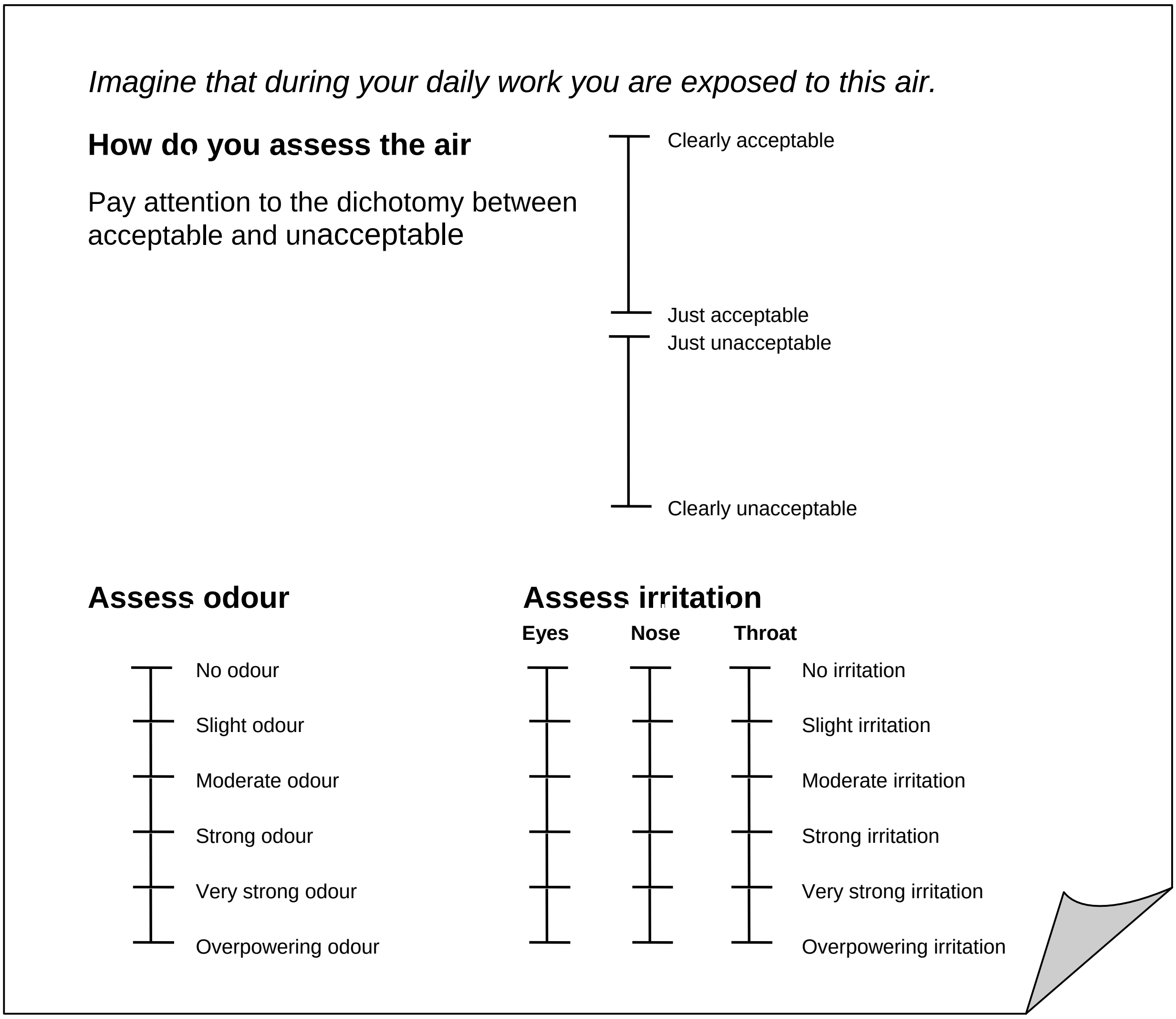
5.2.4 Subjects

Healthy Danish volunteers of both genders were screened for environmental sensitivity using a self-report questionnaire. It was stipulated at the outset that they should not be on regular medication of any kind during the period of the experiment. They were then screened for environmental sensitivity, using a self-report questionnaire. Two categories of subjects potentially sensitive to low humidity were identified (symptoms of hay fever in the pollen season, contact-lens wearers) and a total of 60 subjects were selected at random (aged 19-31, mean 23), 20 from each sensitive category (accepting overlap between categories), and the remainder from neither, with a gender ratio of about 50%. Half of the subjects in each of the three subgroups were assigned at random to the clean air conditions. Within these two treatment groups they were pseudo-randomly assigned to 5 exposure groups of 6 to minimize the possibility of any systematic differences in exposure between the 3 sub-groups: 1) Normal; 2) Sensitive; and 3) Contact-lens wearers. Each exposure group experienced 4 different conditions in balanced order of presentation.

A given exposure group always attended on the same day of the week, so that 30 subjects could be exposed in a working week. ASHRAE ethical rules concerning research involving human subjects were obeyed. The research plan was approved by the local Medical Ethics Committee (KF 01-285/00). If a subject showed any sign of illness or for any other reason would have liked to discontinue an exposure this would have been allowed, although this situation did not arise.

5.2.5 Subjective Measurements

During the experiment the subjects marked visual-analogue scales (VA-scales) to indicate air quality acceptability and odour intensity, from which perceived air quality was calculated, and also to indicate the intensity of specific SBS-related symptoms of eyes, nose, lips, throat and skin irritation and dryness, and general SBS-related symptoms such as headache, fatigue, dizziness, etc. The same VA-scales have been successfully used to obtain subjective assessment of indoor air quality (Fang et al. 1998a,b, 1999a,b) and resulting SBS symptom intensity (Wargocki et al. 1999). Examples of the scales are presented in Figure 5-1.



Imagine that during your daily work you are exposed to this air.

How do you assess the air

Pay attention to the dichotomy between acceptable and unacceptable

Assess odour

Assess irritation

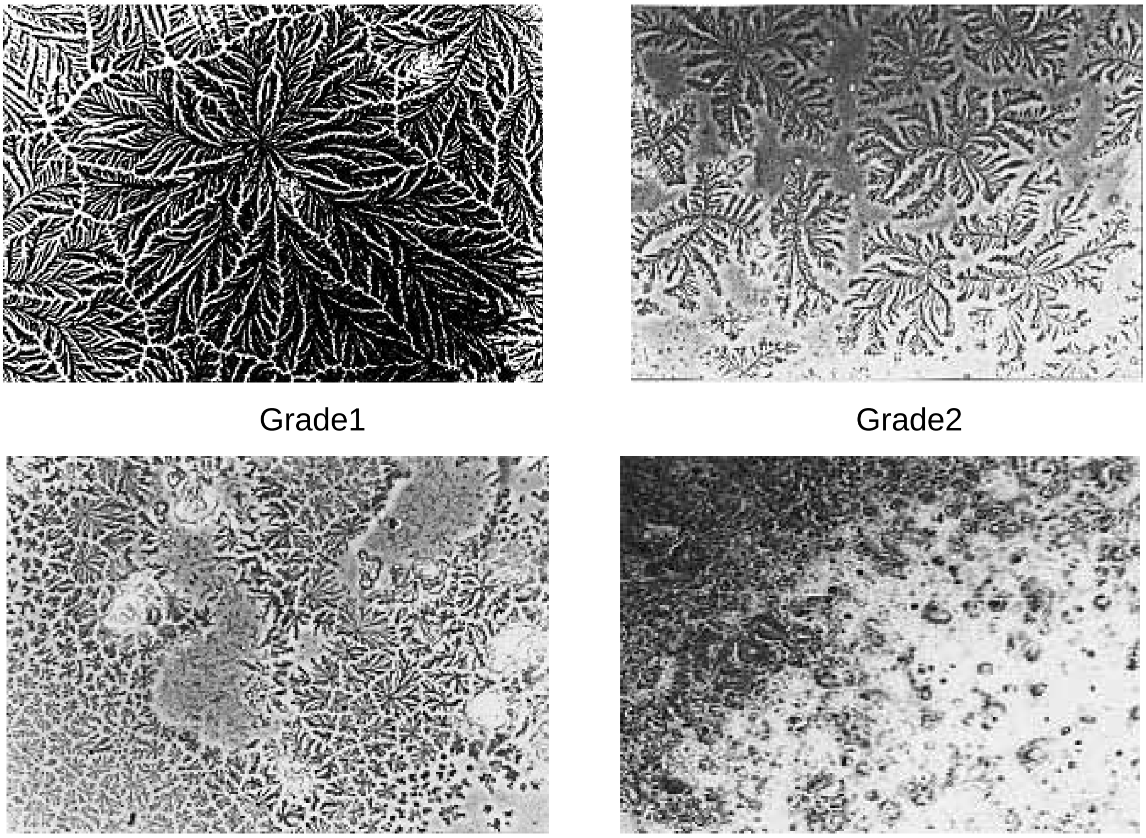
Figure 5-1. A part of the questionnaires used for experiments

5.2.6 Objective Measurements

The objective measures were made in order to be able to verify or reject the following hypothesized mechanisms of causation: 1) Low humidity may have objectively measurable effects on skin humidity, which is directly measurable using a standard dermatological instrument known as a corneometer; 2) Low humidity may decrease tear film stability, which can be directly inferred from measurements of BUT (Break-Up Time) and observations of the average inter-blink interval; 3) Low humidity may affect the consistency of the mucous in the eye and in the nose; 4) These changes in the mucous are considered likely to have a negative influence on the efficiency with which airborne pollutants, making contact with the eye and nose in particulate, vapour-phase or gaseous form, are continuously removed; 5) If pollutants trapped on the mucous layer are removed more slowly, subjects will be rendered more sensitive to air pollution and more likely to experience irritation.

Tear film:

BUT was measured objectively. The method, which is common in ophthalmology, involves placing a drop of dye in the eye, which in itself reduces environmental sensitivity by increasing tear flow, and also involves fixing the head in order to be able to observe the tear film with x200 magnification. Blinkrate was assessed unobtrusively by video-filming the subject in close-up from one side for subsequent observation and timing of each interval between voluntary blinks: Wyon (1992) used this method to demonstrate environmental effects on blinking behaviour. Changes in the mucous layer in the eye induced by increasing the evaporative power of ambient air were observed directly using the mucous ferning test (Wyon & Wyon, 1987), in which a sample of mucus is taken with a glass spoon from the inner canthus (corner) of the eye and deposited on a microscope slide on which the pattern of crystallization that occurs within 10 minutes can be observed and classified. Figure 5-2 gives 4 grades of the crystallization patterns of mucous ferning; Grade-1, which indicates healthy eyes, to Grade-4, which indicates serious dry eye syndrome.



Grade1 Grade2

Grade3 Grade4

Figure 5-2. Four grades of the crystallization patterns of mucous ferning

Eye irritation:

If the efficiency of air pollutant removal is reduced, the risk of irritation and subsequent inflammation is likely to increase. This is true in the eye as well as in the nose.

Wyon (1992) reported significant environmental effects on visible redness in the eye, as assessed by an independent observer. Franck (1986) was able to demonstrate environmental effects on micro-damage to the surface of the cornea, made visible by using Lissamine Green dye to stain them. Another dye in common clinical use, Rose Bengal, was used in this experiment to reveal micro-damage to the corneal epithelium. Three of the VA-scales invite subjects to report subjectively experienced eye irritation as sensation of dryness, smarting or grittiness.

Nasal mucosa:

Changes in the mucous in the nose can be inferred from measurements of Nasal Transit Time (NTT). Andersen et al. (1972) measured NTT as a function of low ambient humidity by placing a radioactive particle on the nasal septum of each subject and observing its motion using collimated Geiger counters. This involved accurate locating the head of the subject with a bite-plate for each measurement, and using radioactive particles is now in any case ethically unacceptable. Andersson et al. (1975) reanalysed their data and showed that low humidity significantly reduced NTT in subjects not exhibiting mucostasis at the time. Andersen later tried using a saccharine particle and measuring NTT as the time elapsing before the subject reported tasting it, but found that the method was too sensitive to the exact placement of the particle to be useful, alternative routes introducing too much variance. This problem was overcome in the present experiment by using a nasal swab soaked in saccharine solution instead of a saccharine particle, making it possible to measure NTT as the time for the shortest route through the nasal cavity. This method has the advantage that subjects can move about normally. The nasal swab method was used in this experoment.

Nasal mucosa irritation:

Irritation of the mucous membranes of the nose is likely to lead to swelling, which can be inferred from measurement of reduced nasal peak flow, which would be reduced by the resulting occlusion of the nasal passage. Measurement of nasal peak flow at inspiration was supplemented by asking subjects to mark a VA-scale to indicate their subjective perception of nasal breathing resistance.

Skin dryness:

Corneometer measurements were used to assess skin dryness, using a standard clinical instrument that measures on an arbitrary scale. Another standard clinical instrument was used to measure transepidermal evaporation. The subjectively experienced dryness of the skin and lips are also reported on VA-scales. Dry skin is likely to be more easily irritated, so after each exposure, a skin challenge test was conducted over the next 24 hours. A patch containing soap solution was attached to the forearm immediately after the end of each exposure. The subject wore it for 24 hours and then returned to the laboratory where it was removed. Skin redness was then quantified using a colorimeter.

5.2.7 Performance Measurements

Subjects performed 4 kinds of tasks that simulated different aspects of office work (Wargocki et al. 1999), as follows:

Text-typing task:

Subjects entered printed text onto a computer. This was subsequently scored for speed and errors using word- processing software.

Proof-reading task:

Subjects read a printed text in which 4 different kinds of error had been inserted: 1) Spelling mistakes; 2) Grammatical mistakes apparent in the immediate phrase in which they occurred; 3) Grammatical mistakes apparent only in the context of the whole sentence in which they occurred; and 4) Logical errors apparent only in the context of the preceding text. Their task was to identify these errors but not to categorise or correct them.

Reading task :

Subjects read a text in which choice-points consisting of three words in parentheses had been inserted at intervals of 2-3 lines. Their task was to indicate which word was correct by underlining it. This provides measures of both reading speed and comprehension. Reading speed is assessed as the number of choice-points attempted, while reading comprehension is assessed as the percentage of choise points correctly marked.

Addition task:

The addition task was presented on a computer screen in two versions: 1) Self-paced, in which the two 2-digit numbers to be added together remained on the screen until the answer had been entered on the keyboard and “Return” had been pressed, and 2) Machine-paced, in which the numbers to be added together remained on the screen only for a limited time (10 seconds) before being replaced by the next two numbers. Machine-pacing was expected to suppress blinking and thus to increase the environmental sensitivity of the eyes. The main purpose of having the subjects perform simulated office work was to ensure that they did not close their eyes for any length of time during the exposure.

5.2.8 Experimental Procedure

The five-hour exposure periods were divided into two sections of 2.3 – 2.5 hours by a 15-minute break. Simulated office tasks were performed throughout each exposure. Subjective ratings were obtained upon entering the chamber and at intervals of about 20 minutes throughout each exposure. The first set of objective medical tests were applied in the examination chamber before subjects entered the exposure chambers. After 5 hours of exposure, the eyes, nose and skin tests were applied. Subjects were instructed to maintain thermal neutrality by self-adjustment of their clothing and were allowed to drink water whenever they required it.

Table 5-2 gives the experimental procedure. Figure 5-3 presents the subject performing the simulated office works.

Table 5-2. Experimental procedure

Exposure Time	Activity	Questionnaire or task
-00:40	Medical test+questionnaires	Entrance questionnaire (normal humidity)
00:00	Enter the exposure chamber + rate the indoor environment	Questionnaire 1
00:06	Addition task (20 min.) *	AT-
00:26	Ratings	Questionnaire 2
00:28	Addition task (20 min.)	AT-
00:48	Ratings	Questionnaire 3
00:50	Text typing (25 min.)	TT-
01:15	Ratings	Questionnaire 2
01:17	Text typing (25 min.)	TT-
01:42	Ratings	Questionnaire 3
01:44	Text typing (25 min.)	TT-
02:09	Ratings	Questionnaire 0
02:13	Break (15min)	
02:28	Ratings	Questionnaire 0
02:32	Reading task (25 min.)	RT-
02:57	Ratings	Questionnaire 2
02:59	Addition task (20 min.)	AT-
03:19	Ratings	Questionnaire 3
03:21	Addition task (20 min.) *	AT-
03:41	Ratings	Questionnaire 2
03:43	Proof reading task (18 min.)	PRT-
04:01	Ratings	Questionnaire 3
04:03	Proof reading task (18 min.) *	PRT-
04:21	Ratings	Questionnaire 0
04:25	Medical test	
05:15	End of experiment	

*: Blink rate observation takes place.

Figure 5-3. The subjects performing the simulated office work

5.2.9 Data Processing and Statistical Analysis

Continuous, normally distributed variables with equal variance were compared by t-test or by analysis of variance, as appropriate. As the rating of the subjective assessments using the visual-analogue scales for different symptoms may not follow a Normal distribution, these data were analysed by non-parametric statistics (Siegel & Castellan 1988).

The three groups of subjects in the laboratory tests - Normal, Self-reported Sensitive, Contact-lens Wearers - were analysed independently, even though some individual subjects will be members of two groups. Note that normal subjects were defined as not being members of either of the other two groups. In subsequent analyses, groups that do not differ significantly from each other on a particular test were pooled to form a larger group.

5.3 RESULTS OF SUBJECTIVE RATING

5.3.1 Ratings of All Subjects

Comparing the 35, 25, 15 and 5%RH conditions at 22ºC in clean air, the following significant changes occurred as humidity decreased: 1) Humidity ratings decreased (P<0.026); 2) Eye dryness increased (P<0.028), both P-values being for the comparisons shown in Figure 5-4 and Figure 5-5 of the two conditions below 20% with the two conditions above 20%RH; 3) Eye irritation increased progressively (P<0.005). No other subjective ratings differed significantly between these conditions.

In pair-wise comparisons between humidity conditions for each of the above ratings, the following significant results were obtained: 1) Humidity was rated lower at 5%RH than at 35%RH (P<0.05) and lower at 15% RH than at 35% RH (P<0.02); 2) Eye dryness was greater at 5%RH than at 25%RH (P<0.02), greater at 15% RH than at 25%RH (P<0.05) and greater at 15% RH than at 35%RH (P<0.01); 3) Eye irritation was greater at 5%RH than at 25%RH (P<0.05), greater at 5%RH than at 35%RH (P<0.01), and greater at 15%RH than at 35% RH (P<0.02). These findings are all compatible with an improvement in subjective eye symptoms at relative humidity values above 20%. In addition, although there was no overall effect of humidity, fatigue was rated significantly higher at 5%RH than at 35%RH (P<0.05), and throat irritation tended to be higher at 5%RH than at 35%RH (P<0.06).

It may be seen in the figures that the degree of discomfort reported was mild even at 5%RH.

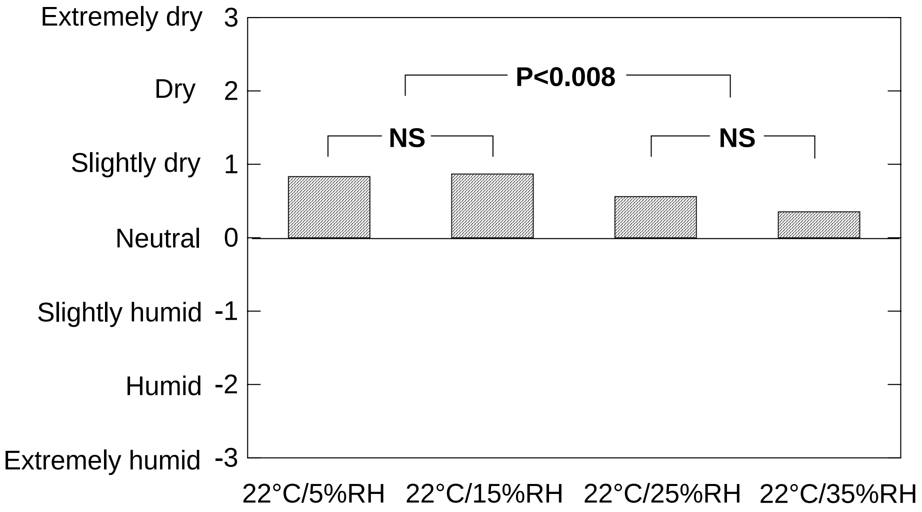


Figure 5-4. Sensation of air humidity after an exposure of 5 hours to 5, 15, 25 and 35% RH in clean air at 22 ºC

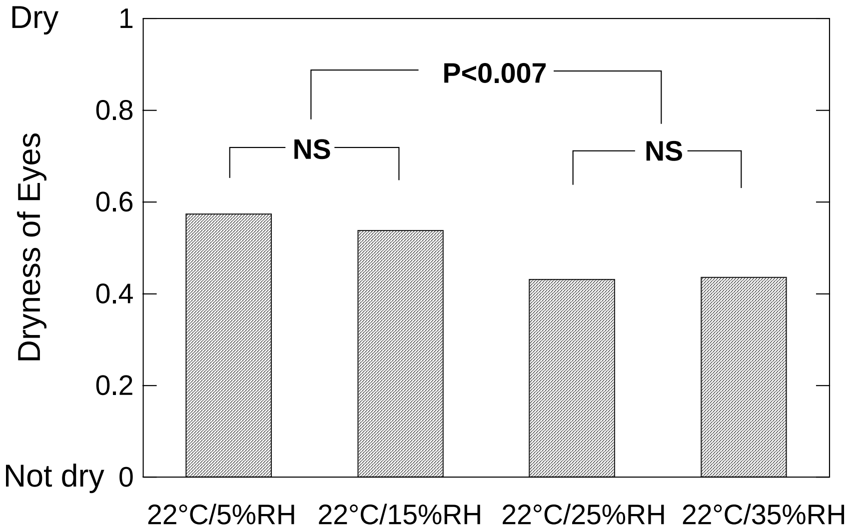


Figure 5-5. Sensation of eye dryness after an exposure of 5 hours to 5, 15, 25 and 35% RH in clean air at 22 ºC

The initial acceptability ratings of air quality corresponded to 9-11% dissatisfied under all clean air conditions, with no effect of humidity, but in the polluted air conditions the initial acceptability decreased significantly between 22ºC and 26ºC (11 and 31% dissatisfied). The Predicted Percentage Dissatisfied calculated from the acceptability ratings obtained in the 22ºC clean air conditions is shown in Figure 5-6 as a function of relative humidity, together with the results of Fang et al. (1998b), which were calculated in the same way from assessments of acceptability. Although no significant effect of humidity can be shown in the region below 35%RH that was studied in the present experiment, it may be seen that the absolute level and the trend are in very good agreement with previously obtained results at higher levels of humidity – the present results correspond to what would have been a direct extrapolation into the low humidity region. Perceived air quality continues to improve as humidity is decreased.

Comparing the three temperature conditions 18, 22 and 26ºC at constant absolute humidity in polluted air, nose irritation increased significantly overall with temperature ($P<0.005$). There were no other significant effects of temperature.

Comparing the conditions 35%RH and 15%RH at 22ºC in polluted air, the following significant differences were found at the lower humidity level: 1) Nose felt more blocked ($P<0.05$); 2) Throat was more irritated ($P<0.05$); 3) Lips felt more dry ($P<0.05$); 4) Skin felt more dry ($P<0.05$).

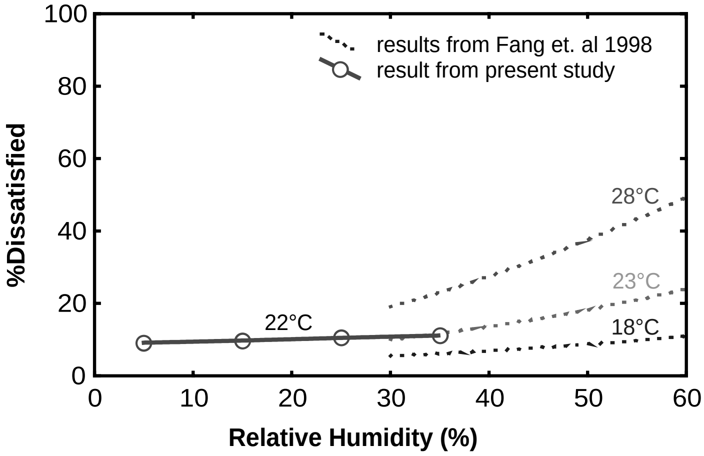


Figure 5-6. Perceived air quality as a function of relative humidity in the present experiment in comparison with results obtained at higher levels of relative humidity (Fang et al., 1998a,b), for 18, 23 and 28ºC

5.3.2 Subjective Data Obtained from Sub-Groups

Comparing the 35, 25, 15 and 5%RH conditions at 22ºC in clean air for each sub-group separately, the sensitive sub-group rated humidity sensation significantly lower at 15% than at 35%RH ($P<0.05$), though not lower at 5%RH than at 35%RH; there were no significant effects on ratings of eye dryness within any sub-group, but eye irritation was rated significantly higher with decreasing humidity by the sensitive sub-group ($P<0.05$) and by the sub-group not wearing contact lenses ($P<0.05$), and significantly higher at 5%RH than at 35%RH by the sensitive group ($P<0.05$) and independently of contact lens wearing ($P<0.05$ in the sub-groups with or without contact lenses). In the sub-group not wearing contact lenses, eye irritation was significantly higher at both 15%RH ($P<0.05$) and 25%RH ($P<0.05$) than at 35%RH, whereas this was not the case for contact lens wearers. These findings are compatible with the existence of a protective effect of contact lens wearing that extends down to 15%RH but not down to 5%RH.

Comparing the three temperature conditions 18, 22 and 26ºC at constant absolute humidity in polluted air, only the sensitive sub-group showed any significant differences: nose irritation increased with temperature ($P<0.05$) and was higher at 26ºC than at 18ºC ($P<0.02$), and they found it more difficult to concentrate at higher temperatures ($P<0.05$). Comparing the conditions 35%RH and 15%RH at 22ºC in polluted air, none of the sub-groups reported any difference in blocked nose, only the non-sensitive sub-group reported that throat irritation ($P<0.05$) or lip dryness ($P<0.05$) increased at the lower humidity, and only the sensitive sub-group reported that skin dryness increased at the lower humidity ($P<0.05$). Contact lens wearing was not expected to influence these symptoms, and did not do so.

5.4 OBJECTIVE TEST RESULTS

5.4.1 Objective Test of All Subjects

On the pooled data from all subjects, only the mucous ferning test, blinkrate and the corneometer measurements indicated any significant effects of low humidity or temperature:

Mucous Ferning test:

Samples were immediately removed from the exposure chamber. The crystallization pattern of the mucous was then observed in a microscope and classified into categories 1-4, where 1 is perfect and 4 is clearly deficient. The Friedman nonparametric two-way analysis of variance shows that there was a significant difference ($P<0.02$) between results obtained in the 5, 15, 25, and 35%RH conditions as shown in Figure 5-7, at 22ºC in clean air.

Pair-wise comparison between conditions by means of the non-parametric Wilcoxon Matched-Pairs Signed-Ranks test reveals that mucous ferning did not differ significantly between 5%RH and 15%RH or between 25%RH and 35%RH, while it was worse at 5%RH than at either 25%RH ($P<0.06$) or 35%RH ($P<0.16$) and significantly worse ($P<0.05$) at 15%RH than at either 25%RH or 35% RH (2-tail P-values). Pooling conditions for each subject, mucous ferning observed at humidity levels below 20%RH was significantly worse ($P<0.002$).

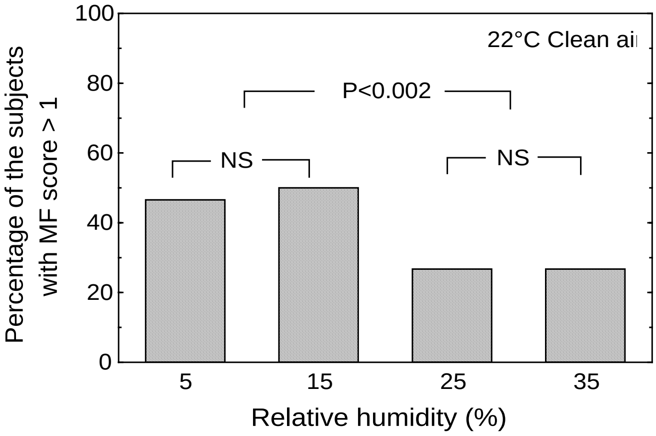


Figure 5-7. The results of mucous ferning test after an exposure of 5 hours at the different levels of air temperature and humidity

Similarly, Friedman analysis shows a significant difference in mucous ferning between the 18, 22 and 26ºC conditions (P<0.02) in polluted air at constant absolute humidity, and subsequent pair-wise comparison using the Wilcoxon test reveals that while there was no significant difference between the two lower or the two higher temperature conditions, mucous ferning was significantly worse at 26ºC than it was at 18ºC (P<0.006). These results are shown in Figure 5-8 as the percentage of samples classed as Category 2 or above under each of the conditions.

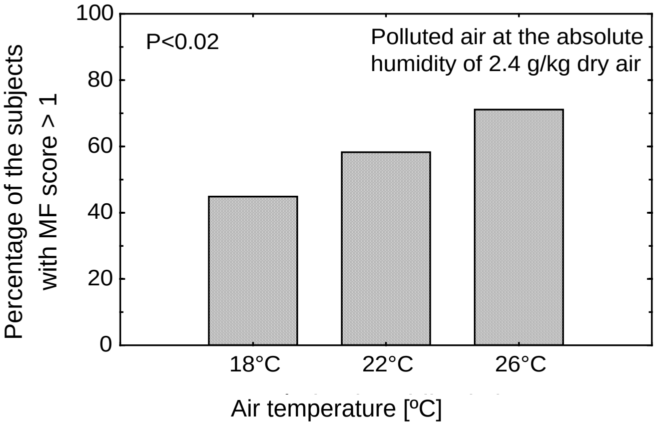


Figure 5-8. The results of mucous ferning test after an exposure of 5 hours at the different levels of air temperature at constant absolute humidity of 2.4 g/kg

Blink-rate:

Average inter-blink interval tended to be shorter at 5% RH than at 35% RH on a Wald-Wolfowitz comparison ($P<0.05$) as shown in Figure 5-9. The difference is most marked for the proportion of average inter-blink intervals below 10 seconds.

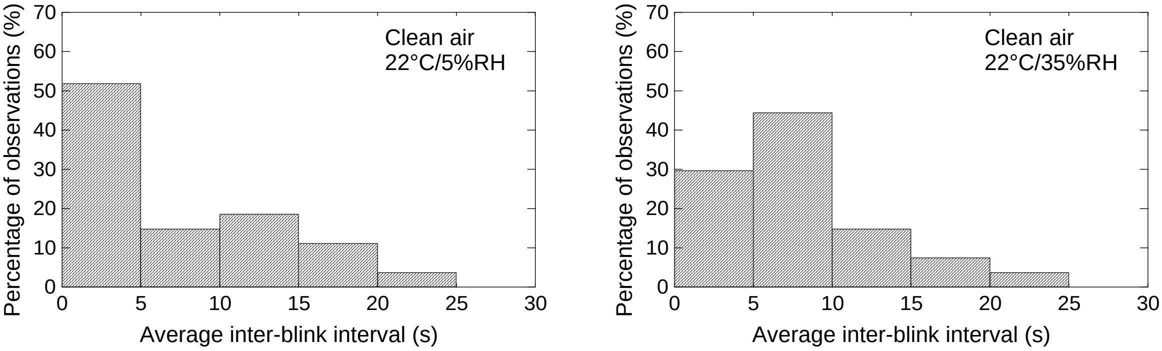


Figure 5-9. Distribution of average inter-blink interval after an exposure of 5 hours to 5%RH and 35%RH in clean air at 22ºC.

Skin tests:

Corneometer values indicate that skin dryness increased during the exposure period in all conditions. Pooling data from clean and polluted air (N=60), the Wilcoxon Matched-Pairs Signed-Ranks test indicates that the increase was significantly higher at 15%RH than at 35%RH ($P<0.003$). The Friedman test shows that in polluted air there was a significant effect of temperature ($P<0.0004$) on transepidermal water loss (TEWL) at constant low absolute humidity: the measured values declined less during the exposure at 26ºC than at the two lower temperatures, as would be expected if some thermal sweating had been initiated at the highest temperature. Note that any effect of temperature on skin dryness would have been in the opposite direction.

5.4.2 Objective Test Results, Sub-Group Data

Mucous Ferning test:

For non-sensitive subjects, a Friedman test across all 4 relative humidity levels in clean air was not significant (P<0.08), although a Wilcoxon Matched-Pairs test of the difference in the expected direction between 15%RH and 35%RH was significant (P<0.028). The deterioration in mucous ferning score that took place during the exposure of this group was significantly greater at reduced humidity across all 4 levels (P<0.016), and was greater at 15%RH than at 35%RH (P<0.012), although it was not significantly greater at 5%RH than at 35%RH (P<0.11, NS). No significant effects of relative humidity in clean air could be shown for the sensitive subjects. Similarly, mucous ferning could be shown to be significantly worse at raised temperatures in polluted air (P<0.02) for the non-sensitive subjects, but not for the sensitive subjects. In the former group, mucous ferning was significantly worse at 26ºC than at 18ºC (P<0.02) and tended to be worse at 26ºC than at 22ºC (P<0.062, NS 2-tail test).

For contact-lens wearers, mucous ferning tended to be worse at reduced relative humidity across all 4 levels in clean air (P<0.06, NS). Similarly, mucous ferning tended to be worse at raised temperatures in polluted air for this group (P<0.09, NS) and was significantly worse at 26ºC than at 18ºC (P<0.043). The deterioration in mucous ferning score that took place during each exposure of this group to clean air tended to be greater at reduced humidity (P<0.065, NS) and was significantly greater at 15%RH than at 25%RH (P<0.043), although it was not significantly greater at 5%RH than at 35%RH. No significant effects of the environmental conditions could be shown for subjects not wearing contact lenses. No difference in mucous ferning could be shown between clean and polluted air at 22ºC, neither at 15%RH nor at 35% RH, for any of the 4 overlapping sub-groups.

Rose Bengal staining test for damage to the corneal epithelium:

The Rose Bengal staining test was only performed on subjects not wearing contact lenses, but still showed a significant effect of humidity, albeit in the unexpected direction.
For sensitive subjects not wearing contact lenses, less damage was observed at 5%RH than at 35%RH (P<0.043) and less at 25%RH than at 35%RH (P<0.043), although no significant

difference could be shown between 15%RH and 35%RH. The same comparisons (between 5 and 35%RH and between 25%RH and 35%RH) were significant ($P<0.05$) in terms of the deterioration that took place during each exposure (i.e. in terms of before/after delta-values derived for each subject). Note that all of these results are in the direction opposite to what was expected, as decreasing humidity appears to have had a positive effect. As no mechanism for this has ever been proposed, these results should properly be disregarded unless they are confirmed in subsequent experiments. No significant effects of temperature in polluted air could be shown for this test.

Other objective tests:

No other objective tests yielded significant effects of environmental conditions within any sub-group.

5.5 TASK PERFORMANCE RESULTS

5.5.1 Performance of All Subjects

Throughout the exposures, subjects were instructed to perform tasks simulating different aspects of office work. The original purpose of this aspect of the experiment was simply to ensure that they would keep their eyes open, with no opportunity of avoiding eye discomfort by keeping them closed for long periods, as passengers on long flights are free to do if they find that low humidity leads to eye discomfort. It has been shown above that very little eye discomfort was experienced even when performing tasks requiring concentration and continuous visual data acquisition – typing, reading and addition. It would have been legitimate to regard the tasks simply as independent variables – one of the stress factors – but for completeness, task performance was compared between conditions.

The results are unexpected and at first sight very surprising: at 22ºC in clean air, the performance of three tasks decreased significantly as relative humidity was reduced, as shown in Figure 5-10, Figure 5-11 and Figure 5-12. Typing speed as measured in words typed per minute decreased progressively from 35%RH to 5%RH, by 4% ($P<0.0002$, parametric ANOVA); proof-reading as measured in lines read per minute decreased progressively over the same range, by 7% ($P<0.03$, Wilcoxon test, 5%RH vs 35%RH); and addition as measured in units attempted per minute decreased by 9% ($P<0.00001$, Friedman test), the decrease in this case apparently occurred below 15%RH rather than progressively. No effect of conditions on reading speed and comprehension could be shown.

In order to examine the possibility that an incompletely balanced design might have allowed learning from first to last exposure to be the underlying cause of the observed differences between conditions, the influence of order of presentation was examined, without regard to environmental conditions. There were no significant effects of learning on typing speed or proofreading, both well-practiced tasks, but there was a significant effect of learning on the relatively unfamiliar task of serial addition ($P<0.05$). This effect was removed by multiplying individual scores in the addition task by a factor reflecting average group performance on each occasion (first, second, third and fourth exposure), and the effect of condition was again examined. Performance of the addition task was still significantly lower at 5%RH than at any of the higher levels of relative humidity (P<0.04, as shown in Figure 5-10), but the size of the effect was now reduced to 5% instead of 9%.

The only significant effects of temperature on performance at constant absolute humidity that could be shown were a decrease in errors in the paced version of the addition task as temperature increased (P<0.01) and an increase in reading speed with temperature (P<0.05). Performance was better in both cases under conditions in which the relative humidity was slightly lower. The error rate in the addition task was 28% higher at 18ºC, in comparison with 22ºC, while reading speed was 7% lower at 18ºC than at 26ºC. It seems likely that these effects were due to the temperature rather than to the accompanying change in relative humidity.

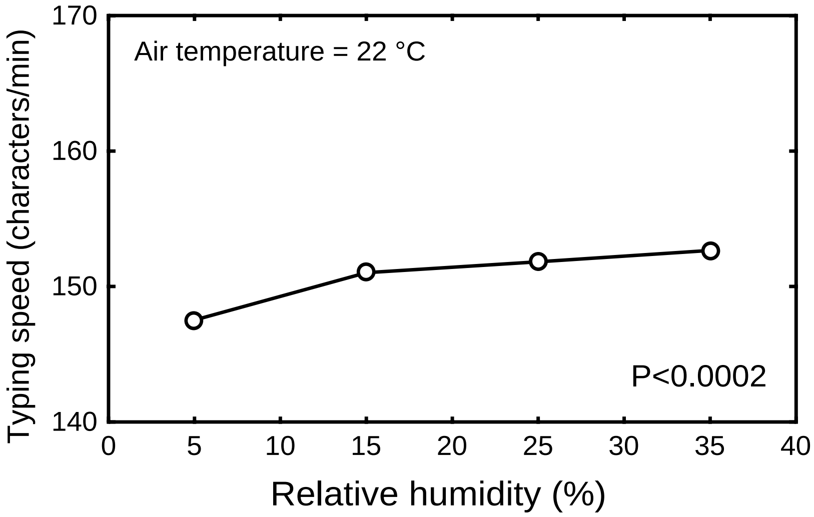


Figure 5-10. Typing speed as a function of relative humidity at 22ºC

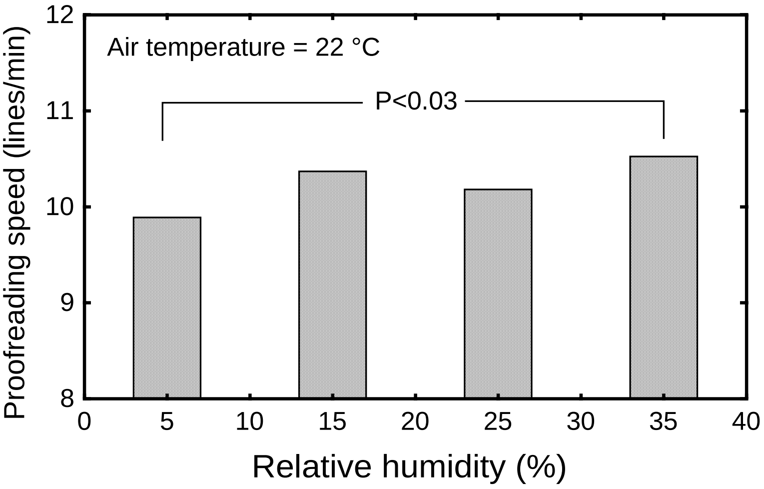


Figure 5-11. Proofreading speed at the four levels of relative humidity

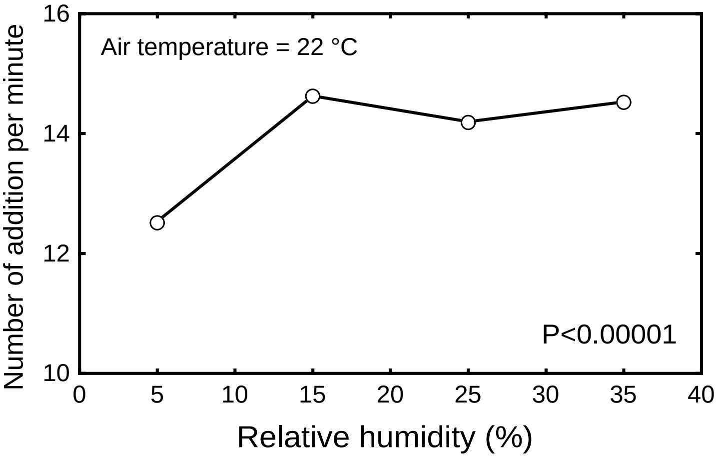


Figure 5-12. Calculation speed as a function of relative humidity before removing the learning effect

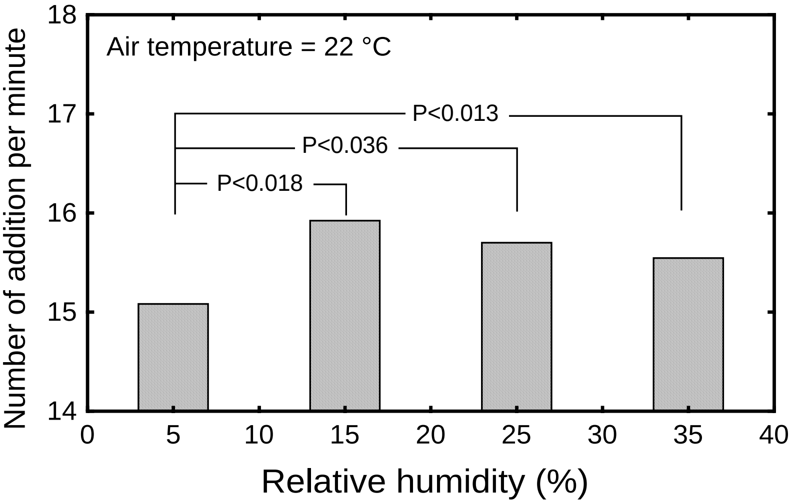


Figure 5-13. Calculation speed after removing the learning effect

5.5.2 Task Performance, Sub-Group Data

Text typing

Although there were significant effects of the environmental conditions on the performance of this task by all subjects, no significant overall effects of humidity or temperature could be shown for any sub-group, and as only one pair-wise comparison reached significance, this should be regarded as a chance result.

Proofreading

No significant overall effects of humidity or temperature on the performance of this task could be shown for any sub-group, but the performance of subjects not wearing contact lenses was significantly worse at 5%RH than at 35%RH (P<0.024) and tended to be worse at 15%RH than at 35%RH (P<0.058, NS, 2-tail test). No other significant effects could be shown for other sub-groups.

Addition task

No significant overall effects of humidity on the performance of this task could be shown for any sub-group, but the performance of subjects not wearing contact lenses was significantly worse at 5%RH than at 15%RH (P<0.009), significantly worse at 5%RH than at 25%RH (P<0.028) and tended to be worse at 5%RH than at 35%RH (P<0.075, NS 2-tail test). No effects could be shown for subjects wearing contact lenses. For sensitive subjects, the performance of this task was significantly worse at 5%RH than at 15%RH (P<0.008), at 5%RH than at 25%RH (P<0.030), and at 5%RH than at 35%RH (P<0.032). Performance appeared to be worse at 18ºC than at 22ºC (P<0.034), though not worse than at 26ºC (P>0.10, NS). This isolated effect of temperature in the unexpected direction is regarded as spurious. No effects of temperature or humidity could be shown for non-sensitive subjects.

Reading and comprehension

There were no significant effects of the environmental conditions on the performance of this task by all subjects, and the only apparently significant effects within sub-groups were isolated, inconsistent and in different directions. They have therefore been disregarded as chance results.

5.6 CONCLUSION

In order to investigate the effects of extremely low humidity on human comfort, health and performance, subjective experiments were carried out at the International Centre for Indoor Environment and Energy, Technical University of Denmark. A total of 60 Subjects were exposed in climate chambers for 5 hours while performing simulated office work. Four humidity conditions in clean air at 22ºC and 4 conditions in polluted air, 3 of which at constant absolute humidity, were imposed.

1) Subjective reports of dry discomfort increased as humidity levels were reduced in the low humidity range (below 35%RH), although the level of discomfort was never more than mild even at 5%RH.
2) Clear evidence was obtained that 5 hours of exposure to 15%RH or below is sufficient for the mucous layer of the tear film to become measurably more dry than at 25%RH or above in clean air.
3) There was an observed increase in blink-rate at low humidity, and this is presumably one of the behavioural strategies that are adopted to reduce perceptibly negative effects of low humidity on the tear film.
4) A large and consistent negative effect of low humidity was found on the performance of three tasks that are representative of office work, for all three of which the rate of visual data acquisition is a critical determinant of performance.
5) The observed increase in blink rate at lower levels of relative humidity may have progressively reduced the rate of visual data acquisition, because blinking intermittently obscures vision, even if we are not fully aware of it.
6) The reduced quality of the mucous layer of the tear film at lower levels of relative humidity may have progressively reduced visual acuity, so that visual data acquisition took longer.
7) Eye discomfort may have acted as a distraction, although the level of discomfort reported in this study was very mild.
8) The sub-group who reported experiencing hay fever in the spring was expected to be environmentally sensitive, and was indeed consistently affected in a negative direction by reduced humidity and raised temperature in terms of subjective sensation of

dryness and skin dryness, and in subjectively reported eye and nose irritation, while the non-sensitive subjects were not.

9) As the objective tests of physiological functions indicated an effect of low humidity and temperature for the non-sensitive sub-group but not for the sensitive sub-group, it would appear that the self-reported sensitivity of the latter group was of a psychological rather than a physiological nature.
10) Environmental effects on subjective discomfort could only be shown for subjects not wearing contact lenses in the present experiment.
11) Environmental effects on mucous ferning could be shown only for subjects wearing contact lenses, but as this did not seem to lead to increased discomfort, it may simply indicate that the tear film tends to evaporate more quickly from a contact lens than from an unprotected eye.
12) Environmental effects on performance appear to have been greater for subjects not wearing contact lenses, and for sensitive subjects. These observations are compatible with a causative mechanism in which subjective discomfort causes distraction, as environmental effects on subjective discomfort were greater for both of these sub-groups, but this does not constitute proof that this was the causative mechanism.

CHAPTER 6

HUMIDITY AND AIR TEMPERATURE IN AIRCRAFT CABINS

Chapter 6

HUMIDITY AND AIR TEMPERATURE IN AIRCRAFT CABINS

6.1 INTRODUCTION

People sometimes feel that the air in certain kinds of transportation in their daily lives is dry, because of low humidity. This study has particularly focused on humidity and air temperature in aircraft cabins. Since passengers and flight attendants are forced to stay in cabins for a long period of time, the cabin environments should be examined as much as the environment in office buildings. However, only few field measurements have been conducted in aircraft cabins, whereas many measurements of the thermal environment in office buildings have been carried out.

The HVAC system of an airplane, “Environmental Control System (ECS)”, compresses the low-pressure outside air and supplies it to the cabin to maintain the cabin pressure at a comfortable level. At a typical cruising altitude of 11,000 m the atmospheric pressure is about 22 kPa compared to 101.3 kPa at sea level, with an air temperature usually about –55°C, and the air containing very little moisture. The minimum cabin pressure and airflow of fresh air is specified by the US Federal Aviation Regulation 25 (FAR 25) that requires a cabin pressure altitude of not more than 2,440 m corresponding to a cabin pressure of 75.2 kPa and a flow rate of fresh air at this cabin pressure of at least 4.7 L/s for each occupant. The ventilation rate, in reality, is normally higher than required in order to control air temperature, which causes a very low humidity in the aircraft cabin.

In this study, field measurements were conducted using portable temperature and humidity sensors in order to find what kind of environment people experience in the aircraft cabin. Polymer film electronic hygrometers were used for measurements due to their portability. However, most humidity sensors are normally designed for usage at 101.3 kPa. It is not known, if humidity sensors can be used for measurement in a cabin at lower pressure during flight. Thus, a calibration of the humidity sensors was made at lower pressure. Three kinds of polymer film electronic hygrometers were examined in a low-pressure environment. An Assmann psychrometer was used for the calibration as a control instrument.

6.2 CALIBRATION OF HYGROMETERS

Calibration tests were conducted from November to December 1999 in a climate chamber, at Waseda University, Japan. For detailed information on HVAC system of the camber, see Chapter 2.

6.2.1 Calibration of Small Size Assmann Psychrometer

A small sized Assmann psychrometer (Mini-Assmann), which can be placed inside the desiccator, was used as a control instrument, although it was not authorized by the Meteorological Agency because of its size. Thus, it was calibrated by a normal sized Assmann psychrometer (Yoshino Ltd.) that was authorized by the Tokyo Meteorological Agency in 1999. Both instruments are shown in Figure 6-1.

Both Assmann psychrometers were placed near each other in the climate chamber. Five experimental conditions were set for this calibration: 10, 15, 20, 25, and 30°C at 50%RH as shown in Table 6-1. After the thermal environment in the chamber reached a steady state under each condition, the values given by the dry-bulb and the wet-bulb of the Mini-Assmann and the dry-bulb by the authorized Assmann were recorded and compared. The Wet bulb of the Mini-Assmann was uncovered with wet gauze in this measurement.

Measured values by the Mini-Assmann and the authorized Assmann are plotted in Figure 6-2 and the following regression lines were obtained:

Dry-bulb: $y= 1.0051x +0.2498$ ($R^2=0.999$)
Wet-bulb: $y = 0.9842x - 0.766$ ($R^2=0.999$)

Where x= values measured by the Mini-Assmann
y= values measured by the authorized Assmann

Measurements with the Mini-Assmann shown in a later section were corrected using these linear expressions obtained from the calibration.

Figure 6-1. Mini-Assmann and normal size Assmann psychrometer

Table 6-1. Experimental conditions for calibration of the Mini-Assmann

Air temperature in the chamber	30°C	25°C	20°C	15°C	10°C
Relative humidity in the chamber	50%RH				

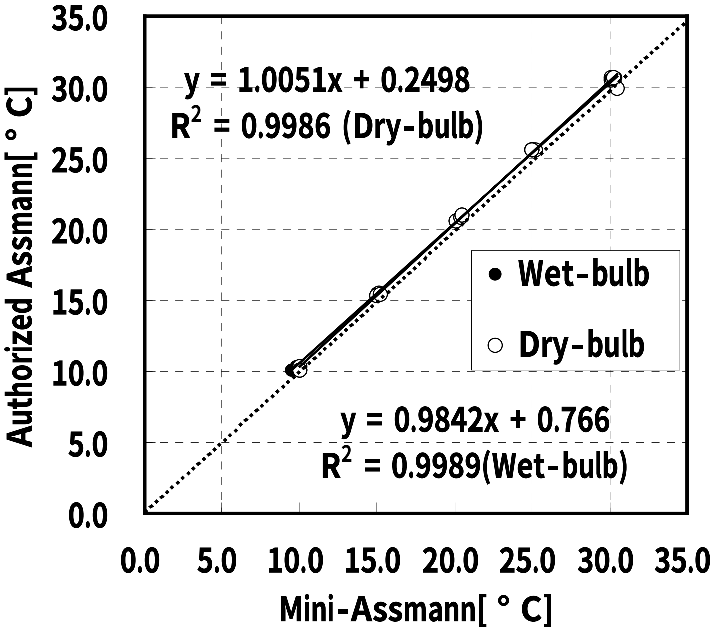


Figure 6-2. Results from calibration of the Mini-Assmann psychrometer

6.2.2 Calibration of Relative Humidity Sensors

The humidity sensors were placed in a sealed desiccator (TGK, 400mm× 355mm×599mmH) made of acrylic plastic that can be evacuated with a pump. Three polymer film electronic hygrometers shown in Table 6-2 and Figure 6-3 were examined: two of them, sensors “E” and “T”, were impedance sensors, and one of them, sensor “V”, was a capacitance sensor. These devices consist of a hygroscopic organic polymer deposited by means of thin or thick film processing technology, on a water-permeable substrate. The advantage of these are: 1) small size, 2) low cost, 3) fast response time (on the order of 1 to 120 sec for a 64% change in relative humidity) and 4) good accuracy over the full range, including the low end (1 to 15%), where most other devices are less accurate.

The saturated salt solution method was used for the calibration based on JIS B7920-1994 (1994). The principle of this method states that the relative humidity of air under a steady state will be determined by the kind of saturated solution used. Steady state, keeping air temperature constant in the chamber with the saturated salt solution, can provide a certain value of relative humidity. JIS B7920-1994 (1994) specifies values of the relative humidity at given temperatures provided by 9 kinds of saturated salt solutions, as shown in Table 6-3.

Four kinds of saturated salt solutions of sodium chloride ($NaCl$), potassium carbonate ($K_2CO_3 \cdot 2H_2O$), magnesium chloride ($MgCl_2 \cdot 6H_2O$) and lithium chloride ($LiCl \cdot 2H_2O$) provided steady-state environments in the desiccator with 75%RH, 43%RH, 33%RH and 11%RH respectively. JIS Z 8703 (1983) suggests conditions for test such as a combination of 20°C, 23°C or 25°C air temperature, 50% or 65% relative humidity and air pressures between 86 kPa and 106 kPa. In the climate chamber, air temperature and relative humidity were kept constant at 25.0°C/50%RH, taking the air temperature in aircraft cabins and accuracy of environmental control of HVAC system of the chamber into consideration. During the experiment, air temperature and relative humidity around the desiccator were measured.

Table 6-2. Hygrometers used for calibration

	Instrument	Method of Operation	Accuracy	
Control Instrument	Small-size Assmann Psychrometer (Hisamatsu)	Evaporative Cooling	Calibrated with normal size Assmann psychrometer	Mini-Assmann
Examined Instruments	Thermo Recorder RS-11 (ESPEC)	Impedance	±5%RH at 1 atm	Sensor “E”
	Relative Humidity Sensor (TDK)	Impedance	±3%RH	Sensor “T”
	Electronic RH Calibrator HMC20 (VAISALA)	Capacitance	±2%RH to saturated salt solutions (0-90%), ±3%RH (90-100%),	Sensor “V”

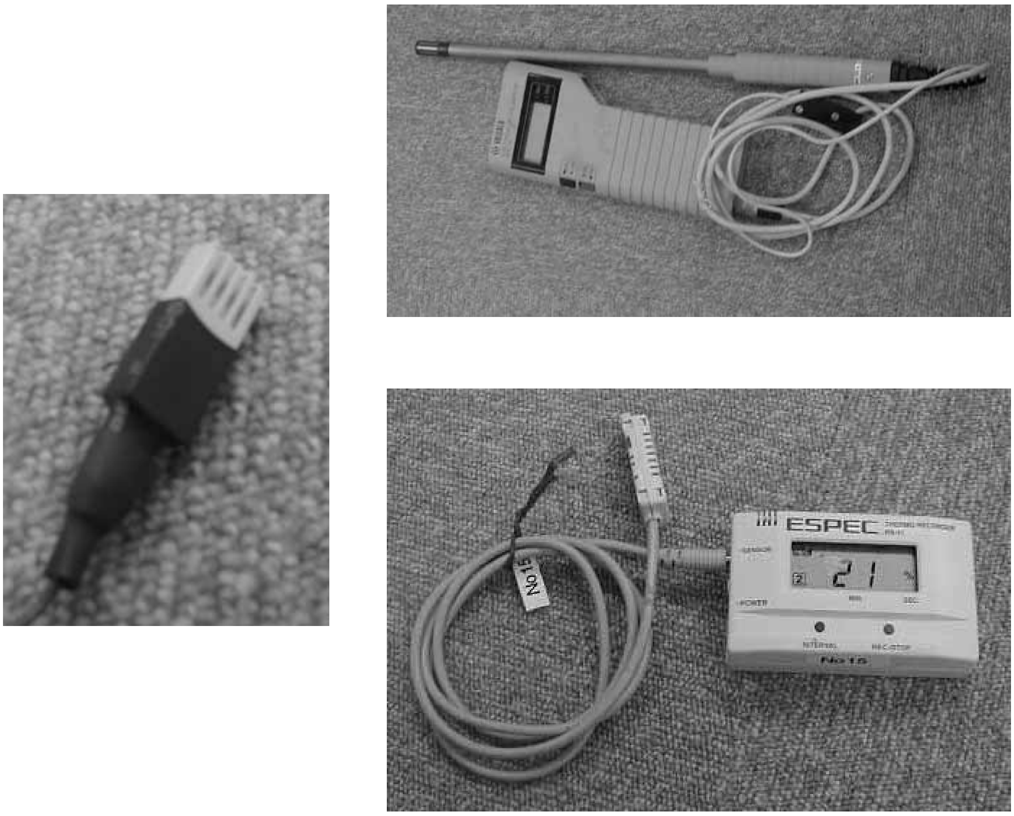


Figure 6-3. Humidity sensors

Table 6-3. Values of relative humidity at given temperatures provided by saturated salt solutions

Temperature [°C] Saturated Salt Solution	0	5	10	15	20	25	30	35	40
Potassium Sulphate (K_2SO_4)	99	98	98	98	98	97	97	97	96
Potassium Nitrate (KNO_3)*	96	96	96	95	95	94	92	91	89
Potassium Chloride (KCl)	89	88	87	86	85	84	84	83	82
Sodium Chloride ($NaCl$)	76	76	76	76	75	75	75	75	75
Sodium Bromide ($NaBr$)	65	64	62	61	59	58	56	55	53
Magnesium Nitrate ($Mg(NO_3)_2 \cdot 6H_2O$)*	60	59	57	56	54	53	51	50	48
Potassium Carbonate ($K_2CO_3 \cdot 2H_2O$)	43	43	43	43	43	43	43	-	-
Magnesium Chloride ($MgCl_2 \cdot 6H_2O$)	34	34	33	33	33	33	32	32	32
Lithium Chloride ($LiCl \cdot 2H_2O$)	11	11	11	11	11	11	11	11	11

*May possibly corrode metals

**Might be unstable at below 20°C

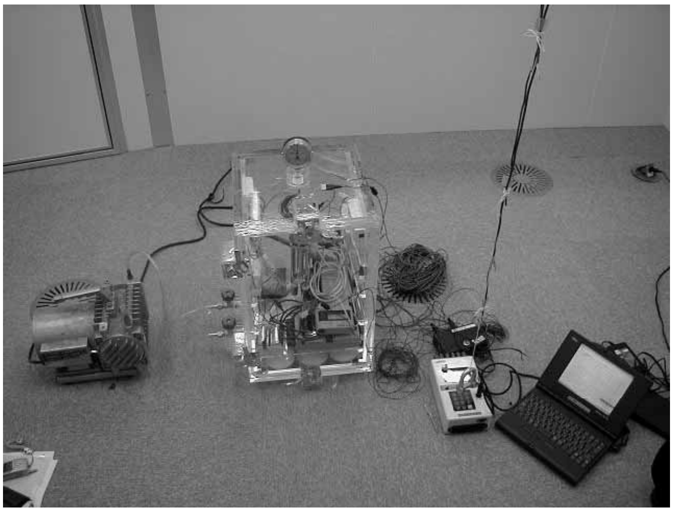


Figure 6-4. Calibration test of humidity sensors

After the environment in the desiccator had reached steady state at 25°C/50%RH, a saturated salt solution was placed inside. The air in the desiccator was mixed by a fan. When the environment in the desiccator was observed to have reached a steady state of humidity as a result of addition of the saturated salt solution, measurements at 101.3 kPa were conducted for 30 minutes. During the 30-minute measuring period, the values of relative humidity given by the sensors were recorded every 5 minutes. After measurement at 101.3 kPa, the air was evacuated from the desiccator using a pump. When the air pressure inside the desiccator was reduced to be 10 kPa lower than 101.3 kPa, the measurements were made again for 30 minutes using the same procedure. The measurements were conducted repeatedly in the way mentioned above at pressure setting 20 kPa, 30 kPa, 40 kPa and 50 kPa lower than 101.3 kPa. Figure 6-4 presents a view of the experiment.

The last 3 values recorded values shown by each sensor at each of the pressure settings were compared with those obtained with the Mini-Assmann. The results obtained at all of the pressure settings and the equations of the linear approximation at 101.3 kPa for each sensor are shown in Figure 6-5, Figure 6-6 and Figure 6-7. The approximations did not change significantly at the different air pressures for any of the three sensors. Therefore, it was concluded that polymer film electronic hygrometers were not affected by lowering of the pressure. However, measurable differences between values obtained by these sensors and the Mini-Assmann were found at low humidity. This is in agreement with that polymer film electronic hygrometers were known to provide somewhat less accurate when measuring under a low humidity condition (Research Committee for Humidity Measurement and Sensors, 1989). Consequently, it appears from these tests that, when polymer film electronic hygrometers are used for measurements at lower air pressure, air pressure calibration is not needed, but humidity calibration is, especially under a low humidity condition. It should be noted that the measurement values of the humidity sensors mentioned in Chapters 2, 3 and 4 were all corrected using the expressions obtained from these calibrations.

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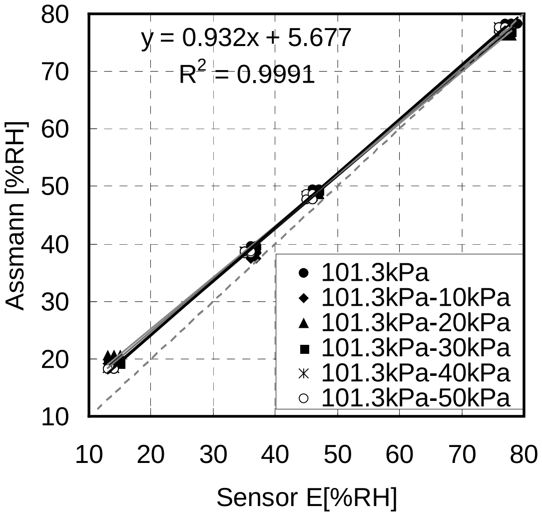

Figure 6-5. Results of calibration (Sensor E)

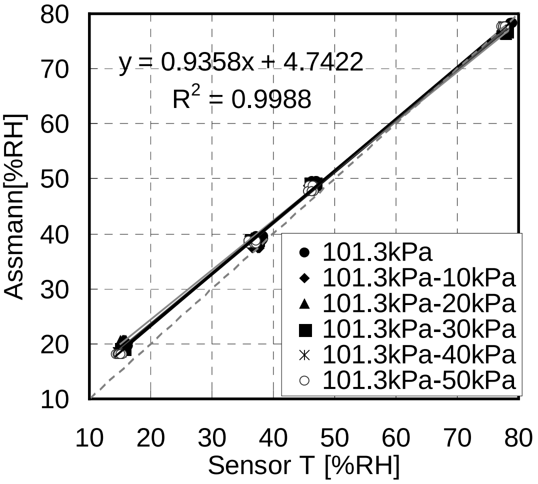

Figure 6-6. Results of calibration (Sensor T)

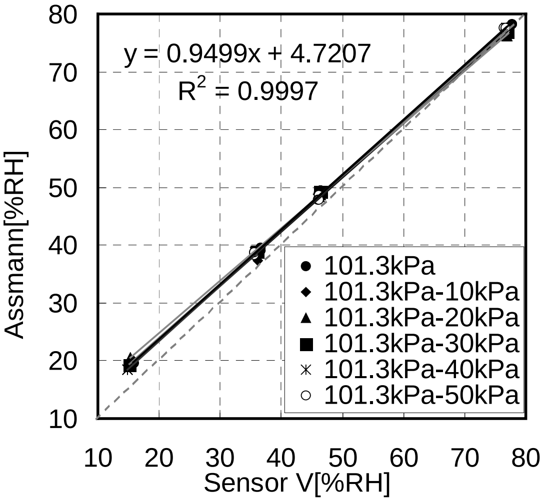

Figure 6-7. Results of calibration (Sensor V)

6.3 MEASUREMENTS OF AIR TEMPERATURE AND HUMIDITY IN AIRCRAFT CABINS

More than 30 field measurements of the thermal environment in aircraft cabins have been carried out since 1999. Thermo recorder RS-11s (ESPEC) were used for the measurements. Air temperature and relative humidity were recorded every minute during the flight at a passenger seat. Other factors, such as mean radiant temperature and air velocity, were not measured. The values shown by the sensor were calibrated, using the equations mentioned before (Figures 6-5, 6-6 and 6-7, See section 6.2).

The data shown from Figure 6-8 to Figure 6-10 are samples of measurements in an air cabin on an international flight.

Figure 6-8 gives humidity and air temperature in the cabin during a flight from Bangkok, Thailand (departed at 01:55 +0700), to Tokyo, Japan (Narita airport, arrived at 10:00 +0900 JST), on 31 July 1999. Since relative humidity varies due to change in air temperature, absolute humidity was calculated, as shown in Figure 6-9.

Figure 6-10 presents humidity and air temperature in a cabin during a flight from London, United Kingdom (Heathrow airport, departed at 12:25 +0000 GMT), to Tokyo, Japan (Narita airport, arrived at 09:01 +0900 JST), on 23 December 2002. In this measurement, skin moisture on the left hand of one passenger was recorded several times during the flight, using a portable skin moisture instrument (Matsushita Electric Industrial Co., Ltd.). This instrument measured electric capacitance of skin and indicated skin moisture in the units of %.

These results show typical change in humidity and aircraft temperature in air cabins throughout the flight. Relative humidity and absolute humidity started decreasing just after the airplanes took off. In contrast, relative humidity and the absolute humidity was increased when the airplane was landing. Relative humidity during international flights often fell below 20%RH, although air temperature was kept constant at about 25°C. In the case of Japanese domestic flights, relative humidity normally reached about 25%RH.

People were exposed to quite low humidity in aircraft cabins for a long time. Although it is difficult to utilize humidification on an airplane because of weight considerations and in order to avoid condensation, the effects of low humidity on human comfort and health clarified in this research would be applicable to the low humidity condition in aircraft cabins.

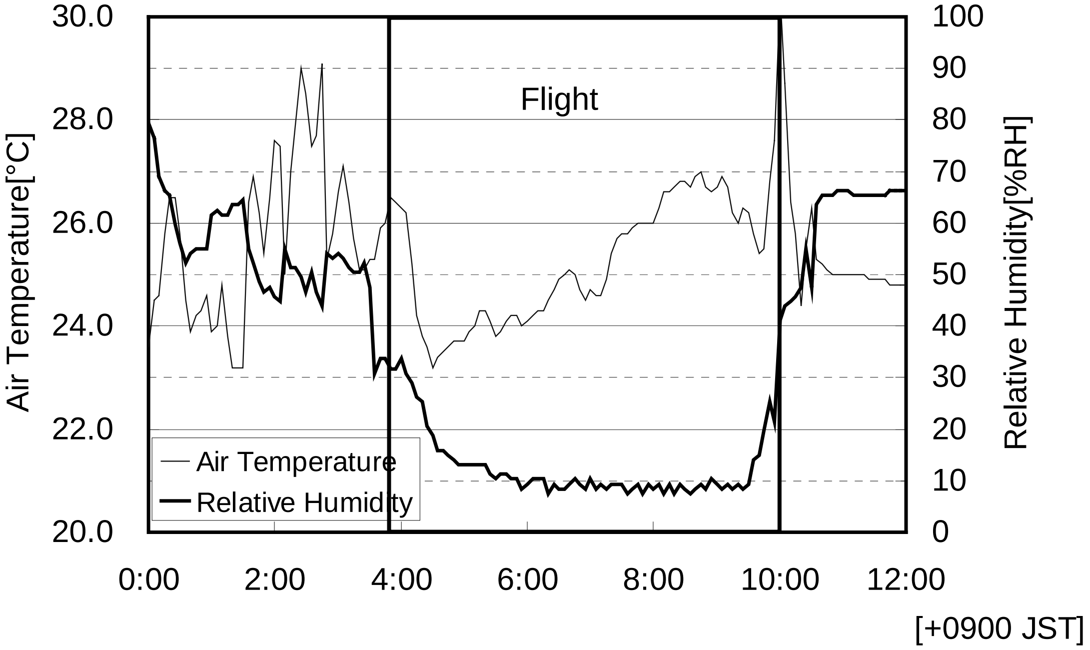

Figure 6-8. Results of measurements of air temperature and relative humidity in the aircraft cabin during the flight from Bangkok, Thailand, to Narita airport, Japan, on 31 July 1999

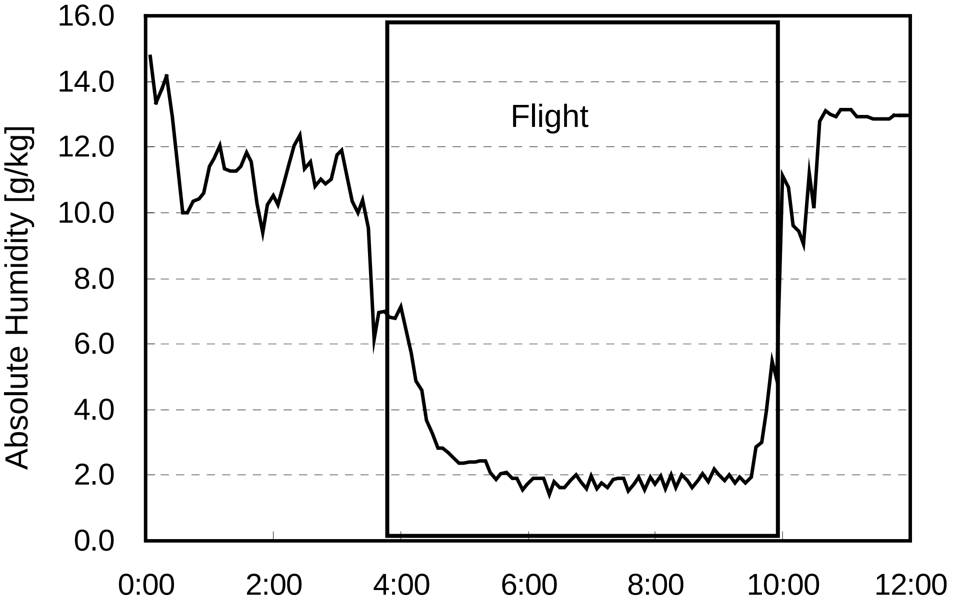

Figure 6-9. Absolute humidity in the aircraft cabin during the flight from Bangkok, Thailand, to Narita airport, Japan, on 31 July 1999

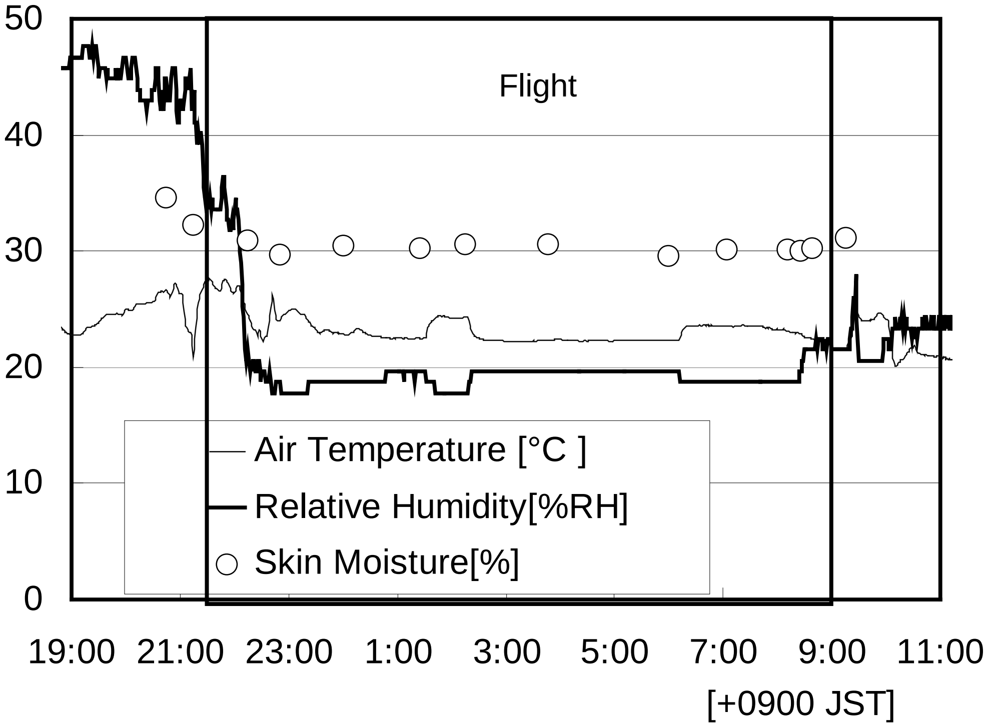

Figure 6-10. Result of measurement in the aircraft cabin during the flight from Heathrow airport, London, to Narita airport, Tokyo, on 23 December 2002.

6.4 CONCLUSION

Field measurements were conducted using a portable temperature and humidity sensor in the aircraft cabins, where people are supposed to be exposed to low humidity. Polymer film electronic hygrometers were used for measurements due to their portability. However, most humidity sensors are normally designed for usage at 101.3kPa i.e. atmospheric pressure at sea level. It is not known if humidity sensors can be used for measurement in aircraft cabins at lower pressure during flights. Thus, three kinds of polymer film electronic hygrometers were examined in a low pressure environments. An Assmann psychrometer was used for the calibration as a control instrument. According to the results of the experiments at pressures of 101.3 kPa, 91.3 kPa, 81.3 kPa, 71.3 kPa, 61.3 kPa and 51.3 kPa respectively, it was concluded that when the polymer film electronic hygrometers were used for measurements, calibration for air pressure was not necessary. However, humidity calibration is required, especially under a low humidity condition.

After more than 30 field measurements in aircraft cabins during international flights it was discovered that relative humidity of them went below 20%RH, although there was a constant air temperature of 25°C. The value in this research is that it focuses on the effects of low humidity on human comfort and health. The conclusions of this research would be important for engineers building plans, even though it is now very difficult to humidify air in aircraft cabins because of the weight of water and humidifiers brought into cabins.

CHAPTER 7

CONCLUSIVE SUMMARY

Chapter 7

CONCLUSIVE SUMMARY

In Japan, the “Law for Maintenance of Sanitation in Buildings (1970)” is applied to offices whose total floor areas exceed 3,000 m^2. It states that the relative humidity in an office space should be kept between 40 and 70%RH. The ASHRAE Standard 55-92 (1992) prescribes a lower boundary humidity of 4.5 g/kg which is equivalent to 30%RH at 20.5°C. The ASHRAE Standard 62-2001 (2001) recommends the relative humidity of 30-60%RH. The lower boundaries of these criteria are intended to limit the low humidity conditions in winter. However, improvement of recent HVAC technology has allowed engineers to use cold air distribution systems in many office buildings, creating a thermal environment with humidity lower than 40%RH during summer. Outdoor air cooling system can reduce indoor air humidity in spring and autumn. Further studies on the effects of low humidity on occupants’ comfort and performance in other seasons are needed, as well as in winter.

Many previous studies have pointed out that the effects of low humidity on thermal comfort were modest under thermally neutral conditions. However, many non-thermal problems such as eye irritation, dry skin, respiratory infection and dryness sensation occur in the spaces with low humidity. Further studies are required to clarify the non-thermal effects of humidity.

Air tightness, the reduction of the ventilation rate for saving energy and use of chemical materials cause problems of high indoor air concentration of formaldehyde or VOCs in many office buildings today. Indoor chemical pollutants irritate occupants' mucous membranes and they possibly perceive this irritation as dryness sensation caused by low humidity. Also, due to the usage of HVAC system, computers and contact lenses, the problem of dry eye syndrome has been getting more serious in office spaces recently. It is generally said that contact lens wearers might be more sensitive to low humidity than non-wearers. It is because contact lenses are used on their cornea.

The objective of this study is to investigate the effects of low humidity on human comfort and productivity.

In Chapter 1, "General Introduction", the objective of this research is given. Background information and related researches are reviewed.

In Chapter 2, "Eye Comfort of Subjects Wearing Contact Lenses at Low Humidity During the Summer Season", subjective experiments were carried out to investigate the dryness of eyes caused by the different types of contact lenses under low humidity in summer. A total of 37 subjects, 10 with soft contact lenses, 7 with hard contact lenses, 10 with glasses and 10 with naked eyes, were exposed for 3 hours in a climate chamber at Waseda University, Japan. Four humidity conditions, 30%RH, 40%RH, 50%RH and 70%RH with constant SET* were set. Subjects rated their sensations every 10 minutes during the exposure and skin moisture and break up time were recorded. The effects of humidity on the subjective general thermal comfort and skin temperature were modest under thermally neutral conditions with constant SET*. Significant differences of general humidity sensation were not found either among the subjective groups or humidity conditions. Skin moisture was high in conditions above 50%RH. Skin moisture was not associated with the general humidity sensation. The contact lens wearers reported more eye discomfort caused by the increment of eye dryness than the non-contact lens wearers. The eye dryness sensation was reported to be greater than the general dryness by all groups of subjects under all conditions. It is concluded that the subjective perception of eye dryness was much more found than the perception of humid eyes. Break up time of the hard contact lens wearers tended to be shorter than that of subjects with naked eyes though significant difference was found among the humidity conditions. The effect of wearing contact lenses on subjective eye comfort was found to be greater than that of environmental humidity.

In Chapter 3, “Thermal Comfort and Productivity under Humidity Conditions with Different Indoor Air Quality Levels in Summer and Winter”, the effects of low humidity and indoor chemical pollutants, formaldehyde, were evaluated from the results of subjective experiments. Experiments were conducted in the climate chamber at Waseda University, Japan in summer and winter with the same procedure in order to investigate the seasonal differences of human responses. A total of 6 conditions with constant SET* were set: 3 humidity conditions (30%RH, 50%RH and 70%RH) × 2 indoor air quality levels (clean condition and polluted condition). An air cleaner was installed under the clean conditions and medium density fibreboards were set in place under the polluted conditions. For each season, 18 subjects were exposed for 3 hours performing 2 kinds of simulated office work: Addition task and Text Typing. Their sensation votes, objective test results and performance were examined in both seasons. Furthermore, subjective fatigue was tested in winter. Lower concentration of formaldehyde was observed under a low humidity condition than under a high humidity condition. This was the case even when the same amount of pollution sources existed. The effects of environmental humidity and concentration of formaldehyde on subjective thermal comfort were small under thermally neutral conditions both in summer and winter. Subjects rated the acceptability of air lower at the beginning of the exposure in the environments polluted with formaldehyde. On the other hand, lower humidity caused subjects to rate air quality higher in clean air. Mucous irritation of the eyes, nose and throat due to formaldehyde was found in winter, though not in summer. Environmental humidity had greater effects on skin moisture than indoor air quality. High skin moisture was obtained in the high humidity environment. Subjects complained of having difficulty concentrating under polluted conditions. Moreover, their performance was found to be lower. Seasonal differences in subjective responses were found for eye dryness, BUT and skin moisture. Changes in eye dryness throughout the exposure time were smaller in winter. Smaller differences in skin moisture between conditions were found in winter than in summer. BUT observed in winter was shorter than in summer. Subjects' performance was affected more by environmental humidity than indoor air quality in winter; performance was found to be higher under high humidity conditions. On the other hand, correct answer speed slightly increased in a low humidity environment in summer.

In Chapter 4, "Effects of Relative Humidity and Absolute Humidity on Subjective Comfort and Productivity", the difference of the relative humidity effects and absolute humidity effects on subjective comfort and performance was shown. Sixteen subjects stayed in a climate chamber under a total of 6 conditions at constant SET*. Subjects performed simulated office work during the 3-hour exposure. Subjects reported their sensations, fatigue and subjective self-estimated performance after each task. Their skin moisture, break up time and oral mucous moisture were measured. Their performance and fatigue were examined. Subjective general dryness sensation got higher under low absolute humidity conditions. High correlation between absolute humidity and general humidity sensation, eye comfort and nose comfort were found, although the differences of vote under different conditions were small. The differences of the effects of relative humidity and absolute humidity on their acceptability of air were not shown. Increasing humidity caused higher skin moisture. However, further study is needed to clarify the difference of the relative humidity effect and absolute humidity effect. Break up time was measured at the same level under all conditions. Oral mucous moisture under the condition of [45%RH /7.0g/kg] was significantly lower than that under the other conditions. Subjective performance did not change with the difference of conditions. The type of subjective fatigue was "general fatigue". Subjects complained less at high relative humidity. As for the subjective difficulty of thinking, subject tended to report that it was difficult to think under the condition with high absolute humidity after the first task. On the other hand, at the end of the exposure, their complaints were found to be lower with the increase of relative humidity.

In Chapter 5, " Limiting Criteria for Human Exposure to Extremely Low Humidity", the results of subjective votes, medical tests of eyes, nose and skin, and performance, obtained from the experiments under extremely low humidity, were described. Subjective experiments were carried out at International Centre for Indoor Environment and Energy, Technical

University of Denmark. Thirty subjects performed simulated office work for 5 hours in climate chambers under 4 humidity conditions (5%RH, 15%RH, 25%RH and 35%RH) at 22°C of clean air. The other 30 subjects were exposed to polluted air with the same absolute humidity as 22°C/15%RH. Subjects were divided into sub groups, -normal, sensitive and contact lens-, and the differences in their responses were examined. Subjective reports of dry discomfort increased as humidity levels were reduced in the low humidity range (below 35%RH), although the level of discomfort was never more than mild even at 5%RH. Clear evidence was obtained that 5 hours of exposure to 15%RH or below is sufficient for the mucous layer of the tear film to become measurably more dry than at 25%RH or above in clean air. There was an observed increase in blink-rate at low humidity, and this is presumably one of the behavioural strategies that are adopted to reduce perceptibly negative effects of low humidity on the tear film. A large and consistent negative effect of low humidity was found on the performance of three tasks that are representative of office work, for all three of which the rate of visual data acquisition is a critical determinant of performance. The observed increase in blink rate at lower levels of relative humidity may have progressively reduced the rate of visual data acquisition, because blinking intermittently obscures vision, even if we are not fully aware of it. The reduced quality of the mucous layer of the tear film at lower levels of relative humidity may have progressively reduced visual acuity, so that visual data acquisition took longer. Eye discomfort may have acted as a distraction, although the level of discomfort reported in this study was very mild. The sub-group who reported experiencing hay fever in the spring was expected to be environmentally sensitive, and was indeed consistently affected in a negative direction by reduced humidity and raised temperature in terms of subjective sensation of dryness and skin dryness, and in subjectively reported eye and nose irritation, while the non-sensitive subjects were not. As the objective tests of physiological functions indicated an effect of low humidity and temperature for the non-sensitive sub-group but not for the sensitive sub-group, it would appear that the self-reported sensitivity of the latter group was of a psychological rather than a physiological nature. Environmental effects on subjective discomfort could only be shown for subjects not wearing contact lenses in the present experiment. Environmental effects on mucous ferning could be shown only for subjects wearing contact lenses, but as this did not seem to lead to increased discomfort, it may simply indicate that the tear film tends to evaporate more quickly from a contact lens than from an unprotected eye. Environmental effects on performance appear to have been greater for subjects not wearing contact lenses, and for sensitive subjects. These observations are compatible with a causative mechanism in which subjective discomfort causes distraction, as environmental effects on subjective discomfort were greater for both of these sub-groups, but this does not constitute proof that this was the causative mechanism.

In Chapter 6, “Humidity and Air Temperature in Aircraft Cabins”, field measurements were conducted using a portable temperature and humidity sensor in the aircraft cabins, where people are supposed to be exposed to low humidity. Polymer film electronic hygrometers were used for measurements due to their portability. However, most humidity sensors are normally designed for usage at 101.3kPa i.e. atmospheric pressure at sea level. It is not known if humidity sensors can be used for measurement in aircraft cabins at lower pressure during flights. Thus, three kinds of polymer film electronic hygrometers were examined in a low pressure environments. An Assmann psychrometer was used for the calibration as a control instrument. According to the results of the experiments at pressures of 101.3 kPa, 91.3 kPa, 81.3 kPa, 71.3 kPa, 61.3 kPa and 51.3 kPa respectively, it was concluded that when the polymer film electronic hygrometers were used for measurements, calibration for air pressure was not necessary. However, humidity calibration is required, especially under a low humidity condition. After more than 30 field measurements in aircraft cabins during international flights it was discovered that relative humidity of them went below 20%RH, although there was a constant air temperature of 25°C. The value in this research is that it focuses on the effects of low humidity on human comfort and health. The conclusions of this research would be important for engineers building plans, even though it is now very difficult to humidify air in aircraft cabins because of the weight of water and humidifiers brought into cabins.

The subjective experiments reported in this study result the negative effects of environmental humidity on human comfort and productivity was not found under the thermally neutral condition at 30%RH in the clean air in summer, spring and autumn. Some positive effects of low humidity, such as decreasing the concentration of formaldehyde in the air and the improvement of subjective indoor air acceptability, were obtained. Contact lens wears and the people who have hey fever or some other allergy might be sensitive.

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研究業績（1）

種類別	題名、	発表・発行掲載誌名、	発表・発行年月日、	連名者
論文〇	湿度環境とホルムアルデヒドが熱的快適性・知的生産性に与える影響に関する被験者実験	日本建築学会環境系論文集、第 572 号	2003 年 10 月	堤仁美 田辺新一 秋元孝之 鈴木孝佳
論文〇	夏季における低湿度環境とコンタクトレンズ装用が在室者に与える影響に関する研究	日本建築学会計画系論文集、第 564 号	2003 年 2 月	堤仁美 田辺新一 秋元孝之 鈴木孝佳
講演（海外）	Effects of Humidity and Indoor Air Chemical Pollutants on Human Comfort and Productivity	Proceedings of Healthy Buildings 2003	2003 年 12 月	H Tsutsumi Y Chen T Akimoto S Tanabe T Suzuki
	Subjective Experiments on the Effects of Relative Humidity and Humidity Ratio During Summer Season	Proceedings of Healthy Buildings 2003	2003 年 12 月	Y Chen, H Tsutsumi T Akimoto S Tanabe T Takagi
	Effects of Low Humidity on Sensation of Eye Dryness Caused by Using Different Type of Contact Lenses in Summer Season	Proceedings of Indoor Air 2002	2002 年 7 月	H Tsutsumi A Toyota T Akimoto S Tanabe T Suzuki
	Limiting Criteria for Human Exposure to Low Humidity Indoors	Proceedings of Indoor Air 2002	2002 年 7 月	DP Wyon L Fang HW Meyer J Sundell CG Weisoe N Sederberg-Olesen H Tsutsumi T Agner PO Fanger
	Effects of Low Humidity on Subjective Feeling of Dryness during the Summer Time	Proceeding of Moving Thermal Comfort Standards into the 21st Century	2001 年 4 月	H Tsutsumi A Toyota T Akimoto S Tanabe T Suzuki
	Field Investigation on the Transient Thermal Comfort in Buffer Zones from Outdoor to Indoor	Proceedings of Indoor Air '99	1999 年 8 月	J Nakano H Tsutsumi S Horikawa S Tanabe K Kimura
講演（国内）	オフィス空間における在室者の乾燥感に関する研究(その 4) 低湿度環境における相対湿度・絶対湿度の人体影響に関する夏季被験者実験概要	日本建築学会大会学術講演梗概集	2003 年 9 月	田中佑昌 堤仁美 陳宇華 加藤豊治 秋元孝之 田辺新一
	オフィス空間における在室者の乾燥感に関する研究(その 5) 相対湿度・絶対湿度が被験者の生理量及び知的生産性に与える影響	日本建築学会大会学術講演梗概集	2003 年 9 月	陳宇華 堤仁美 田中佑昌 加藤豊治 秋元孝之 田辺新一

研究業績（2）

種類別	題名、	発表・発行掲載誌名、	発表・発行年月日、	連名者
講演 （国内）	オフィス空間における在室者の乾燥感に関する研究 (その 6) 相対湿度・絶対湿度が被験者の心理量に与える影響	日本建築学会大会学術講演梗概集	2003 年 9 月	堤仁美 陳宇華 田中佑昌 加藤豊治 秋元孝之 田辺新一
	夏季における相対湿度・絶対湿度が在室者に与える影響の違いに関する被験者実験 (その 1) 実験概要及び心理量測定結果	空気調和・衛生工学会学術講演会講演論文集	2003 年 9 月	加藤豊治 堤仁美 陳宇華 田中佑昌 秋元孝之 田辺新一
	夏季における相対湿度・絶対湿度が在室者に与える影響の違いに関する被験者実験 (その 2) 生理量及び知的生産性測定結果	空気調和・衛生工学会学術講演会講演論文集	2003 年 9 月	堤仁美 加藤豊治 陳宇華 田中佑昌 秋元孝之 田辺新一
	劇場ホールにおける床吹出し空調に関する研究 (その 1）計画概要および予備実験と空間温度の経時変化	空気調和・衛生工学会学術講演会講演論文集	2003 年 9 月	山崎祐二 秋元孝之 堀川晋 李晟在 堤仁美 尚夏生
	劇場ホールにおける床吹出し空調に関する研究（その 2）熱環境評価	空気調和・衛生工学会学術講演会講演論文集	2003 年 9 月	秋元孝之 堀川晋 山崎祐二 李晟在 堤仁美 尚夏生
	劇場ホールにおける床吹出し空調に関する研究（その 3）換気性能評価	空気調和・衛生工学会学術講演会講演論文集	2003 年 9 月	李晟在 秋元孝之 堀川晋 山崎祐二 堤仁美 尚夏生
	オフィス空間における在室者の乾燥感に関する研究 (その 1) 湿度環境とホルムアルデヒドの複合影響に関する夏季被験者実験方法	日本建築学会大会学術講演梗概集	2002 年 8 月	松田順平 陳宇華 堤仁美 秋元孝之 田辺新一
	オフィス空間における在室者の乾燥感に関する研究 (その 2) 湿度環境とホルムアルデヒドが被験者の生理量及び知的生産性に与える影響	日本建築学会大会学術講演梗概集	2002 年 8 月	陳宇華 松田順平 堤仁美 秋元孝之 田辺新一
	オフィス空間における在室者の乾燥感に関する研究 (その 3) 湿度環境とホルムアルデヒドが被験者に及ぼす心理的影響	日本建築学会大会学術講演梗概集	2002 年 8 月	堤仁美 陳宇華 松田順平 秋元孝之 田辺新一
	湿度環境と室内空気質が在室者に与える複合影響に関する研究 (その 1) 冬季被験者実験概要及び結果・考察	空気調和・衛生工学会学術講演会講演論文集	2002 年 9 月	陳宇華 堤仁美 秋元孝之 田辺新一

研究業績（３）

種類別	題名、	発表・発行掲載誌名、	発表・発行年月日、	連名者
講演（国内）	湿度環境と室内空気質が在室者に与える複合影響に関する研究（その 2）夏季実験結果と冬季実験結果の比較検討	空気調和・衛生工学会学術講演会講演論文集	2002 年 9 月	堤仁美 陳宇華 秋元孝之 田辺新一
	夏季におけるコンタクトレンズ装用による低湿度の生理的影響	日本建築学会大会学術講演梗概集	2001 年 9 月	堤仁美 田辺新一 秋元孝之 鈴木孝佳
	夏季のコンタクトレンズ装着による低湿度の心理的影響に関する影響、	空気調和・衛生工学会学術講演会講演論文集	2001 年 9 月	堤仁美 豊田章巨 田辺新一 秋元孝之 鈴木孝佳
	乗り物内低湿度環境の実測と人体影響	日本建築学会大会学術講演梗概集	2000 年 9 月	堤仁美 田辺新一
	低気圧環境を含む乗り物内温湿度環境の実測	空気調和・衛生工学会学術講演会講演論文集	2000 年 9 月	堤仁美 田辺新一
	非定常温熱環境評価のための 81Node 体温調節モデルに関する研究	日本建築学会大会学術講演梗概集	1999 年 9 月	小林弘造 中野淳太 堤仁美 堀川晋 田辺新一 木村建一
	65 分割体温調節モデル計算結果と被験者実験生理量との比較	空気調和・衛生工学会学術講演会講演論文集	1998 年 8 月	堤仁美 田辺新一 堀川晋 金政秀
	半屋外を含む連続空間における温熱環境評価の研究（その 1）実測方法と冬季実測結果	日本建築学会大会学術講演梗概集	1998 年 9 月	中野淳太 金政秀 磐田靖子 堤仁美 高山真 堀川晋 大高一博 田辺新一 木村建一
	半屋外を含む連続空間における温熱環境評価の研究（その 2）三季節の環境調整手法の評価及び実測結果	日本建築学会大会学術講演梗概集	1998 年 9 月	磐田靖子 金政秀 中野淳太 堤仁美 高山真 堀川晋 大高一博 田辺新一 木村建一
	半屋外を含む連続空間における温熱環境評価の研究（その 3）65node 体温調節数値計算モデルを用いた連続空間の評価	日本建築学会大会学術講演梗概集	1998 年 9 月	金政秀 中野淳太 磐田靖子 堤仁美 高山真 堀川晋 大高一博 田辺新一 木村建一