Behavior change as a result of post-earthquake energy shortages and the consequences for indoor environment and comfort of office employees

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Ph.D. Thesis

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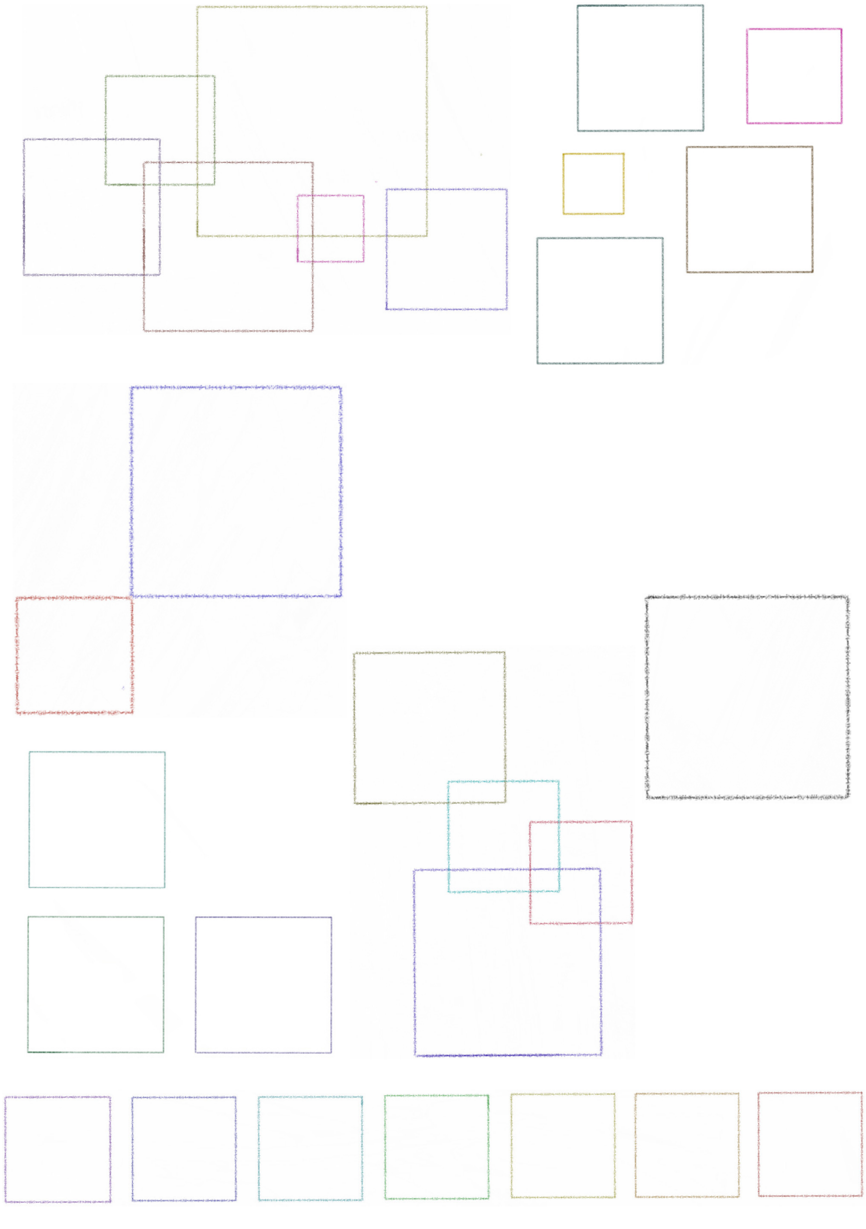

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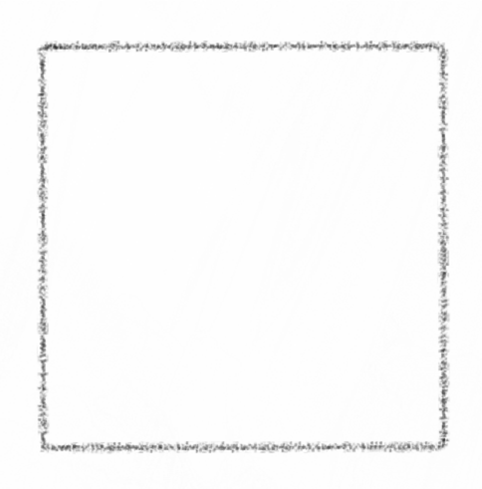

Chapter 1

General Introduction

1.1 Objectives

Since the oil crisis in the 1970s, the field of architecture has continuously engaged in efforts to protect energy resources and prevent global warming and energy conservation measures have been widely implemented in office buildings. In recent years, interest in eco-conscious architecture as well as in environmental performance evaluation schemes such as CASBEE (Comprehensive Assessment System for Built Environment Efficiency) [1] and LEED (Leadership in Energy and Environmental Design) [2] has increased all over the world. The goal of Zero Energy Buildings (ZEB) was set for the construction of all new commercial buildings by 2030 in Japan [3].

The quality of office environment is an important factor in the satisfaction level, health conditions, and the productivity of office workers, who spend long hours at their office. Since the number of Asian companies in the world has increased in recent years and global competition has intensified, domestic companies have started to pay more attention to improving productivity and providing knowledge-creation activities to get ahead [4]. The "satisfaction level of workers" has been shown to contribute to worker productivity [5], thus it has been regarded as an important indicator in indoor environmental assessment.

To establish office environments with low energy consumption but high worker satisfaction and productivity, workers should engage in more sustainable behaviors [6, 7, 8]. Behavior change is: *an extremely general term referring to any psychological intervention that changes the behavior of a person. It may involve techniques such as behavior modification or behavior therapy, other psychotherapies or treatment, or indeed any other practice that either intentionally or incidentally changes the behavior* [9]. One of the most influential applications of behavioral science on health-related behavior occurred in the 1970s with the development of the stages of change model, also known as the trans-theoretical model [10]. The study of behavior, now common to modern psychology, social science, economics, and education, in which the fields of sociology and psychology merge, is becoming an increasingly important area of research to reduce energy consumption [11]. In this study, we focus on the change of energy saving behavior of office workers caused by altered perception and acceptance of the indoor environment.

The COOL BIZ campaign [12], which started in 2005, is one good example of “behavior change" efforts applied in Japan. The campaign recommends that room temperature be set at 28 °C and that the business dress code be relaxed in offices during summer. These have been widely implemented in office buildings. After the Great East Japan Earthquake of March 2011 [13] caused the accident at the Fukushima No. 1 nuclear power plant, additional mandatory electricity saving measures were forced on the customers having large contracts in the Greater Tokyo region [14]. Due to electricity shortages, it was obligated to take various electricity conservation measures for the facilities which design the indoor environment even in the offices supporting economic development.

The main objectives of this thesis are (1) to examine the quantitative impacts of the post-earthquake behavior change caused by altered perception and acceptance of the indoor environment on the level of energy consumption and comfort in offices, and (2) to obtain quantitative knowledge that can be used to save energy in offices with better indoor environment. No conclusive studies have been conducted to date on how much the earthquake disaster changed worker behavior or subsequently affected the energy consumption and comfort levels in offices. Follow-up surveys of the changes in worker behavior caused by electricity-saving experiences are needed. The results might help create better office environments in the future, even in countries that have not experienced earthquake disasters.

1.2 Background

1.2.1 The Great East Japan Earthquake and power shortages in the Tokyo area

The Great East Japan Earthquake of 11 March 2011 caused widespread damage (Figure 1-1). It was the most powerful earthquake ever to hit Japan, with a magnitude of 9.0 on the Richter scale and a maximum intensity of 7 on the Japan Meteorological Agency (JMA) seismic scale. Even in Tokyo, a JMA seismic intensity level of 5-upper was observed. The hypocenter area extended 500km from north to south and 200km from east to west. The earthquake produced a tsunami over 10m high on the east coast of Japan. Direct earthquake damage was limited because of the strict earthquake resistance criteria implemented after the Great Hanshin Earthquake of 1995; however, the tsunami caused considerable damage to nuclear and thermal power stations and washed out all facilities, houses and buildings. The economic impact of the disaster has been estimated at 210–330 billion US dollars. The earthquake resulted in 15,843 dead and 3469 missing, as of 22 December 2011. Over 430,000 people were evacuated from the affected areas, and during the week following the earthquake, supplies of food, water and medicine were required as a result of a fuel shortage.

Figure 1-1. View after tsunami (courtesy of Junji Katsura).

Japan has 54 nuclear power reactors at 17 sites. The tsunami resulted in critical damage to the Fukushima Daiichi nuclear power station, which has six reactors (Table 1-1); four of the reactors were severely damaged, whereas the others were stopped safely. On 11 March after the earthquake at 2:46 p.m., off-site power was lost at Fukushima. At 3:25 p.m., the reactors were stopped automatically. However at 11:35 p.m., the cooling system failed because of tsunami damage to the on-site diesel generators. All motor-operated pumps, including the emergency core cooling system, became inoperable. Workers then began pouring sea water directly into the nuclear reactor but this resulted in a hydrogen explosion, which dramatically increased the amount of radioactivity released. The damage sustained by the Fukushima plant resulted in a dramatic and prolonged energy shortage in the surrounding area.

Table 1-1. Nuclear power stations at Fukushima Daiichi.

	Commissioned	Capacity	Manufacturer	Condition
Unit 1	1971	460 MW	GE	damaged
Unit 2	1974	784 MW	GE	damaged
Unit 3	1978	784 MW	Toshiba	damaged
Unit 4	1978	784 MW	Hitachi	damaged
Unit 5	1978	784 MW	Toshiba	safely stopped
Unit 6	1979	1100 MW	GE	safely stopped

Before the earthquake, TEPCO (Tokyo Electric Power Company) had a power generation capacity of 63GW, of which 14% was hydro, 59% was thermal, 27% was nuclear and less than 1% was renewable energy. As a consequence of the events of 11 March, this capacity was reduced to 38GW. TEPCO and the Ministry of Economy, Trade and Industry (METI) estimated that they could recover up to 54GW of power generation capacity by the summer. However, peak power during the summer of 2010 was about 60GW. Thus, in May the government announced an expected shortage of about 10% in the Tokyo area during peak days in summer.

A reduction of 6GW is difficult to achieve: one new nuclear power station in Japan can generate around 1,100MW (1.1GW), which is equivalent to the energy produced by 1,283,333 houses, each with a 4-kW photovoltaic (PV) system. Note that nuclear power stations may operate with up to 70% efficiency, whereas PV systems routinely achieve only 15%. Furthermore, it is difficult to install 4-kW PV systems on over one million homes immediately. Thus, measures to reduce energy use were required.

As a result, rolling blackouts were implemented during March, causing serious economic damage to industry. In May 2011, the government mandated a 15% peak-power reduction for large consumers (more than 500kW of power contracts). They also asked small commercial and residential consumers to achieve this 15% reduction [14]. Figure 1-2 shows electricity consumption on the peak day of 23 June 2010, before the earthquake occurred. It is clear that the peak is not sharp, but seems to form a plateau extending from

8 a.m. to 9 p.m. Therefore, in fact we had to save electricity not for temporal hours but most daytime hours of a day. The Japanese word for electricity savings, *setsuden*, which included the meaning of peak-power cut became very popular in Japan. Note that in April 2014 after the earthquake, amended Act on the Rational Use of Energy went into effect and it says that energy management should be carried out taking time into consideration and conscious of power supply and demand balance [15]. METI reported the results of *setsuden* during the summer of 2011 in the following October [16]. A total of 18% peak reduction was achieved in the Tokyo area during the summer season in 2011. Large consumers reduced their peak electricity consumption by 29% (27% after outdoor temperature adjustment), small and medium consumers did so by 19% (19%) and residential consumers did so by 6% (11%). Many companies mentioned the tremendous negative impacts these energy-saving measures created on their business.

Under such stringent cuts, even the setting of indoor temperature becomes critical. These types of energy cuts are becoming more common across the world as global outdoor temperatures soar and fuel poverty rises.

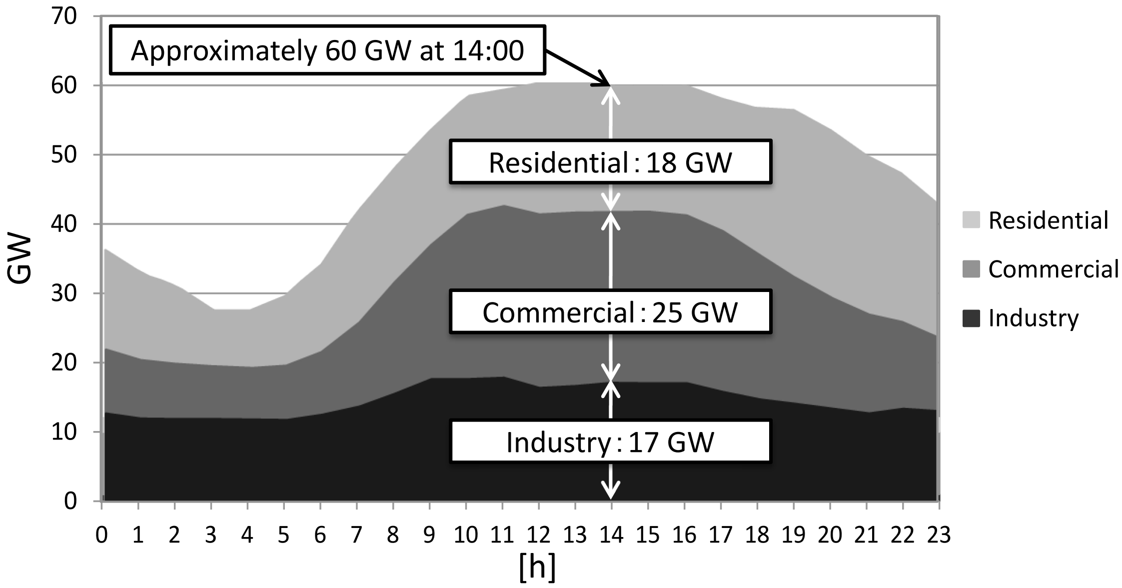

Figure 1-2. Breakdown of energy consumption on June 23, 2010 (peak day).

1.2.2 Energy-saving approaches for office buildings before and after the earthquake

Social situations influence the operation of energy saving options in domestic office buildings. The Kyoto Protocol, which came into effect in 2005, set a target to reduce CO_2 emissions by 6% between 2008 and 2012 (below 1990 levels). As a result, the government program COOL BIZ was proposed in 2005 suggesting wearing lighter clothes in offices and setting air conditioners to 28 °C in the summer [12]. Afterwards, Zero Emission Architecture was debated in the Ministerial Council on Economic Measures in 2008, leading to the establishment of the Committee on Realization and Deployment of ZEB within the METI, to start its journey toward zero-energy architecture in response to the significant increase in energy consumption by the civilian sector in Japan [17]. In addition, during the summer of 2011, there was a serious electricity shortage caused by the Great East Japan Earthquake that occurred on March 11 of the same year, and a target restriction of 15% reduction in peak-power usage was issued [9] for large customers within the TEPCO jurisdiction. After 2012, there were no more electricity saving requests with numerical targets within the TEPCO jurisdiction. However voluntary electricity savings were requested in most areas of Japan. In Japan, the "realization of new buildings as a whole by 2030" [3] is defined as the goal for ZEB conversion. In order to achieve the goal, it is important to reduce energy consumption not only at the design stage, but also at the operation stage after construction by workers' efforts and "behavior change" measures. With increasing interest in environmental performance evaluation systems such as CASBEE [1] and LEED [2], energy conservation measures in offices have been widely implemented. Interest in eco-conscious architecture is also increasing not only in Japan but also all over the world.

1.2.3 Towards a focus on worker-centered concerns

People spend about 80–90% of their time indoors, and scientific studies have determined various comfort and health effects associated with the characteristics of buildings, ventilation and air conditioning systems, and the indoor environment [18]. Therefore, the aspects of not only energy savings, but also "workers," are critical in evaluating office space in buildings. Recently, worker's well-being has also been drawing attention [19, 20, 21]. There has actually been a shift in the direction of scientific research from a focus on the energy use and environmental performance of buildings towards a focus on human-centered concerns (in this research: worker-centered concerns), as outlined in the paper by Steemers [22]. What is more, in the past, most thermal comfort questions about buildings and building designs were addressed by applying instrumental observations or simulations of indoor climate parameters to predictive models of human thermal comfort. However, in the last few decades, field studies involving large samples of actual occupants in real buildings have highlighted the shortcomings of such models [23].

Indoor environmental quality affects worker comfort, satisfaction, and productivity. Self-estimated productivity is correlated with actual productivity and worker satisfaction, an important attribute of worker productivity, is a significant indicator of the indoor work environment [5]. To investigate the relationship between worker satisfaction and the indoor environment, many studies have conducted surveys based on the Subjective Assessment of Workplace Productivity (SAP) 2013 [24]. The SAP is the modified system in Japan based on a web-based CBE (Center for the Built Environment) occupant satisfaction survey of evaluations of indoor environmental quality and building features [25]. Based on that survey, our study measured occupant satisfaction in the following categories: thermal comfort, air quality, lighting, acoustic quality, office layout, and ICT environment; as well as the overall satisfaction with the workspace and building. The structure: ‘How satisfied are you with…’ was used for questions about the satisfaction level. The satisfaction questions were answered using a 7-point scale ranging from ‘very satisfied’ (+3) to ‘very dissatisfied’ (−3) with a neutral midpoint (0). In case respondents vote ‘dissatisfied’ to a given question, we proceeded to other questions aimed at diagnosing the source of dissatisfaction. We also collected background information about the survey participants including gender, age group, type of work performed, awareness of energy savings, and the effect of environment on their work performance. Sugiura et al. [26] showed that subjective evaluations can give the same results as objective evaluations unless ambiguous and incomprehensible questions are asked.

In this research, we mainly focused on thermal comfort, air quality, and lighting; the aspects of the environment over which the environmental control systems have a significant effect, and how these aspects affect comfort, satisfaction, and productivity of occupants. All of these aspects were subjectively assessed by the respondents.

1.2.4 Standards for indoor environment

Indoor environmental standards as indicators of the operation of the current office spaces in Japan are defined by the "Law for Maintenance of Sanitation in Buildings (1970)" [27], Industrial Safety and Health Act [28], JIS (Japanese Industrial Standard) standard [29].

The "Law for Maintenance of Sanitation in Buildings (1970)" is applied to specially designed buildings with an area of 3,000 m^2 or more, and that are used for specific purposes such as offices, entertainment facilities, assembly halls, libraries, museums, and stores. For offices operated by workers (area more than 3,000 m^2), regulations for office hygiene standards are stipulated by the Industrial Safety and Health Act. For other offices whose area is less than 3,000 m^2, regulations for Ordinance on Health Standards in Offices are stipulated by the Industrial Safety and Health Act. Indoor illumination criteria are determined by the JIS standards. An amendment to the JIS standard was issued after the Great East Japan Earthquake stating that an illuminance range of 500–1,000 lux would be added to the previously recommended illuminance level of 750 lux in the offices [30].

Table 1-2 shows the Guideline for indoor climate stated in the Law for Maintenance of Sanitation in Buildings. Table 1-3 shows the Guideline for indoor climate stated in the Industrial Safety and Health Act.

Table 1-2. 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 1-3. Guideline for indoor climate stated in the Industrial Safety and Health Act.

Amount of Suspended Particles	Not more than 0.15 milligrams per cubic meter of air (1 atmospheric pressure, 25°C)
Content of Carbon Monoxide (CO)	Not more than 10 parts per million (<10 ppm) Not more than 20 ppm when outside air is polluted and difficult to introduce fresh air
Content of Carbon Dioxide (CO_2)	Not more than 1,000 parts per million (<1,000 ppm)
Air Flow	Not more than 0.5 meters per second
Temperature and Relative Humidity	Not less than 17 degrees and not more than 28 degrees Not less than 40 percent and not more than 70 percent

There have been many active discussions regarding the criteria for indoor air quality. Pettenkofer [31] proposed to use CO_2, the main human inorganic bioeffluent, as a marker of the quality of air polluted by human bioeffluents, assuming that other indoor pollutants not related to humans are removed or avoided. Ever since he proposed a CO_2 concentration of 1,000 ppm as the level above which indoor air quality would be unacceptable (700 ppm was proposed for bedrooms), CO_2 has been used as a proxy for indoor air quality. Pure CO_2 at the levels normally occurring indoors was not considered by Pettenkofer [32] to pose risks to humans. Recent studies by Zhang et al. [33, 34] confirmed that pure CO_2 below 5,000 ppm does not produce sensory discomfort, self-reported acute health symptoms, or reduced performance on cognitive tasks. However, a few other experiments suggest, on the contrary, that CO_2 at levels as low as 1,000–2,500 ppm can reduce the ability to make decisions [35, 36], and that CO_2 at 4,000 ppm could decrease perceived air quality, causing people to report some acute health symptoms and reduction of performance for proof-reading (Kajtar and Herczeg, [37]). In Japan, there are discussions whether the CO_2 concentration of 1,000 ppm is a good criterion to follow in all cases. Even globally, the outdoor CO_2 concentrations increase based on the time of day, seasons, and location [38].

1.3 Literature review

1.3.1 Environmental effect on worker comfort and productivity

(1) Thermal comfort and Indoor Air Quality

As suggested by many studies summarized in this section, if the worker satisfaction with the indoor work environment decreases, then the productivity of the workers will decrease. Parsons [39] defined productivity as the extent to which activities result in the achievement of system goals, and connected it to office economy. Seppänen and Fisk [40] studied the relationship between air temperature and productivity in central and northern Europe, and observed the maximum work performance at 21.6 °C. Tanabe et al. [41] calculated that raising the indoor air temperature by 1.0 °C (from 25.0 to 26.0 °C) would lead to a reduction in performance of 1.9% using a regression model of the indoor air temperature and call response rate in Japan. This was almost the same as the model presented by Seppänen et al. [42]. A survey of indoor environment and the number of responses in a large-scale call center showed that the number of call responses decreased by 0.15/h each time the room temperature rose by 1 °C [43]. In addition, Tanabe's group reported that the cost of maintaining performance, namely avoiding fatigue, is important in evaluating and predicting productivity [44]. In other words, the thermal environment affects physiological and psychological processes, which may in turn affect the performance and overall productivity. In contrast, de Dear and Brager [45] suggest, with their adaptive comfort theory, that optimum productivity can be attained over a wider range of indoor temperatures.

Haneda et al. [46] performed an experiment at the operative temperature of 25.5 and 28.5 °C, and the ventilation rate of 11 and 90 $m^3/(h \cdot p)$. The percentage of workers dissatisfied with air quality was higher at higher temperatures and lower ventilation rates. The study also evaluated the relationships between task performance, satisfaction with the indoor environment, and the level of fatigue. On the other hand, Maeda et al. [47] performed an experiment at different values of ventilation rate: 318 and 20 $m^3/(h \cdot p)$ and showed that the number of incorrect answers in a number memorization test increased when the ventilation rate is low and the CO_2 concentration is high, however the subjects could not perceive the differences in air quality or in odor intensity at different ventilation rates. Melikov et al. [48] conducted subjective experiments by varying the indoor temperature, air pollution level, and airflow velocity at the relative humidity of 30%. Indoor temperature, degree of air pollution, and air velocity did not affect the odor intensity, but the presence of air flow lowered the satisfaction level due to the high room temperature and high degree of contamination. Fang et al. [49] conducted a subjective experiment and showed that the air freshness was not affected by the ventilation rate and that it improved when indoor air enthalpy decreased. However, neither the enthalpy of the indoor air nor the ventilation rate affected the odor intensity. The acceptability of air quality improved at a low level of indoor air enthalpy, and the instantaneous air quality acceptance decreased at a low ventilation rate. Regarding indoor air quality, Wargocki et al. [50] documented that removing a pollution source or increasing the ventilation rate will improve perceived air quality, reduce the intensity of several Sick Building Syndrome (SBS) symptoms and improve the productivity of office workers. The quantitative relationship was 1.1 % change in performance of simulated office work per 10% dissatisfied toward indoor air quality, in the range 25-70% dissatisfied,

(2) Lighting environment

Sato et al. [51] showed that using daylight illumination improved self-estimated productivity and workers' satisfaction with the lighting environment. Nishikawa et al. [52] showed that the satisfaction level increased when the task illumination was controllable by the workers. In addition, the satisfaction with the light environment was correlated positively with the work performance. Shiratori et al. [53] evaluated the environmental improvements of a new office building from 2005 to 2006. As a result, despite lowering the overall illuminance, the percentage of dissatisfied people decreased by introducing task lights. However, the rate of dissatisfaction with the thermal environment deteriorated by the increase in the preset room temperature.

1.3.2 Studies of the indoor environmental state in offices under normal operation

(1) Studies in Japan

Hayashi et al. [54] and Mitamura et al. [55] conducted field surveys of six offices from 2003 to 2004. The average air temperature during summer was 24-27 °C, indicating that the characteristics of the thermal environment differed within the office. Gotoh et al. [56] conducted an additional survey on the thermal adaptability of workers in those offices. The results showed that the comfortable range in the summer varied depending on the ease of clothing adjustment, operability of the thermal environment by people in the room, and the personal indoor temperature preferences. Moreover, Inomata et al. [57, 58] showed that self-reported comfortable temperature was about 26 °C, which is nearly equal to the comfortable air temperature guidance by Predicted Mean Vote (PMV) considering the influence of the amount of clothing and metabolic rate.

Haneda et al. [59] showed that the rate of thermal dissatisfaction exceeded 70% at 28 °C in an office where COOL BIZ was implemented in 2007. The air temperature was high at the interior side where the heat generation unit of the OA (Office Automation) equipment was located and low at the perimeter side where the FCU (Fan Coil Unit) was installed. As a result, a non-uniform distribution of the air temperature and occasional indoor air temperature levels of 30 °C were observed.

Yamamoto et al. [60] revealed the transition of design temperature conditions in Japan by a literature survey. Design temperature conditions in Japan were determined with reference to the standards in the United States at the time of the introduction of air conditioning equipment in the 1950s. Up to the present age, the set temperature during the summer under normal conditions has been 26 to 27 °C, but since the oil crisis in the 1970s, the recommended upper limit for energy conservation is 28 °C . Kawaguchi et al. [61] compared the indoor air temperature in an actual office with the standard air conditioner temperature setting. The air conditioning temperature standards in the target office had been changed according to the social background and preferences of workers. In 1990 and 1997, the standard set temperature was raised, but in 2007 it was lowered again in contradiction to the previous energy saving standards.

In a study of indoor air quality, the indoor CO_2 concentrations in large-scale buildings in Tokyo were investigated from 1971 to 2009 [62]. The violation rate (> 1,000 ppm) was 15–20% in the 1970s, but increased to 32% in 2009. On the other hand, the average office CO_2 concentrations measured from 2011 to 2013 by authors reported in chapter 4, was about 710 ppm, which was much lower than the limit.

For the lighting environment, Miura et al. [63] conducted long-term measurements of the office indoor environment from 1989 to 1992, and in the summer and winter of 1998. Although the average desk top illuminance value was distributed over the range of 800-1,700 lux, the average declaration of a bright sensation was almost the same. Narishima et al. [64] extracted 484 data points on the illuminance of actual offices from 28 studies about the subjective evaluation of the lighting environment. Before the 1980s, the actual illuminance level of Japanese offices was higher than the recommended JIS level (750 lux), but later it settled to less than the recommended JIS standard.

(2) Studies in other countries

In contrast to the Japanese offices, offices in other countries have lower indoor air temperatures, higher ventilation rates, and lower illuminance.

G. E. Schiller et al. [65] conducted an actual survey in 10 office buildings in San Francisco (USA) in the summer and winter of 1988, and compared it with the ASHRAE Standard 55-81 [66]. According to the results, the thermoneutral temperature was 22.6 °C in summer and 22.0 °C in winter, but the preferred temperature was 0.3 to 0.6 °C lower both in summer and winter.

De Dear et al. [67] carried out an actual measurement of 12 office buildings in Townsville (Australia) in 1994, using the same method as that of Schiller et al. According to the survey results, the average indoor temperature was 23.3 °C in the dry season and 23.6 °C in the rainy season. The thermoneutral temperature according to the ASHRAE's seven-step scale was 24.4 °C for both rainy and dry seasons, but the preferred indoor temperature was 23.5 °C. In addition, the acceptability of the thermal environment was 90% at 23.5 °C, but 80% at 22.5 and 24.5 °C.

According to a survey by Sekhar et al. [68], office room temperatures in Singapore were between 20 to 23 °C. De Dear et al. [69] measured 12 air-conditioned office buildings in Singapore in 1986 and reported that the average room temperature in the office building was 22.9 °C, the average operating temperature was 23.5 °C, and the average value of the relative humidity was 56%.

Mui et al. [70] proposed mathematical expressions to evaluate the thermal comfort conditions using the optimum neutral temperature from a field survey of 422 occupants' responses in an air-conditioned office building in summer and winter in Hong Kong in 2005. The office room temperature was in the range of 23 (±1.5) °C. The thermoneutral temperatures in the subtropical office were 23.6 °C in the summer and 21.4 °C in the winter, but a slightly cool environment, corresponding to 22.6 °C in summer and 20.5 °C in the winter, was required to satisfy most of the occupants in the office.

Contemporary ventilation standards are defined by several organizations (e.g., ASHRAE, 2013 [71]; EN, 2007 [72]). These standards limit CO_2 concentrations to 1,000 ppm, the same as in Japan. Bluyssen et al. [73] presented the results of an audit in 56 office buildings in nine European countries during the heating season of 1993–1994. The results showed that the average indoor CO_2 level was 673 ppm. No evidence of geographic differences could be found along north-south or east-west axes, or between maritime and more continental settings.

For the lighting environment, 500 lux is recommended for activities such as normal office work by ISO, 2002 [74] as well as EN, 2014 [75]. Nicol and Wilson [76] reported that the mean measured desktop illuminance level inside 26 office buildings in five European countries was 548 lux.

1.3.3 Studies on behavior change

Besides technical measures, occupant behavior is one of the most important determinants of energy conservation in houses and office buildings. Recently, various initiatives have been launched in the architectural field to evoke behavioral changes, such as environmental education, energy saving competitions, incentives, benchmarks, and energy conservation advice by experts.

Ouyang and Hokao [6] evaluated the electricity use by “improved households” and showed that improving occupant behavior in domestic life through energy-saving education can save 10% (on average) of household electricity use. Mulville et al. [7] demonstrated that in the commercial office setting, behavioral change can save a significant amount of energy by utilizing feedback, goal setting, or using information. On average, the study found that savings of 18.8% were possible, with 28% for the comparative feedback group, 18% for the basic feedback group, and 10% for the individual and basic feedback group. Omar and Magali [8] investigated the effectiveness of non-price information strategies to motivate the conservation behavior based on a panel of 3.4 million hourly appliance-level kWh observations for 118 residences. They reported that environmental and health-based information treatments –messages about the amount of pollutants, childhood asthma, and cancer– increased energy savings by 8%, and were particularly effective for families with children, who achieved up to 19% of energy savings.

1.4 Structure of the present research

The contents and structure of this thesis are shown in Figure 1-3 and Figure 1-4, respectively. Each chapter belongs to the phases of the relationships between “indoor environment and comfort”, “behavior change and change in indoor environment” or “change in indoor environment and building equipment”.

In Chapter 1, the objectives of the research are stated and the relevant previous researches are summarized.

In Chapter 2, the field and questionnaire surveys conducted in five buildings under mandatory electricity saving to investigate the energy efficient electricity-saving measures that do not decrease the comfort and productivity of the occupants are discussed. In five out of seven floors in each building, the temperature, illumination, and ventilation rate settings were changed with a total of 22 environmental conditions surveyed. Further, we investigated three additional office buildings, only asking the occupants about their views on electricity saving without taking any physical measurements or carrying out satisfaction surveys. A total of 2046 questionnaires from employees were collected. A strong correlation was found between dissatisfaction and room temperature; in particular, thermal satisfaction decreased steeply at temperatures over 27°C. On the other hand, employees widely accepted the suggested decrease in illumination from 650 to 200 lux; the lowered illumination reduced energy consumption to a greater degree than the turning up of the temperature in the air conditioning system. A gradual increase in dissatisfaction was found with an increase in the concentration of carbon dioxide (CO_2) in the range of 600–1200 ppm. The perception of the indoor air quality was also affected by the thermal environment. According to the questionnaire results on electricity saving, increased awareness regarding electricity saving was observed, with more than 90% of the employees willing to implement electricity-saving measures. However, 72% of the respondents expressed some degree of inconvenience caused by the measures. Accordingly, self-estimated productivity in the summer of 2011 was 6.6% lower than the previous year.

In Chapter 3, a web-based questionnaire that was conducted for 1200 employees in Tokyo, Nagoya, and Osaka to investigate whether different earthquake and electricity-saving experiences affected their awareness, electricity-saving measures, and comfort is discussed. Similar electricity-saving measures were implemented in three areas; especially, the measure of “increasing the set temperature point” was practiced by more than 60% of the respondents. However, this was also considered the most annoying measure. Lowering the illumination caused lower dissatisfaction than turning up the set point of the air conditioning as mentioned in Chapter 2. However, employees’ awareness towards saving electricity was different; employees in Tokyo who had directly experienced the earthquake were more positive towards saving electricity. Moreover, the more positive about saving electricity the workers were, the less thermal dissatisfaction rate they reported in all the three areas, although the indoor environments of the offices were assumed to be almost the same. The satisfaction of the employees towards the office environment was affected to a larger degree by their feelings than the indoor environment or their gender and age. It was observed that the post-earthquake experiences of the mandatory electricity saving had changed the awareness of the workers more in Tokyo than in the other regions.

Chapter 4 reveals the extent to which employees' behaviors had changed regarding energy consumption and productivity since the impact of the earthquake disaster. The authors conducted continuous field and questionnaire surveys in seven electricity-saving office buildings in the summers of 2011–2013. Additionally, the past research data of our laboratory were collated, and in total, 60 cases with 3692 questionnaires were analyzed. The internal heat load decreased after the earthquake in several ways; the average desk level illuminance decreased substantially to 391 lux from the typical 750 lux setting and energy-efficient office automation (OA) equipment was introduced and implemented. Additionally, excessive indoor air temperatures were avoided, thereby increasing the number of offices with 27°C indoor temperature by about 15%. The CO_2 concentration did not change; the average was about 710 ppm. The awareness of the workers regarding saving electricity hardly diminished after peaking in 2011; about 90% of the workers felt positive about saving electricity. Measures that are not very stressful, such as wearing light clothing and turning off lighting during lunch, were continuously practiced. This resulted in the 2011 pre-earthquake self-estimated productivity change rate of -6.6% to rise to about 0% in the post-earthquake years. Electricity saving was implemented in a proper manner such that it did not negatively affect the comfort of the workers. This behavior change was established in offices after the earthquake. In addition, it was shown that the satisfaction of the workers depended on the indoor air quality and thermal environment more than the other environmental factors such as lighting, sound, space, and usability of ICT (Information and Communication Technology) facilities. However, the post-earthquake satisfactions in the areas of indoor air quality and thermal environment were still poor; hence, effective improvement measures were needed.

Chapter 5 presents the problems caused by the post-earthquake behavioral change in the workers that resulted in an internal heat load decrease as explained in Chapter 4. The internal heat load and the operation of a multi-split type air-conditioning system of an indoor-air conditioner (VRV: Variable Refrigerant Volume) and a DOAS (Dedicated Outdoor Air System) which consists of two parallel systems: a dedicated system for delivering outdoor air ventilation and a parallel system to handle the indoor loads, were investigated in an office drawing a low heat load. Two indoor air temperature settings, 26°C and 27°C, were chosen to investigate the changes in the operation of the DOAS. Field and questionnaire surveys and an energy consumption analysis were also performed. The results showed that the primary energy consumption of the OA equipment was approximately 95 MJ/m^2 per year and 235 MJ/m^2 per year for the lighting. The average desk lighting illuminance was 520 lux. These values are relatively small compared to the officially published average energy consumption value of 369 MJ/m^2 for OA and 363 MJ/m^2 for lighting. The total cooling capacity settings of the VRV and the DOAS were 158 W/m^2, which is relatively small considering the common cooling capacity of 200 W/m^2. However, the average load factor for both the VRV and the DOAS under normal operation was small; below 30%. The actual indoor air temperature was controlled as desired. The relaxation of the air-conditioning setting temperature and the improvement in the control of the air conditioning operation reduced the energy consumption. However, it was confirmed that the operational balance of the VRV and the DOAS collapsed due to stoppage or excessive operation of the DOAS. Furthermore, it was found that the humidity setting of the system was the main cause for the change in operation. The operational method of the DOAS had a large influence on the total electric energy consumption in offices practicing internal load reduction. Thus, introducing the air-conditioning systems having appropriate capacity and a comprehensive energy saving operation method, rather than a partial optimization of each device, would be beneficial in terms of total energy saving.

Chapter 6 attempts to identify the under-researched problems of perceived air quality stated in Chapter 2. Since the focus on human bioeffluents and their contribution to indoor air quality has increased again recently, an experiment to investigate the difference between the effects of exhaled and dermally-emitted bioeffluents on perceived air quality

(PAQ) was conducted as the first attempt by chemical analysis and sensory evaluation of humans bioeffluents. Conditions in which exhaled and dermally emitted bioeffluents could be sampled separately or together (whole-body emission) were created. Lightly-dressed subjects sat in a ventilated climate chamber, located at the International Centre for Indoor Environment and Energy, Technical University of Denmark, with very low surface emissions. They exhaled the air through a mask to another, identical (twin) chamber or without a mask to the chamber in which they were sitting; the outdoor air supply rate was the same in both chambers. The carbon dioxide concentration in the chambers with exhaled air was 2,000 ppm. Chamber temperatures were 23°C or 28°C and ozone was present or absent in the supply airflow. When dermally-emitted bioeffluents were present, the PAQ was less acceptable and the odour intensity was higher than when only exhaled bioeffluents were present. The presence or absence of exhaled bioeffluents in the unoccupied chamber made no significant difference to the PAQ. At 28°C and with ozone present, the odor intensity increased and the PAQ was less acceptable in the chambers with whole-body bioeffluents. The concentrations of nonanal, decanal, geranylacetone and 6-MHO were higher when dermally-emitted bioeffluents were present and they increased further when ozone was present; the concentration of squalene then decreased and increased again at 28°C. Dermally-emitted bioeffluents seem to play a major role in the sensory nuisance experienced when occupied volumes are inadequately ventilated.

In Chapter 7, results of the above chapters were summarized and discussed.

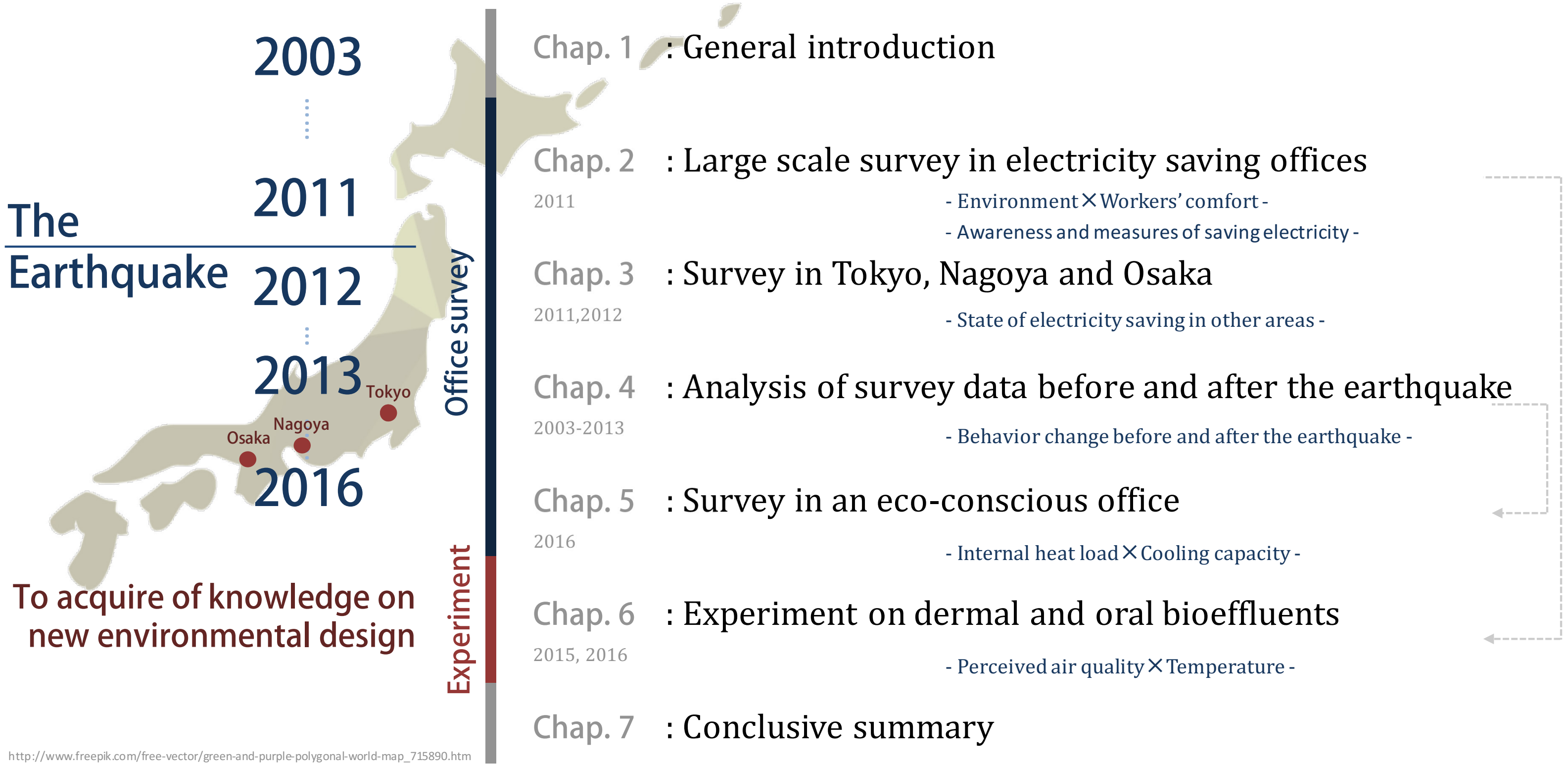

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Figure 1-3. Contents of the thesis.

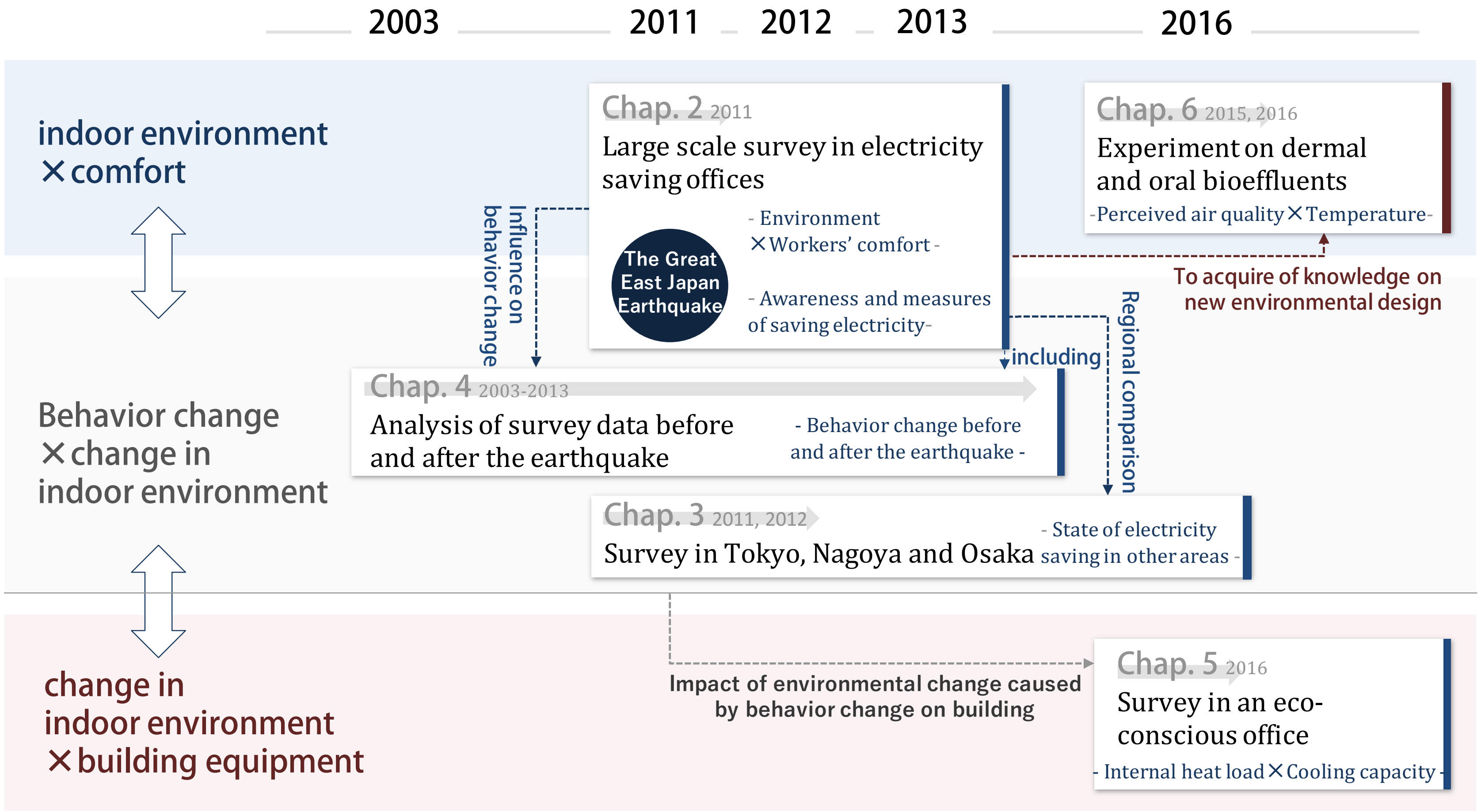

Figure 1-4. Structure of the thesis.

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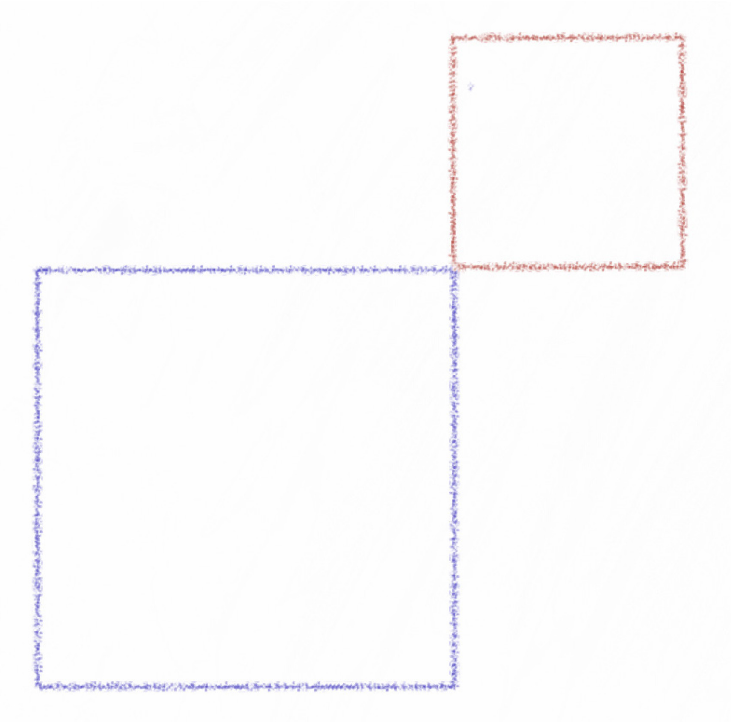
Outline

Chapter 2

Experimental field surveys in Tokyo offices to investigate mandatory electricity-saving effect on thermal comfort and productivity



2.1 Objective and general approach

The Great East Japan Earthquake of March 11, 2011 caused widespread damage, resulting in significant electricity shortages. For this reason, the Japanese government directed large-lot electricity users to cut their energy consumption by 15% from their peak-period demand of the previous summer in 2011 [1, 2]. Most companies in Tokyo opted to limit electricity consumption by reducing their use of lights and air conditioning systems in their offices. However, excessive electricity-saving measures forced office workers to bear discomfort and could lead to productivity declines [3, 4].

Little is known of employee comfort and productivity under special conditions, specifically those that prevail after large disasters.

The purpose of this study was to find efficient strategies for electricity-saving that do not affect workers' comfort and productivity by examining different strategies.

Field surveys to measure environmental variables and energy consumption, and questionnaire surveys to investigate employee comfort and productivity were conducted in five office buildings in Tokyo during the 2011 summer season (after the earthquake), when mandatory electricity-saving measures were being implemented. In five out of seven floors, the temperature, illumination, and ventilation rate settings were Intentionally hanged with a total of 22 environmental conditions surveyed.

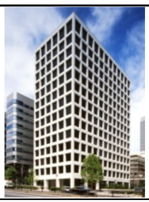
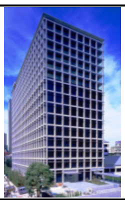
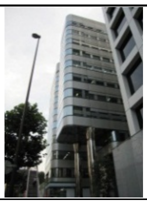
2.2 Methodologies

In the summer of 2011, just after the Great East Japan Earthquake, field surveys to investigate the effects of electricity-saving were conducted in five office buildings in Tokyo. This study varied indoor environmental parameters (luminance, room temperature, and outdoor air supply rate) in target floors to investigate these parameters' effects on comfort and productivity.

2.2.1 Investigated offices

Field studies investigating the effects of *setsuden* were conducted in five office buildings in Tokyo during the summer season. Table 2-1 lists the characteristics of these buildings. Given that the studies were carried out during the hot and humid summer season (Jul. 19–Aug. 12, 2011), all selected buildings had functioning air conditioning systems. In three of the five buildings, the temperature, illumination and ventilation rate were changed. Three additional office buildings were also investigated, only asking the occupants their overall feelings about *setsuden* without taking any physical measurements or carrying out satisfaction assessments. The indoor environment, productivity and energy conservation steps were recorded. All five buildings achieved more than 15% energy reduction during summer.

Table 2-1. Outline of five buildings.

Name	A	B	C	D	E
Photo					
Completion year	2007	2007	1989	1988	1993
Number of floors	14F*+2BF*	15F+2BF	9F+1BF	10F+1BF	18F+2BF
Area/Floor	910m^2	2,722m^2	5,080m^2	1,350m^2	3,202m^2
Total Floor Area	15,163m^2	33,517m^2	29,468m^2	11,187m^2	43,320m^2
Target Floors	8F, 10F	2F, 9F	4F	3F	7F

*F: Floor, **BF: Basement floor

2.2.2 Environmental settings and physical measurements

Table 2-2 lists the settings for illuminance, room temperature and outside air intake; these parameters were varied to investigate their effects on comfort and productivity. Each case lasted two or three days. Office plan and measurement points of each floor are shown in the supplementary material S1. All cases were operated by AC mode and outside air was supplied by a mechanical system. Physical conditions were recorded over long time and short time periods for detailed measurements. Table 2-3 shows the variables measured over long time periods. Air temperature and relative humidity were recorded at 2–12 points on each floor, depending on the size of each floor. Average values during office hours, namely 9:00 a.m. to 5:00 p.m., were calculated and used for further analyses. Detailed measurements of vertical temperature distribution, air velocity, noise level, illuminance, occupancy rate and occupants' behavior were also conducted on the representative day under four sets of conditions in five floors of Buildings A, B and C (Table 2-4). For the other two buildings, surveys in the condition prevailing at that time were only conducted. That is to say, the surveys were conducted under 22 environmental conditions. Table 2-5 lists the numbers of employees on each floor and the total numbers of responses collected; the percentage of occupants participating was high. Data were collected for a total of 22 conditions.

Table 2-2. Settings of illuminance, room temperature, and outside air intake in Buildings A, B, and C.

	Illuminance (lux)	Temperature (°C)	Outside Air (%)
Case 1	500	26	100
Case 2	500	27	100
Case 3	300	27	100(A+B)*/50(C)**
Case 4	300	28	50

*set to 100% of outside air intake for Buildings A and B

**set to 50% of outside air intake for Building C

All cases were operated by AC mode and outside air was supplied by mechanical system.

Table 2-3. Physical parameters measured over a long-time period.

Parameter	Position	Interval	No of points on each floor
Air temperature	1.1m above floor	10 min	12 points at A, B, C 3 points at D, F
Relative humidity	1.1m above floor	10 min	
Globe temperature	1.1m above floor	10 min	1
WBGT	0.8m above floor	1 min	1
CO_2	0.7m above floor	1 min	1
Illuminance	At desk level	1 min	1

Table 2-4. Detailed physical measurement items on the represent day for 4 conditions in Buildings A, B, and C.

Item	Position	Time	No. of points on each floor
Thermo-vision	Each direction	10:00 13:00 16:00	
Vertical temperature and humidity	0.1, 0.6, 1.1, 1.7, and 2.2m above floor		3–9 points per line
Air velocity	0.7m above floor		
Noise level	0.7m above floor		
Illuminance	At desk level		
Occupancy	Visual inspection		
Task light, cooling devices, blind operation			

Table 2-5. Numbers of employees and collected surveys.

	Number of employees	Number of setting conditions	Total number of responses
A 8F	49	4	143
A 10F	51	4	164
B 2F	56	4	202
B 9F	107	4	311
C 4F	118	4	402
D 3F	62	1	50
E 7F	77	1	68
Total	520	22	1340

2.2.3 Satisfaction and productivity questionnaires

Indoor environmental quality in office buildings has been assessed extensively by the Center for the Built Environment (CBE) at the University of California, Berkeley. The survey implemented in CBE research measures occupant satisfaction and self-reported productivity in nine Indoor Environmental Quality categories in an invite-style web-based questionnaire as described by Abbaszadeh et al [5]. The present study uses a similar questionnaire for the assessment of visual comfort, air quality and thermal comfort.

Figure 2-1 shows the options that occupants were presented with to rate their satisfaction–dissatisfaction level. Thermal sensation was also measured on the ASHRAE scale, with +3: hot, +2: warm, +1: slightly warm, 0: neutral, −1: slightly cool, −2: cool and −3: cold. Questionnaires were delivered directly to occupants' desks; we requested that occupants place the completed questionnaires in a sealed box.

Are you satisfied or dissatisfied with present light environment in this space?
-2: dissatisfied, -1: slightly dissatisfied, 0: neutral, +1: slightly satisfied, +2: satisfied

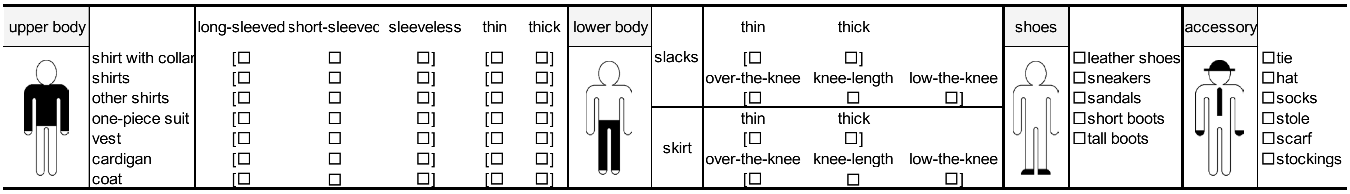
Are you satisfied or dissatisfied with present thermal environment in this space?
-2: dissatisfied, -1: slightly dissatisfied, 0: neutral, +1: slightly satisfied, +2: satisfied

Are you satisfied or dissatisfied with present indoor air quality in this space?
-2: dissatisfied, -1: slightly dissatisfied, 0: neutral, +1: slightly satisfied, +2: satisfied

Figure 2-1. Questions for satisfied-dissatisfied assessment of indoor environment.

2.2.4 Clothing and outdoor temperature data

To evaluate thermal comfort, it is important to determine clothing and activity characteristics of respondents. Figure 2-2 shows the questionnaire used to assess clothing ensembles. A clothing (clo) value was estimated based on this questionnaire. Activity levels of office employees were observed by investigators and reported as metabolic rate (MET) values. Since normal office work was conducted for the most part, we estimated a MET value of 1.2, except for the second floors of Building B and Building D. On the second floor of Building B, 75% of occupants were female and employed in secretarial roles, so we estimated a MET value of 1.1. Conversely, on the second floor of Building D, many occupants are businessmen who move in and out of the office frequently; therefore, we estimated a MET value of 1.4 in this case. Data from Tokyo meteorological stations close to these buildings were used to represent outdoor conditions. Table 2-6 categorizes the occupants by gender, age and type of employment.



upper body		long-sleeved	short-sleeved	sleeveless	thin	thick
	shirt with collar	[☐	☐	☐]	[☐	☐]
	shirts	[☐	☐	☐]	[☐	☐]
	other shirts	[☐	☐	☐]	[☐	☐]
	one-piece suit	[☐	☐	☐]	[☐	☐]
	vest	[☐	☐	☐]	[☐	☐]
	cardigan	[☐	☐	☐]	[☐	☐]
	coat	[☐	☐	☐]	[☐	☐]

lower body				
	slacks	thin [☐	thick ☐]	
		over-the-knee [☐	knee-length ☐	low-the-knee ☐]
	skirt	thin [☐	thick ☐]	
		over-the-knee [☐	knee-length ☐	low-the-knee ☐]

shoes		accessory	
	☐leather shoes ☐sneakers ☐sandals ☐short boots ☐tall boots		☐tie ☐hat ☐socks ☐stole ☐scarf ☐stockings

Figure 2-2. Questionnaire for clothing ensembles.

Table 2-6. Gender, age, and type of employment by floor.

Investigated floors	Number of employees	Percentages males (%)	Age (%)					Job type (%)				
			20s	30s	40s	50s	60s	Clerical	Engineer	Researcher	Sales	Manager
A 8F	49	62	9	28	32	23	7	50	7	4	31	7
A 10F	51	70	6	26	26	22	20	78	5	0	0	17
B 2F	56	26	10	16	48	15	11	91	0	0	0	9
B 9F	107	78	0	27	26	27	20	23	36	0	0	41
C 4F	118	88	36	10	33	16	5	4	91	1	0	4
D 3F	62	90	24	12	37	14	12	11	57	2	0	30
E 7F	77	82	15	10	28	40	7	16	47	0	19	18
Total	550	71	15	19	33	21	12	36	41	1	4	18

2.3 Results and discussion

2.3.1 Physical environment and clothing

Table 2-7 lists the measured physical environment parameters, mean daily outdoor temperatures based on metrological station data and estimated clo values. The mean clo value for males was 0.53 and that for females was 0.48. These basic clothing insulation values are lower than those for normal business garments; this indicates that occupants were adhering to the guidelines set out by the Super Cool Biz campaign. Cool Biz has been started in summer 2005 to reduce energy consumption by the Japanese Ministry of the Environment by limiting the use of air conditioning. Following the Great East Japan Earthquake in March 2011, the Japanese government asked for more efforts for the public. Especially they are allowed to wear sportswear outfits and T-shirts including jeans and sandals under special conditions. However, it may be hard to accept those kinds of clothing widely. Typical clothing insulation values for semi-outdoor environments such as atria or open cafés have been shown to be between 0.4 and 0.6 (Nakano and Tanabe 2004; based on 2248 observations). For social reasons, it is very difficult for office workers to wear clothing with an insulation value lower than 0.4 clo, but the basic clothing insulation values observed in these offices was somewhat similar to this level. Observed data for thermal comfort including visual and indoor air quality (IAQ) satisfaction votes are shown in Table 2-8.

Table 2-7. Measured values for the physical environment and clothing.

	Period	Case	Outdoor (°C)	Illuminance (lux)	CO_2 (ppm)	Air Tempera -ture (°C)	Humidity (rh%)	male (clo)	Female (clo)
A/8F*	11.Aug-12.Aug	case1	31.1	551	605	27.3 (1.0)	53	0.53	0.47
	4.Aug-5.Aug	case2	27.6	540	620	28.0 (0.9)	55	0.52	0.50
	8.Aug-10-Aug	case3	30.0	339	650	28.0 (1.0)	55	0.51	0.45
	1.Aug-3.Aug	case4	25.4	347	679	29.0 (0.9)	51	0.56	0.48
A/10F	27.Jul-29.Jul	case1	26.5	599	640	26.2 (0.4)	60	0.51	0.44
	21.Jul-22.Jul	case2	20.9	599	581	27.6 (0.2)	45	0.55	0.46
	25.Jul-27.Jul	case3	27.6	513	617	27.0 (0.4)	58	0.52	0.48
	19.Jul-20.Jul	case4	24.5	513	740	28.1 (0.3)	54	0.53	0.50
B/2F	28.Jul-29.Jul	case1	26.5	540	745	25.3 (0.3)	54	0.51	0.49
	21.Jul-22.Jul	case2	20.9	540	662	26.2 (0.3)	46	0.51	0.54
	25.Jul-27.Jul	case3	27.6	481	753	26.2 (0.3)	51	0.51	0.51
	19.Jul-20.Jul	case4	24.5	481	809	27.1 (0.5)	51	0.47	0.48
B/9F	28.Jul-29.Jul	case1	26.5	542	666	25.4 (0.4)	57	0.53	0.47
	21.Jul-22.Jul	case2	20.9	537	708	26.3 (0.3)	46	0.52	0.50
	25.Jul-27.Jul	case3	27.6	306	696	26.3 (0.4)	54	0.52	0.47
	19.Jul-20.Jul	case4	24.5	334	847	27.1 (0.6)	54	0.53	0.48
C/4F	11.Aug-12.Aug	case1	31.1	322	683	26.2 (0.7)	57	0.54	0.50
	4.Aug-5.Aug	case2	27.6	218	707	26.2 (0.6)	57	0.55	0.55
	8.Aug-10-Aug	case3	30.0	253	738	26.6 (0.7)	56	0.55	0.47
	1.Aug-3.Aug	case4	25.4	212	719	26.2 (0.5)	55	0.54	0.52
D/3F	10.Aug-12.Aug	-	30.9	269	800	27.5 (1.0)	51	0.54	0.41
E/7F	8.Aug-12.Aug	-	30.4	640	1127	26.5 (1.1)	51	0.53	0.43

( ) means standard deviation

*A/8F: Building A, 8th floor, A/10F: Building A, 10th floor
B/10F: Building B, 2nd floor, B/9F: Building B, 9th floor
All cases were operated by AC mode.

Table 2-8. Results of voting in each case

	Case	Thermal Sensation Vote	Thermal Satisfaction	Visual Satisfaction	IAQ Satisfaction
A/8F*	case1	-0.19 (1.7)	-0.28 (1.3)	0.38 (0.9)	-0.06 (1.0)
	case2	1.05 (1.3)	-0.79 (1.1)	0.16 (1.1)	-0.45 (1.1)
	case3	1.14 (1.2)	-0.67 (1.0)	0.08 (0.9)	-0.39 (1.1)
	case4	1.97 (1.3)	-1.03 (0.9)	0.33 (1.1)	-0.50 (1.0)
A/10F	case1	-0.24 (1.2)	0.05 (0.7)	0.19 (0.9)	0.05 (0.8)
	case2	0.24 (0.9)	-0.11 (0.9)	-0.08 (1.0)	-0.05 (1.0)
	case3	0.64 (1.1)	-0.32 (0.7)	-0.02 (1.0)	-0.05 (0.9)
	case4	0.82 (1.0)	-0.43 (0.8)	0.09 (0.9)	-0.16 (0.9)
B/2F	case1	-0.74 (1.1)	0.06 (1.0)	0.12 (1.0)	0.04 (1.1)
	case2	-0.14 (1.1)	0.32 (1.1)	0.22 (1.0)	0.20 (1.0
	case3	-0.29 (1.2)	0.09 (1.0)	-0.07 (0.9)	-0.06 (1.0)
	case4	0.23 (1.1)	-0.02 (1.1)	0.06 (1.0)	0.09 (1.1)
B/9F	case1	-0.53 (1.0)	0.10 (0.8)	0.24 (0.8)	0.34 (0.8)
	case2	-0.11 (0.9)	0.27 (0.9)	0.36 (1.0)	0.34 (0.9)
	case3	0.03 (1.1)	0.19 (0.9)	0.12 (0.9)	0.27 (0.9)
	case4	0.61 (1.3)	-0.18 (1.0)	0.21 (1.0)	0.17 (0.9)
C/4F	case1	0.10 (1.1)	0.15 (0.9)	0.55 (0.9)	0.24 (0.7)
	case2	0.21 (1.1)	0.05 (1.0)	0.16 (1.0)	0.17 (0.8)
	case3	0.34 (1.1)	0.13 (1.0)	0.32 (1.0)	0.23 (0.7)
	case4	0.09 (1.0)	0.07 (1.0)	0.05 (1.2)	0.20 (0.8)
D/3F	-	1.90 (1.2)	-0.94 (0.8)	-0.23 (0.9)	-0.54 (0.9)
E/7F	-	-0.12 (1.4)	-0.39 (0.9)	0.25 (1.1)	-0.03 (1.0)

( ) means standard deviation

2.3.2 Lighting and visual environment

The relationship between visual satisfaction and illuminance at the desk level is shown in Figure 2-3. Prior to 11 March, it was common to have over 750 lux at desk level. The range of measured illuminance was 200–650 lux. We found a very weak correlation between dissatisfaction and illumination intensity. In Japan, the design value for illuminance is 750 lux. The Japanese Industrial Standard number JIS Z9110 2010 [6] recommends that illumination intensity at desk level in offices should be 750 lux. This value may be too high, and a government-published supplement (JIS Z 9110 2011 [7]) suggested that illumination should be in the range 500–1000 lux. In fact, we are currently studying ways to decrease design illumination level. Although illumination intensity had little effect on visual satisfaction for the group as a whole, discomfort was observed in elder workers below 300 lux. Special a ttention to task-appropriate lighting may be required for those who have grown far-sighted.

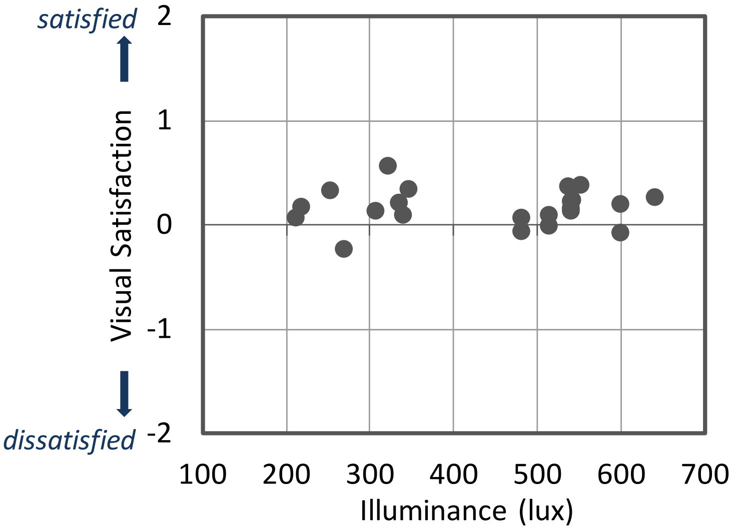


Figure 2-3. Relationship between illumination intensity at desk level and level of satisfaction (n=22).

2.3.3 Thermal comfort

The relationship between mean room air temperature and thermal sensation is shown in Figure 2-4. Each point presents one of the 22 cases listed in Table 2-9. Globe temperatures were close to the operative temperatures shown as the abscissa of this figure. A neutral temperature of 26.3 °C was calculated from regression analysis; a good linear relationship was observed with the exception of one point ($y = 0.65x - 17.0$, $R^2 = 0.72$, $p < 0.001$). Occupants in Building D expressed votes of very high thermal sensation; this may have been caused by the high activity levels in this building. Air temperature, mean radiant temperature and air velocity were measured at the representative points, so we used grouped data for analyses. Bigger deviations may be observed with raw data. Standard deviation of each group data was shown in Table 2-10.

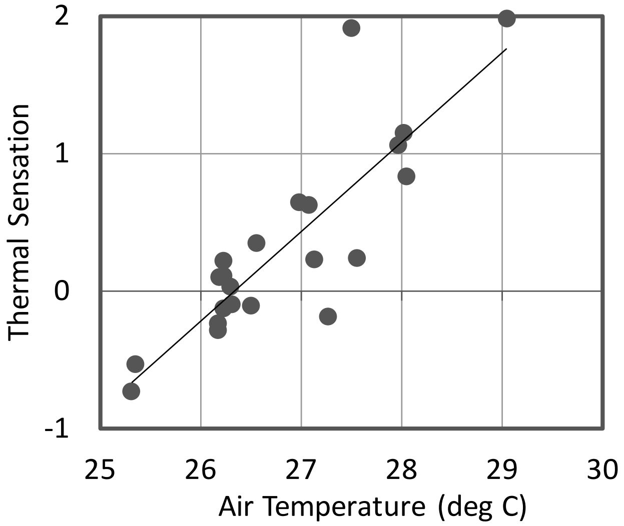


Figure 2-4. Relationship between mean room air temperature and thermal sensation vote ($y=0.65x-17.0$, $R^2=0.72$, $p<0.001$, $n=22$).

Relative humidity was controlled by a heating, ventilating and air-conditioning system within a narrow range between 46 and 60% (Table 2-11), so humidity did not have a significant effect on results. All cases were operated by AC mode. Air velocity was also within a narrow range, between 0.10 and 0.17 m/s; no high air movement caused by personal fans was observed. In 2011, the plug-in power supply was also strictly controlled. However, if occupants could use small, energy-efficient fans, thermal sensation may be improved. The wet-bulb globe temperature (WBGT) was measured to address government concerns about heat stress in offices. However, WBGT was not more than 23.5 °C, indicating that there was almost no risk of heat stroke.

Figure 2-5 shows the relationship between predicted mean vote (PMV; Fanger 1970 [8]) and thermal sensation vote. PMV was calculated by using average measurement values of air temperature, mean radiant temperature, relative air velocity, relative humidity and clothing (clo) value as well as estimated metabolic rate; 1.1 or 1.2 depending on their work style. Average clo value was calculated based on ISO9920 [9] for each part as shown in Figure. 4-1, and summed up to calculate overall clothing value. In this study, chair insulation was not included in the calculation of overall clothing value. A good linear relationship was observed ($y = 1.71x - 0.71$, $R^2 = 0.72$, $p < 0.001$), but PMV is underestimated at values of thermal sensation. The discrepancy between thermal sensation vote and PMV was around +1.

As shown in Figure 2-6, a strong correlation was found between dissatisfaction and room temperature ($y = -0.073x^2 + 3.62x - 44.45$, $R^2 = 0.71$, $p < 0.001$); dissatisfaction was higher at higher temperatures, and thermal satisfaction decreased rapidly above 27 °C. The Japanese government recommended that room air temperature should be 28 °C as part of the Cool Biz scheme. However, temperatures of 28 °C were associated with high levels of dissatisfaction. Therefore, we recommend keeping the operative temperature lower than 27 °C to maintain employee performance.

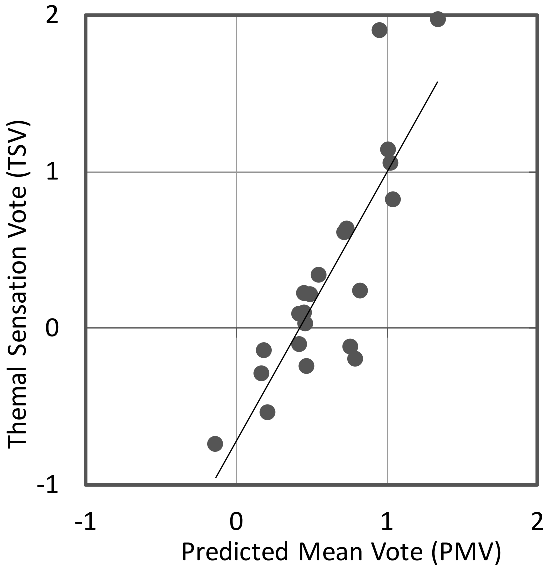


Figure 2-5. Relationship between calculated PMV and thermal sensation vote ($y=1.71x-0.71$, $R^2=0.72$, $p<0.001$, $n=22$).

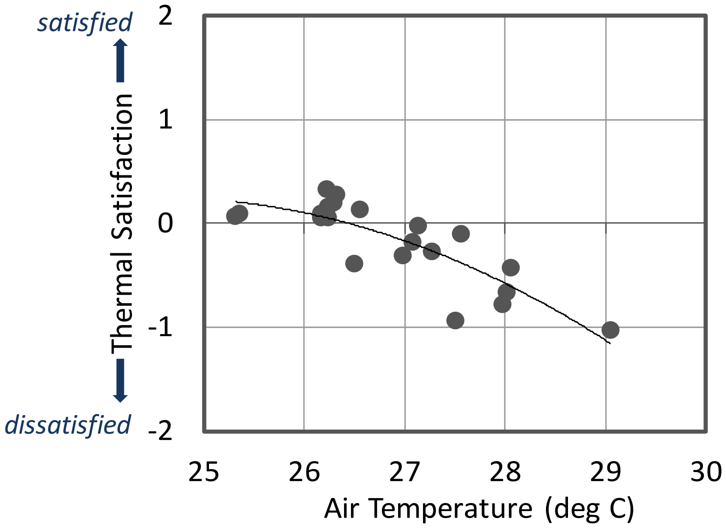


Figure 2-6. Relationship between room temperature and level of satisfaction ($y=-0.073x^2+3.62x-44.45$, $R^2=0.71$, $p<0.001$, $n=22$).

2.3.4 Indoor air quality

A strong correlation between satisfaction with IAQ and the level of CO_2 Figure 2-7) could not be found. For CO_2 concentrations in the range of 600–1200 ppm, a gradual increase in dissatisfaction with an increase in concentration was found. The perception of IAQ is also affected by the thermal environment. Furthermore, indoor temperature has a significant influence on perceived air quality (Figure 2-8) ($y = -0.23x + 6.05$, $R^2 = 0.61$, $p < 0.001$). Fang, Clausen, and Fanger found that when compared with the direct impact of temperature and humidity on the perception of air quality, the impact of temperature and humidity on chemical emissions from building materials has a secondary influence on perceived air quality [10]. Generally, at higher air temperatures and humidity conditions, the vapour pressures of chemical substances become higher. Moreover, Fang et al. studied a simulated office space at three levels of air temperature and humidity and two levels of ventilation rate [11]. Their study confirmed the previously observed impact of temperature and humidity on perceived air quality and the linear correlation between acceptability and enthalpy. The required ventilation rate for comfort and health should no longer be independent of indoor air temperature and humidity. Their result was confirmed by an assessment of a large number of occupants in real office buildings.

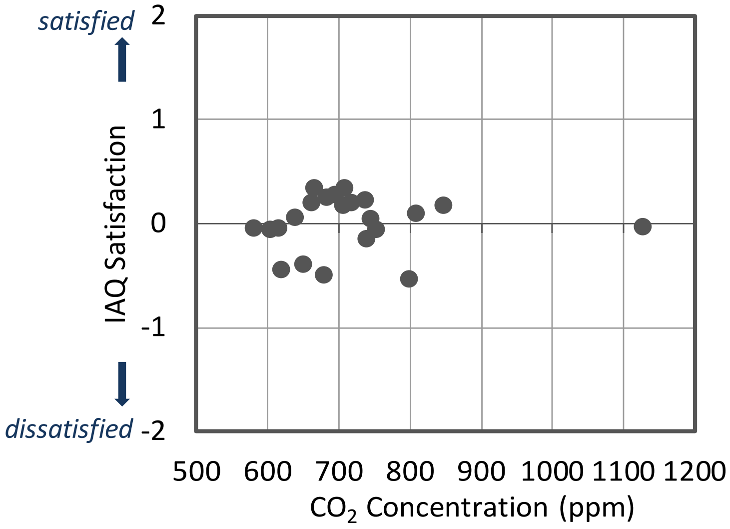


Figure 2-7. Relationship between CO$_2$ concentration and level of satisfaction for indoor air quality (IAQ) (n=22).

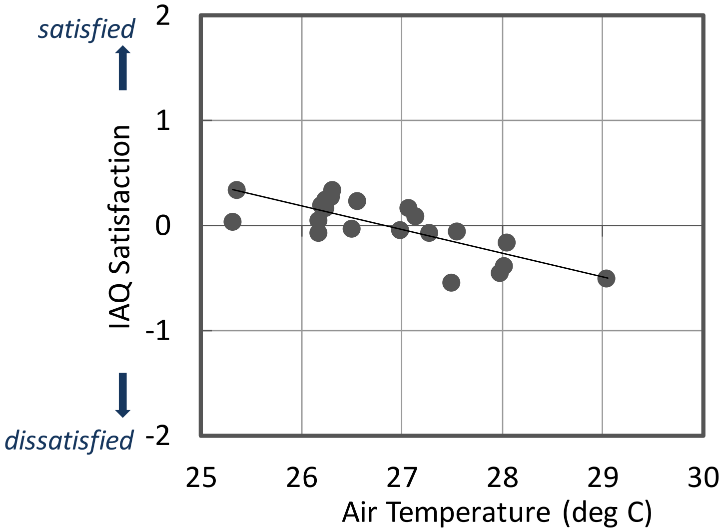


Figure 2-8. Relationship between air temperature and level of satisfaction for indoor air quality (IAQ) ($y=-0.23x+6.05$, $R^2=0.61$, $p<0.001$, n=22).

2.3.5 Energy savings and peak cut

Energy consumption was recorded in Buildings A, B and C using a building energy management system. Figure 2-9 shows the relationship between electricity consumption for lighting and outside solar radiation per hour for each case. For 750 lux setting condition, the data of the summer of 2010 was used. Energy consumption is slightly affected by outdoor solar radiation because of daylight. The mean electricity consumption was 14.4 W/m² at 750 lux, 10.2 W/m² at 500 lux and 8.1 W/m² at 300 lux. Thus, lowering the illumination to 500 lux from 750 lux can be expected to cause a 4.2 W/m² reduction in electricity consumption, and a reduction from 750 to 300 lux corresponds to a reduction of 6.3 W/m². These electricity savings also have an impact on the cooling load.

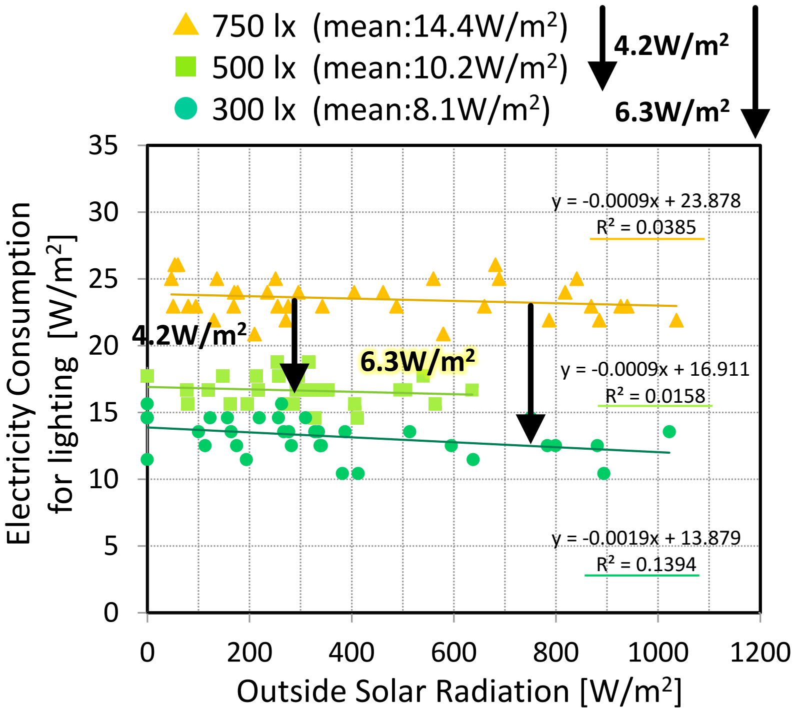


Figure 2-9. Energy savings and lighting.

Figure 2-10 shows the relationship between electricity consumption for cooling and difference of enthalpy between outdoors and indoors per hour for each case. The heat load of the lighting was unified to 300 lux *1). The average value of the cooling electricity consumption at 27 °C was calculated excluding Case 2 where the outside air temperature was extremely low. The result shows that we cannot expect changes in cooling conditions to result in energy reductions as large as those possible for lighting.

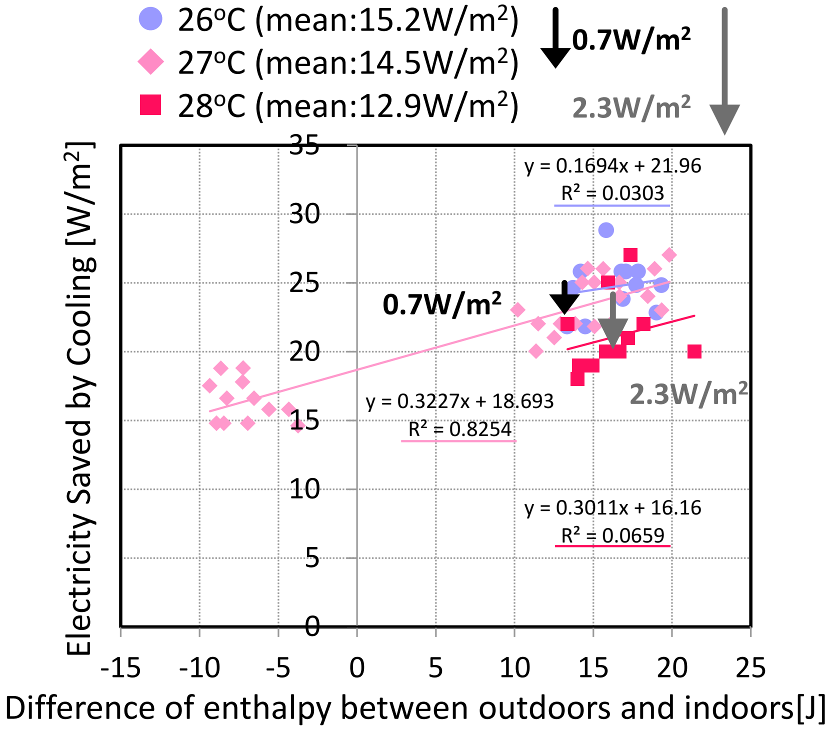


Figure 2-10. Energy savings by changing temperature.

*1) Electricity consumption for lighting [W/m²] at 27°C, 500 lux as well as 27°C, 300 lux were calculated from the BEMS (Building Energy Management System) data under each condition of cooling set temperature. By dividing the difference of obtained electricity consumption for each illuminance setting by the system COP of the air conditioner, the reduction value of cooling electricity consumption by changing the setting for illuminance was calculated. Cooling electricity consumption was unified as with 300 lux illuminance by subtracting this reduction value from cooling electricity consumption in Cases 1 and 2.

2.3.6 Awareness of electricity-savings and productivity

To investigate the attitudes of office workers towards *setsuden* in the five buildings discussed above and in three additional buildings, we asked the following questions: ‘Are you positive or negative to save electricity in offices?’ (Figure 2-11-1), ‘Did your attitude of saving electricity change after the Great East Japan Earthquake?’ (Figure 2-11-2) and ‘How do you feel about this office under electricity-saving conditions as of now?’ (Figure 2-11-3) Almost 90% of respondents answered they are positive to save energy in offices and over half of the respondents admitted to having no prior awareness but agreed that their awareness had been heightened since the earthquake. However, 72% of respondents expressed some degree of inconvenience caused by the measures. (Figure 2-11)

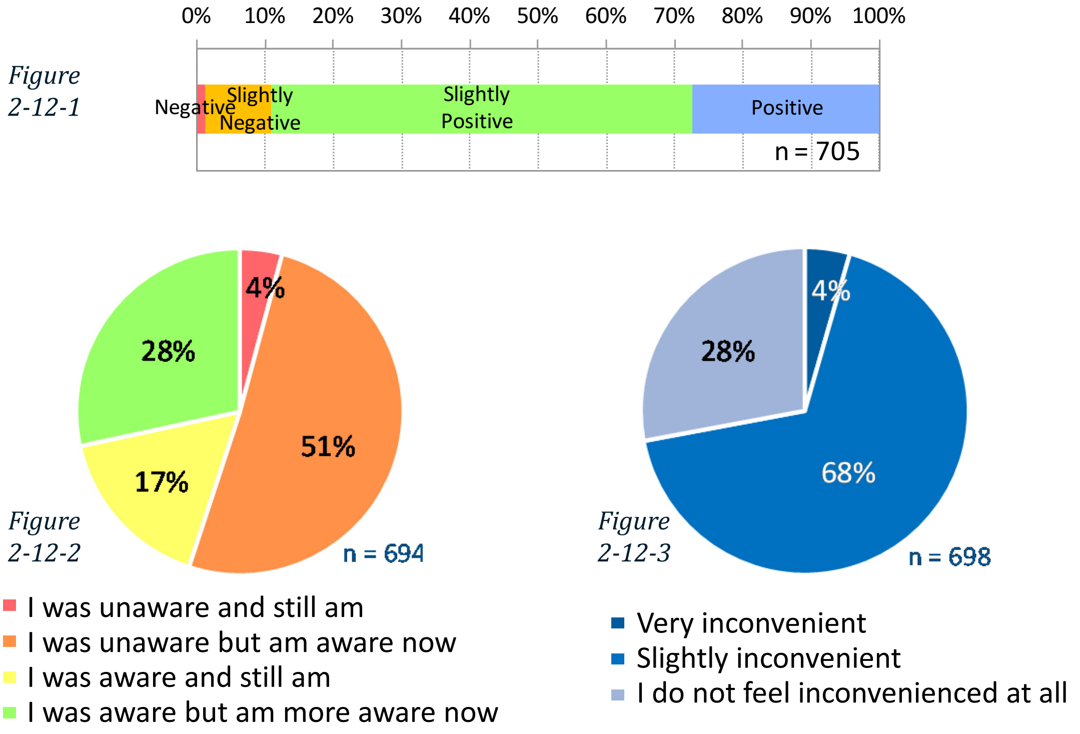


Figure 2-12-1

Figure 2-12-2

Figure 2-12-3

Figure 2-11. Awareness of office workers of energy-saving measures.

Respondents was asked to rate the most annoying measures taken to conserve electricity , allowing them to check multiple answers (Figure 2-12), as well as the number of years they expect these measures to be necessary. Respondents felt that they suffered most from increasing the set temperature point of air-conditioning systems, less elevator operation and turning off ceiling lights. Conversely, measures such as adoption of Cool Biz, cutting stand-by electricity and turning off lighting after-office hours and during lunch were fairly well accepted. These results suggest that it is important to consider comfort aspects to apply energy-saving measures in offices.

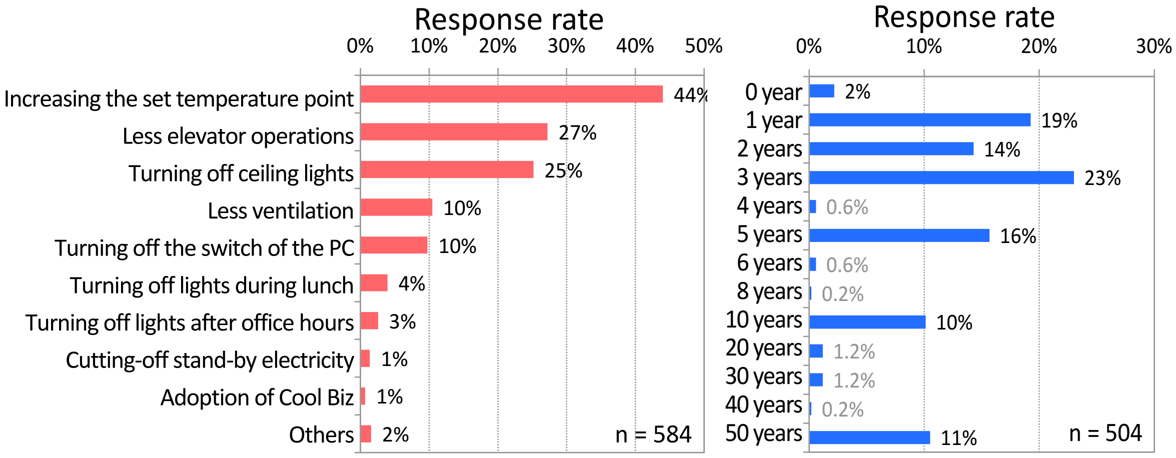


Figure 2-12. Most annoying means of conserving energy and the expected number of years necessary for *setsuden*.

The following question: ‘How many years can you continue implementing electricity-saving measures such as those introduced this year (including this year)?’ was asked. Over 75% of workers felt that they could only continue with such measures for up to 5 years. Office employees were also asked to rate their own loss in productivity by asking the question ‘Compared with last summer, how much would you estimate you have lost or gained in terms of productivity?’ Humphreys and Nicol asked self-assessed productivity in the office environment [12]. In this experiment, the same kinds of methods are applied. Taking the average of the 474 respondents, we found that loss in productivity because of *setsuden* was 6.6% (Figure 2-13). This represents a considerable economic impact. Therefore, it is important to find good strategies for saving electricity without affecting productivity. However, it cannot be claimed that such changes in productivity are purely a result of environmental conditions and thermal comfort: office workers in Tokyo in the summer of 2011 may have had other reasons for reduced productivity. We intend to investigate further in a future study.

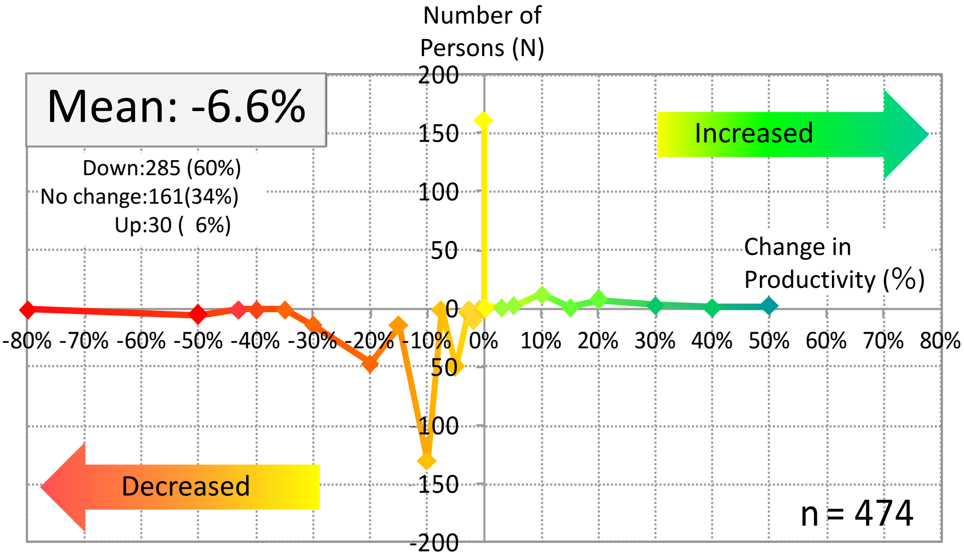


Figure 2-13. Productivity losses under *setsuden*.

2.4 Conclusions

Comfort and productivity of occupants of five office buildings in Tokyo during the summer season under mandatory electricity savings after the Great East Japan Earthquake were investigated. The purpose of this study was to investigate the effects of electricity-saving measures on the thermal comfort, productivity and energy levels of office workers. Our conclusions can be summarized as follows.

1. Occupants generally expressed discomfort relating to high temperatures over 27 °C, but widely accepted the decrease in illumination from 750 to 300–500 lux.
2. Increased awareness regarding power savings was found, with more than 90% of people accepting the poor indoor environment in light of the power shortages that year.
3. Recommendations for clothing and increasing the set temperature point, made by the Super Cool Biz campaign, were followed in most offices.
4. A strong correlation was found between dissatisfaction and room temperature; in particular, thermal satisfaction decreased steeply at temperatures over 27 °C. Thus, keeping operative temperature less than 27 °C to maintain employee performance is recommended.
5. Self-estimated productivity in the summer of 2011 was 6.6% lower than the previous year. Thus, strategies for electricity savings that do not affect productivity are necessary.

References

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Outline

Chapter 3

Web-based questionnaire survey on region-wise awareness and measures of saving electricity
– Tokyo, Nagoya, and Osaka –

3.1 Objective and general approach

Field interventions and surveys to investigate employee comfort and productivity in offices under mandatory electricity-saving were conducted in Tokyo as reported in Chapter 2 [1, 2]. However, a nationwide survey was needed because saving electricity were ongoing all over Japan in the summer of 2012 following the events of 2011. The electricity-saving target values differed by region and year and this created a “natural” experiment.

The following three regions being the three largest areas characterized by a large number of offices [3] were chosen for investigation: Tokyo, Nagoya, and Osaka. These three regions had different electricity-saving target values during the summers of 2011 and 2012 as followings [4]:

- In the Tokyo Electric Power Company (TEPCO) region including Tokyo: 15% mandatory electricity-savings requests were made in the 2011 summer followed by a voluntary electricity-savings request in the 2012 summer
- In Chubu Electric Power Company region including Nagoya: voluntary electricity savings were requested in both two summers
- In the Kansai Electric Power Company (KEPCO) region including Osaka: 10% voluntary power-savings request was made in the 2011 summer followed by a voluntary electricity-savings request of 10% (5% in some areas) in the 2012 summer

In this study, a web-based questionnaire survey for 1200 employees in Tokyo, Nagoya, and Osaka was undertaken to investigate whether different earthquake and electricity-saving experiences affected their awareness, electricity saving measures, and comfort is discussed. To evaluate indoor environmental quality, we took employee characteristics including gender and age as well as regional differences into account, because it was reported that employee indoor environmental satisfaction and productivity were different according to characteristics such as gender and age [1].

3.2 Methodology

3.2.1 Date and questionnaire contents

A web-based questionnaire survey was conducted from October 10, 2012 (Wednesday) to October 12 (Friday) of the same year. People could answer the questionnaire on their PCs at any time during this period. Questionnaire contents were decided on the basis of SAP 2009 [5]; these were about perceptions and satisfaction with each element of the indoor environment including lighting, thermal sensation, air quality, sound, space, and IT in offices saving power in the summers of 2011 and 2012, and how those measures impacted productivity. In addition, the questionnaire contents related to newly added power-saving measures and awareness of saving electricity before and after the earthquake.

3.2.2 Database description

Questionnaire respondents were chosen from the questionnaire monitors of Nomura Research Institute “TrueNavi.” The screening survey was carried out in advance in order to increase the accuracy of the questionnaire subjects under the following conditions:

1. Location of the work place (office): **Tokyo** (including inside and outside of Tokyo’s 23 cities and suburbs such as Yokohama, Kawasaki, Chiba, etc.); **Nagoya** (including suburbs of Nagoya city such as Gifu, Tsu, etc.); or **Osaka** (including suburbs of Osaka city such as Kobe, Nara, Kyoto, etc.)
2. The number of employees who mostly do desk work in the workplace (office): offices with more than 1000 employees including managers and executive officers, but not including site-based employees such as salespersons or independent business people.

We then collected more than 400 questionnaire results for each region, and randomly selected 400 questionnaire results (in total 1200 results) from those questionnaires that met conditions 1 and 2 above.

Figure 3-1 shows the location of the workplace, and Figure 3-2 shows the number of employees in the work place. The number of employees and respondents in Nagoya was larger than in Tokyo and Osaka. This is because Nagoya has many companies running large-scale manufacturing industries.

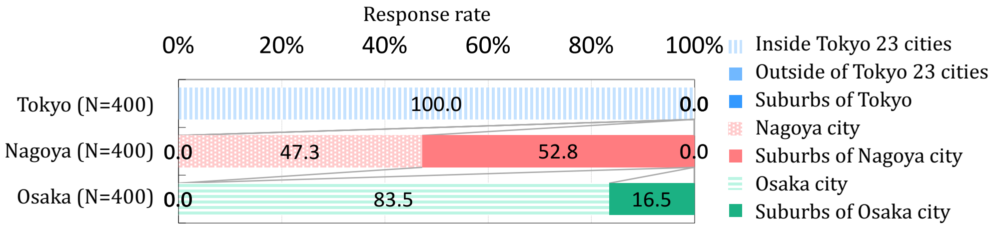


Figure 3-1. The location of the workplace.

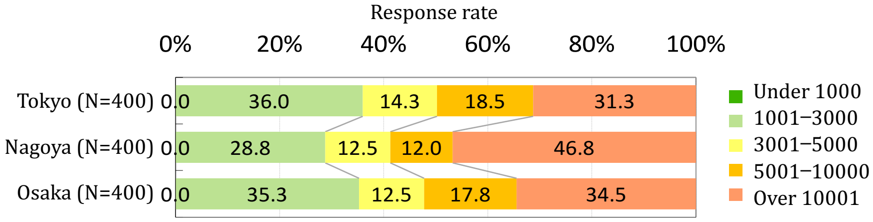


Figure 3-2. The number of employees in the workplace.

3.3 Results of basic information

3.3.1 The weather in each location in the summers of 2011 and 2012

Figure 3-3 shows the average outdoor temperature during work hours in the summers of 2011 and 2012, while Figure 3-4 shows the average enthalpy of outdoor air during work hours in the summers of 2011 and 2012.

The average outdoor temperature and average outdoor enthalpy during office hours (9:00–18:00) in the electricity-saving period (July 2–September 7) in Tokyo, Nagoya, and Osaka were calculated for each day using Japan Meteorological Agency's past weather data [6]. Graphs included data on Saturdays and Sundays. The average outdoor temperatures during office hours were around 30 °C in the three regions in both years; however, they were higher by about 1–2 °C in Osaka than in Nagoya, which was higher than in Tokyo. On the other hand, average outdoor enthalpy, was higher in Nagoya than in Osaka, which was higher than in Tokyo in 2011; they were almost at the same level in the summer of 2012.

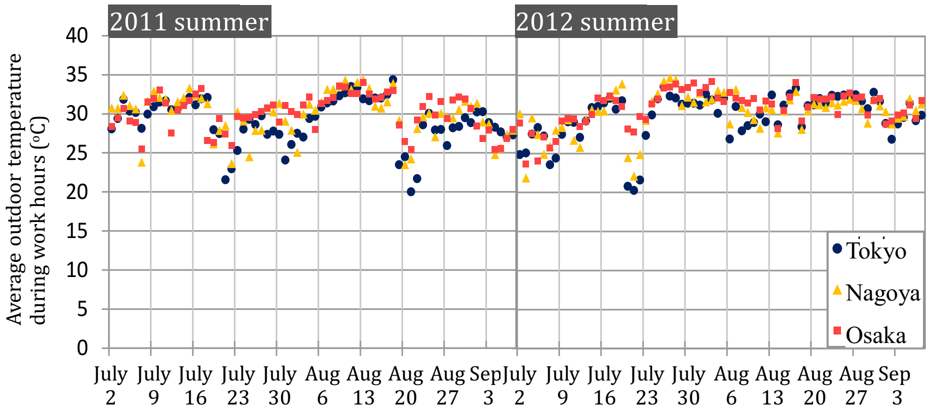


Figure 3-3. Average outdoor temperature during work hours in the summers of 2011 and 2012.

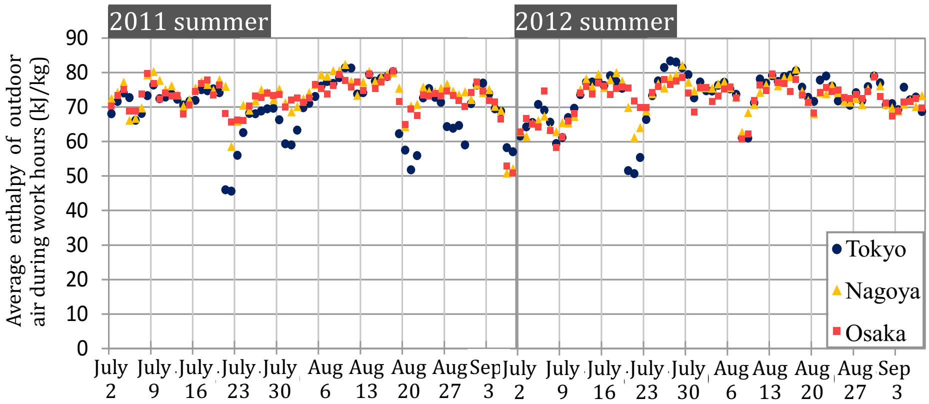


Figure 3-4. Average enthalpy of outdoor air during work hours in the summers of 2011 and 2012.

3.3.2 Feature of questionnaire answerers and the buildings of their work place

Table 3-1 shows the features of questionnaire respondents and their workplace buildings. The total number of floors of a workplace was higher in Tokyo than in Osaka, which was higher than in Nagoya. Buildings with 1–5 floors accounted for 44% of the total in Nagoya. On the other hand, differences in the age of the workplace buildings in the three regions were small, therefore building performance in the three regions was also assumed to be small. Regarding gender, the percentage of females in Osaka was a little higher than in Tokyo and Nagoya; however, the percentage of males accounted for about 80% in all regions. A wide range of ages was included: those in their 20s and 30s were 28.4%, those in their 40s were 40.7%, and over 50s accounted for 30.9%. Regarding job type, clerical workers made up the largest percentage (44%) followed by engineers (29%). In addition, most large industries were manufacturing industries in all three regions followed by the information and communication industry; in particular, the proportion of manufacturing industries in Nagoya accounted for more than 60% of the total.

Table 3-1. Features of questionnaire respondents and their workplace buildings.

		Tokyo	Nagoya	Osaka	Total
		real number (relative frequency)	real number (relative frequency)	real number (relative frequency)	real number (relative frequency)
Total		400 (100%)	400 (100%)	400 (100%)	1200 (100%)
The total number of floors of work place (F)	1–5	30 (7.5)	176 (44.0)	86 (21.5)	292 (24.3)
	6–10	115 (28.8)	128 (32.0)	133 (33.3)	376 (31.3)
	11–20	109 (27.3)	73 (18.3)	95 (23.8)	277 (23.1)
	21–30	84 (21.0)	12 (3.0)	45 (11.3)	141 (11.8)
	Over 31	62 (15.5)	11 (2.8)	41 (10.3)	114 (9.5)
Age of the of the work buildings (Year)	Under 1	9 (2.3)	2 (0.5)	3 (0.8)	14 (1.2)
	1–5	44 (11.0)	49 (12.3)	35 (8.8)	128 (10.7)
	6–10	61 (15.3)	54 (13.5)	27 (6.8)	142 (11.8)
	11–20	83 (20.8)	78 (19.5)	74 (18.5)	235 (19.6)
	21–30	50 (12.5)	62 (15.5)	61 (15.3)	173 (14.4)
	Over 31	63 (15.8)	69 (17.3)	73 (18.3)	205 (17.1)
	unknown	90 (22.5)	86 (21.5)	127 (31.8)	303 (25.3)
Gender	Male	328 (82.0)	336 (84.0)	299 (74.8)	963 (80.3)
	Female	72 (18.0)	64 (16.0)	101 (25.3)	237 (19.8)
Age	20s	24 (6.0)	23 (5.8)	18 (4.5)	65 (5.4)
	30s	76 (19.0)	100 (25.0)	100 (25.0)	276 (23.0)
	40s	151 (37.8)	166 (41.5)	171 (42.8)	488 (40.7)
	50s	124 (31.0)	99 (24.8)	90 (22.5)	313 (26.1)
	Over 60s	25 (6.3)	12 (3.0)	21 (5.3)	58 (4.8)
Job type	Clerical	190 (47.5)	131 (32.8)	203 (50.8)	524 (43.7)
	Engineer	82 (20.5)	154 (38.5)	108 (27.0)	344 (28.7)
	Researcher	14 (3.5)	23 (5.8)	25 (6.3)	62 (5.2)
	Sales	20 (5.0)	10 (2.5)	14 (3.5)	44 (3.7)
	Manager	94 (23.5)	78 (19.5)	49 (12.3)	221 (18.4)
	Others	0 (0.0)	4 (1.0)	1 (0.3)	5 (0.4)

Figure 3-5 shows more detailed features of respondents' gender and age by region. Comparing the survey respondents' rate by gender and age in each region confirmed up to 9% of the difference (the ratio of the men in their 50s in Tokyo and Osaka). We could not completely align the response rate by gender and age in each region in this way, therefore, gender and age were carefully analyzed when comparing the data by region.

The proportion of job types by region varies greatly as shown in Figure 3-6. The proportion of clerical workers was the highest with about 50% in Tokyo and Osaka, while the proportion of engineers (40%) was the highest in Nagoya. In particular, Tokyo had the highest proportion of managers, Nagoya had the highest proportion of technical employees, and Osaka had the highest proportion of clerical workers. In short, about 80% of the total women were clerical workers regardless of regional or age. Clerical staff also accounted for a certain percentage (about 30–40%) of men of all ages and in all regions; however, employees in technical positions decreased and management employees increased significantly according to increased age. Overall, there were differences in job style by region that were regarded as characteristic of the regions.

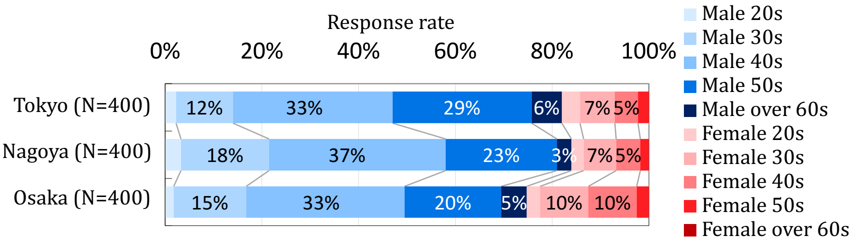


Figure 3-5. Respondents' gender and age by region.

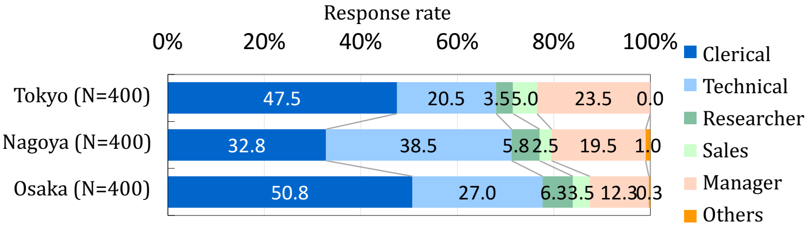


Figure 3-6. Proportion of job types by region.

3.3.3 Feature of work style

Figure 3-7 shows the rate of time spent sitting during work hours. In all regions, more than 90% of respondents answered that they were at the own seat for at least 40% of working hours in a day. The indoor environment around their seats where employees spend most of their time doing their work was considered important.

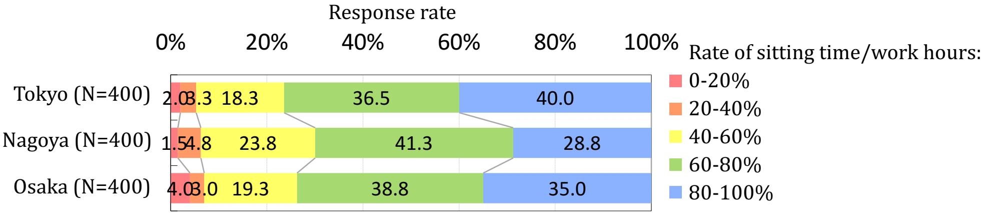
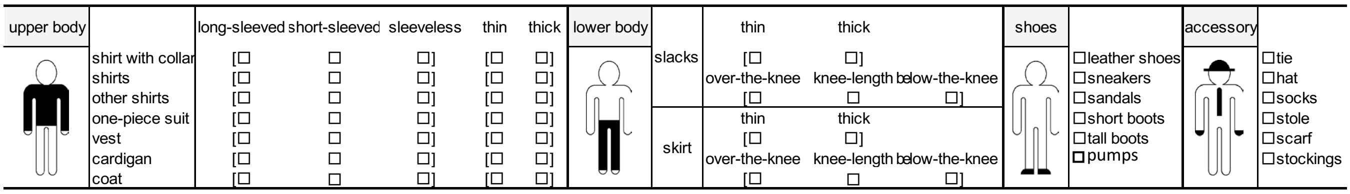


Figure 3-7. Rate of time spent sitting during working hours.

Figure 3-8 shows the questionnaire used to assess clothing ensembles. A clothing (clo) value was estimated based on this questionnaire, referred to as ISO9920[7]. Employees answered they wore well-worn clothing in the work place. Well-worn clothes were “long-sleeved or short-sleeved shirts with collars (thin), below-the-knee slacks (thin), leather shoes and socks” for males, and “short-sleeved shirts with or without collars (thin), long-sleeved cardigans (thin), below-the-knee slacks (thin) or knee-length skirts (thin), pumps or sandals and socks or stockings” for female. Total clothing insulation values (= clo values) were calculated by adding clo values of above clothing to that of underwear; 0.51–0.57 clo for male and 0.58–0.72 clo for female. Total clo value for female without adding cardigan is 0.35–0.49 clo which is lower than male’s minimum clo value: 0.51 clo.



upper body		long-sleeved	short-sleeved	sleeveless	thin	thick
	shirt with collar	[☐	☐	☐]	[☐	☐]
	shirts	[☐	☐	☐]	[☐	☐]
	other shirts	[☐	☐	☐]	[☐	☐]
	one-piece suit	[☐	☐	☐]	[☐	☐]
	vest	[☐	☐	☐]	[☐	☐]
	cardigan	[☐	☐	☐]	[☐	☐]
	coat	[☐	☐	☐]	[☐	☐]

lower body				
	slacks	thin	thick	
		[☐	☐]	
		over-the-knee	knee-length	below-the-knee
		[☐	☐	☐]
	skirt	thin	thick	
		[☐	☐]	
		over-the-knee	knee-length	below-the-knee
		[☐	☐	☐]

shoes
☐leather shoes
☐sneakers
☐sandals
☐short boots
☐tall boots
☐pumps

accessory
☐tie
☐hat
☐socks
☐stole
☐scarf
☐stockings

Figure 3-8. Questionnaire to assess clothing ensembles.

3.3.4 Indoor environment in work space

Table 3-2 shows the declaration of average air temperature in work spaces. Because we did not conduct field surveys in the actual offices, we asked respondents about the setting temperature in offices in the following question; "What was the air-conditioning setting temperature in offices in this summer? If you don't know the exact value, then please write down your 'feels like' air temperature." The exact number of employees who had responded the actual air-conditioning setting temperature was not grasped. As a result, the average declaration of air temperature for each region was 27.2 °C (Tokyo), 27.4 °C (Nagoya), and 27.3 °C (Osaka). These may be estimated values, but the average air temperature setting in the three regions was almost the same. Incidentally, we did not ask about the settings of other items such as illumination, ventilation rate and so on, as it seemed difficult for employees to report on those settings.

Table 3-2. Declaration of average air temperatures in work spaces.

Air conditioning setting temperature (°C)	Tokyo	Nagoya	Osaka	Average
Average (S.D.)	27.2 (1.4)	27.4 (1.5)	27.3 (1.5)	27.3 (1.5)

3.4 Results and discussion of investigation of saving electricity

3.4.1 Means of saving electricity

The following question was asked: “Please answer with respect to all of the electricity-saving measures practiced in the summers of 2011 and 2012.” Figure 3-9 shows electricity-saving measures practiced in the summers of 2011 and 2012, Figure 3-10 shows rates of change of electricity-saving measures practiced in the summers of 2011 and 2012 (based on 2011).

As a result, it was found that three regions had conducted similar electricity-saving measures in both years, and “Increasing the set temperature point,” “Turning off light during lunch” and “Adoption of Cool Biz” especially, had been conducted more than 50% of the time. On the other hand, the rate at which “Abstaining from using task lighting” and “Natural ventilation” were practiced was under 10%. Regarding the rate of change, “Turn off the light during lunch” was the worst with a value of -5.1% in Tokyo, although the rate of change increased 4.0% in Osaka. In addition, the rate of change of “Increasing the set temperature point” in Osaka was high (+5.0%) while that of “Nothing” was -2.8%, which meant that the rate of electricity-saving measures practiced increased more than in other regions. The average rate of change of all electricity-saving measures practiced was -1.7% for Tokyo, +0.4% for Nagoya and +2.3% for Osaka. The rates of change in each region were not the same, and the rate of change of specific electricity-saving measures related to air conditioning and lighting showed large variations.

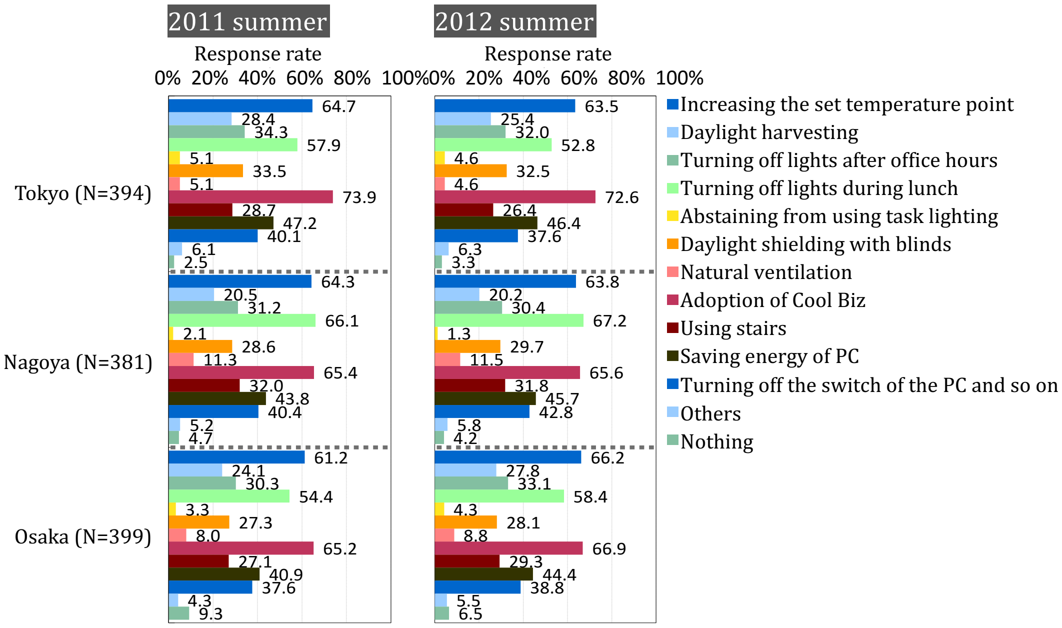
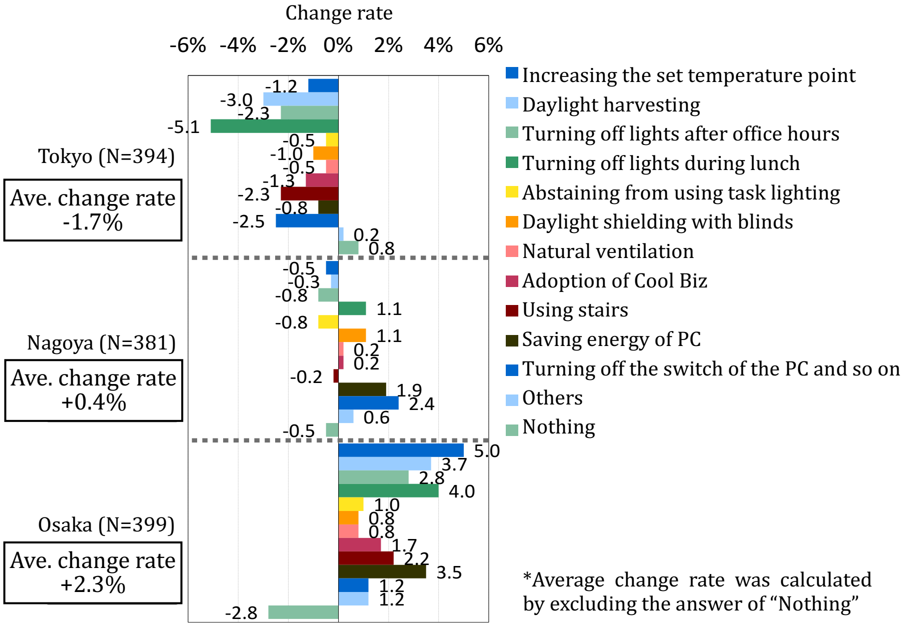


Figure 3-9. Electricity-saving measures practiced in the summers of 2011 and 2012.



*Average change rate was calculated by excluding the answer of “Nothing”

Figure 3-10. Rates of change of electricity-saving measures practiced in the summers of 2011 and 2012.

Many electricity-saving measures affect the indoor environmental qualities such as thermal sensations, lighting, indoor air, and usability of ICT (Information and Communication Technology) facilities, and so on. Figure 3-11 shows the rate of the most annoying measures taken to conserve electricity (multiple answers allowed). Respondents felt that they suffered most from increasing the room set-point temperature of air-conditioning systems (more than 35%) followed by "Turning off ceiling lights" and "Less elevator operations." More than 10% of people who chose "others" answered that they did not have such measures which annoyed them. Other reasons cited were "Turning off air-conditioning system after office hours," "Dimming of the ceiling light," "Turning off the tea supply machine," "Turning off the air towel," and so on.

Figure 3-12 shows cooling items used in the summers of 2011 and 2012 (multiple answers allowed). The most used items were paper fans and *sensu* in the three regions. In the 2012 summer, the use rate of the small electric fan increased a little, and the answer [using] "nothing" decreased a little. However, the use rate of each cooling item did not change a great deal by year and region. We need to consider that using a small electric fan and task-oriented air conditioning may have been prohibited depending on the office policy about saving electricity.

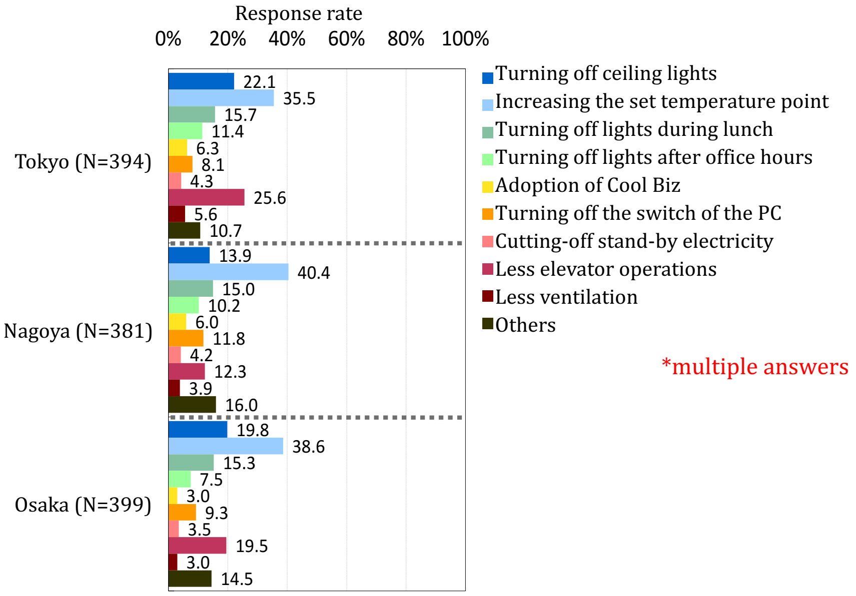


Figure 3-11. Rate of the most annoying measures taken to conserve electricity.

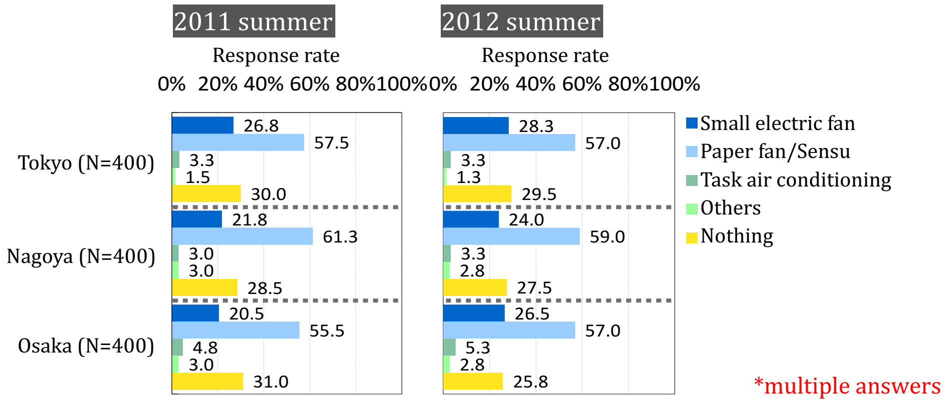


Figure 3-12. Cooling items used in the summers of 2011 and 2012.

3.4.2 Awareness of electricity-savings

To investigate the attitudes of office employees toward electricity savings by region, we asked questions about awareness of electricity-saving. In advance, we confirmed the differences in awareness between males and females, and between age groups (20–30s, 40s, and over 50s) because the differences by region could have influenced the results. However, pre-analysis revealed that these kinds of differences were not so large. Therefore, the differences in the gender and age of respondents from each region were not taken into account when comparing awareness of electricity-saving by region.

(1) Changes in the awareness of electricity-saving

Figure 3-13 shows changes in the awareness of electricity-saving after the earthquake, and Figure 3-14 shows changes in the awareness of electricity-saving from 2011 to 2012. As a result, 58.8 (34.8+23.8) % of respondents in Tokyo agreed that their awareness had been heightened since the earthquake. On the other hand, more employees in Nagoya and Osaka answered that they were aware of electricity saving even before the earthquake. Through 2011–2012, a higher percentage of awareness of electricity-saving was found with Osaka being higher than Nagoya, which in turn was higher than Tokyo.

Figure 3-15 shows positive or negative attitudes about saving electricity, Figure 3-16 shows the convenience of electricity saving in the office, and Figure 3-17 shows the acceptability of decreasing comfort because of electricity-saving measures in place. Regarding electricity saving, there was a higher percentage of positive opinions in Tokyo than in Nagoya, which in turn was higher than in Osaka. However, over a half of respondents expressed some degree of inconvenience caused by the measures in the three regions, and about 65% of employees in Osaka expressed inconvenience. About the acceptability of decreasing comfort because of electricity saving, declarations of acceptable and unacceptable were almost equal. Especially in Tokyo, acceptability was over 60%, which was over 10% higher than in Nagoya and Osaka.

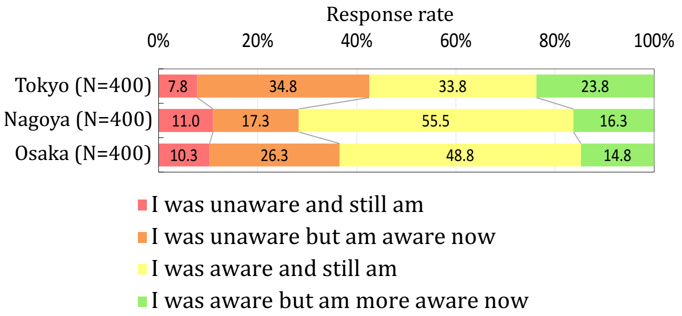


Figure 3-13. Changes in awareness of electricity-saving after the earthquake.

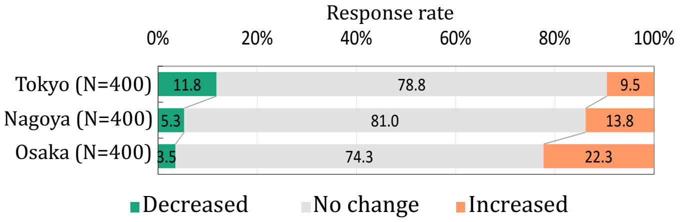


Figure 3-14. Changes in awareness of electricity-saving from 2011 to 2012.

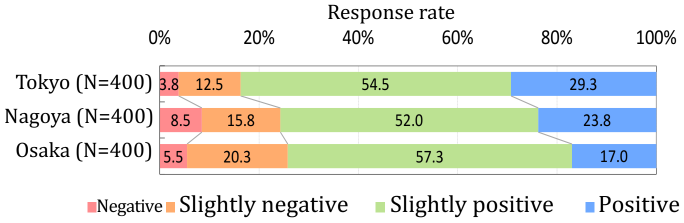


Figure 3-15. Positive or negative attitudes to saving electricity.

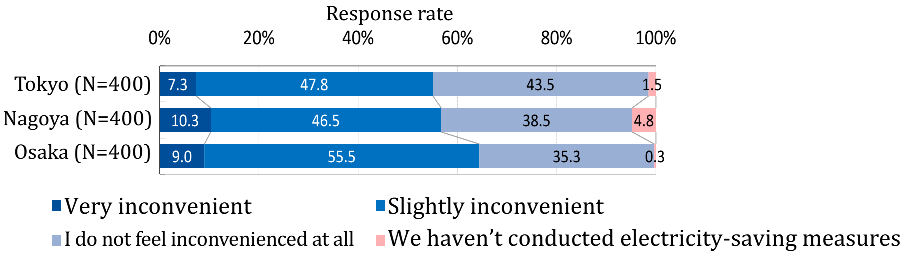


Figure 3-16. Convenience of electricity saving in the office.

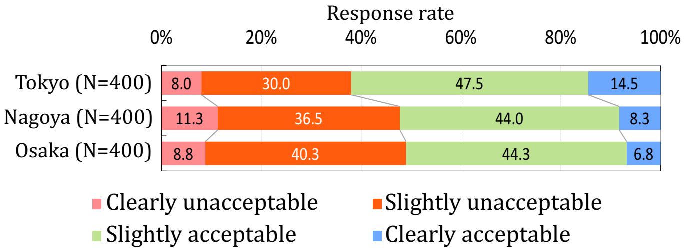


Figure 3-17. Acceptability of decreasing comfort because of electricity-saving measures.

(2) Continuation of electricity-saving measures

Figure 3-18 shows agreement or disagreement with continued measures to save electricity in the upcoming fiscal year, and Figure 3-19 shows the number of possible years of continuing electricity-saving measures. For these two questions, answers were only from people who worked for companies that implemented electricity saving in the summer of 2012.

About a half of respondents in Tokyo declared agreement with continuing electricity saving after the next year as well. However, respondents agreed in Nagoya and Osaka were less than in Tokyo by over 10%, where declarations of “agree” and “disagree” in Nagoya and Osaka were almost the same.

To investigate the number of possible years of continuing with electricity-saving measures, the following question was asked, “Can you continue with similar electricity saving as this year? If yes, then how many years can you continue?” The answer “Can be continued forever” accounted for over 70% in all regions, especially for respondents in Tokyo, which had the highest willingness of continuing to save electricity. The average number of possible years of continuing to save electricity for those who answered “Can be continued for a limited time” was 2.8 (±2.8) years.

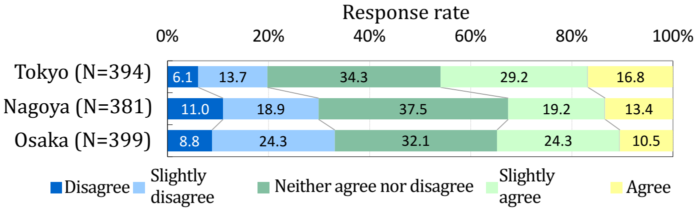


Figure 3-18. Agreement or disagreement with continued measures to save electricity in the upcoming fiscal year.

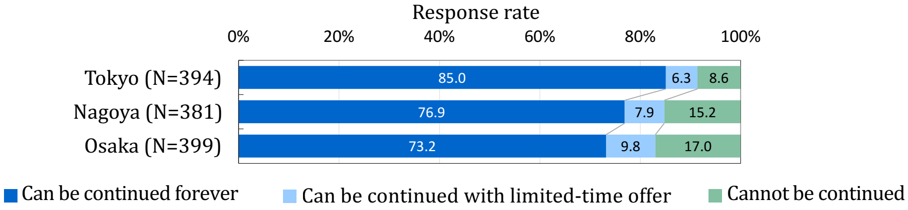


Figure 3-19. The number of possible years of continuing electricity-saving measures.

(3) Changes in self-estimated productivity

Figure 3-20 shows changes in productivity from 2010. The question was “Compared with the summer of 2010, how much would you estimate you have lost or gained in terms of productivity in the summers of 2011 and 2012?” Note that self-reported productivity is not identical to actual productivity, although Humphreys et al. [8] reported that self-assessed productivity in the office environment has a certain relationship with actual productivity, and an especially strong relationship with employee satisfaction. The average self-estimated productivity change was calculated by excluding answers of “No work at office in this year or previous year.” As a result, the average values of the three regions were -3.4% in 2011 and -2.1% in 2012. These values improved from -3.9% in 2011 to -1.5% in 2012 in Tokyo, and from -3.8% in 2011 to -2.1% in 2012 in Nagoya. However, they did not change in Osaka where they were -2.7% in 2011 and in 2012.

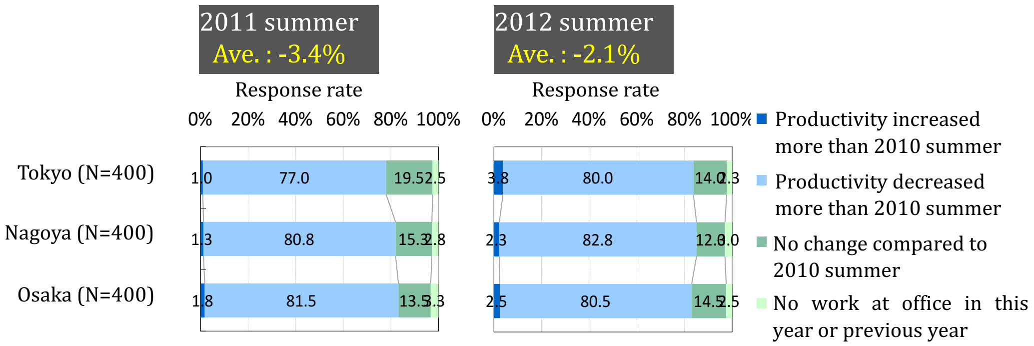


Figure 3-20. Changes in productivity from 2010.

Dividing the above results about electricity saving (Figure 3-13–Figure 3-19) into positive or negative groups, it was found that there were many negative answers concerning electricity saving with Osaka first, followed by Nagoya and Tokyo in that order. Strongly negative answers, such as “Negative,” “Very inconvenient,” and “Clearly unacceptable,” were larger in Nagoya than in Osaka. The following reasons can be considered for these results of differences in electricity-saving awareness by region:

1. The power plants of Chubu Electric Power (including Nagoya), and Kansai Electric Power (including Osaka) were not directly affected by the earthquake.
2. Changes in the electricity-saving target values from the 2011 summer to the 2012 summer were different by region.

3.5 Results and discussion of indoor environmental quality by region, gender, and age

The results of the questionnaire about indoor environmental quality in the 2012 summer are shown in section 3.5. Comparative analyses by region as well as by employee gender and age were conducted. The number of respondents in their 20s and 60s was small in this research, therefore we analyzed the data by dividing all respondents into three groups as follows: those in their 20–30s (n = 341), those in their 40s (n = 488) and those over 50 (n = 371). The number of respondents in each region was 400, of whom 963 were male and 237 were female.

The Mann-Whitney U test was performed to identify the significant difference between two items (= gender). To find a significant difference among three items (= region and age), the Kruskal-Wallis test was first performed. The Mann-Whitney U test was then performed along with the adjustment of the Holm–Bonnferoni method by one set for significant differences identified by the Kruskal-Wallis test.

Those which were significant at $p < 0.05$ were indicated as “*” in the figures, while significance at $p < 0.01$ are indicated as “**.” All significance tests were performed using the same methods as indicated above.

3.5.1 Perception of the working environment

(1) Brightness

Figure 3-21 shows the level of brightness on the employees' desk using a scale of -2 (very dark) to +2 (very bright). To the left is the bar graph showing the Response rate, while the error bar showing the average value and the standard deviation are on the right. The same format applies to subsequent figures.

The ratings given to "very dark" and "dark" made up less than 15% in all classification groups while "neutral" accounted for more than 80% of the total. There were no significant differences between male and female, or among the three age groups. However, there was a significant difference according to region; the ratings of dark or very dark in Nagoya were significantly lower ($p < 0.05$) than in Tokyo and Osaka. One of the reasons may be that the rate of electricity-saving measures practiced, such as "Daylight harvesting and turning off lights" and "Abstaining from using task lighting," and so on were lower than in Tokyo and Osaka as shown in Figure 3-9.

Respondents were also asked about the level of brightness in the office. The stated rate of darkness in the work room was a few percentage points higher (about 15% of the total) than with respect to the desk, but no significant differences were found in any of the classification groups.

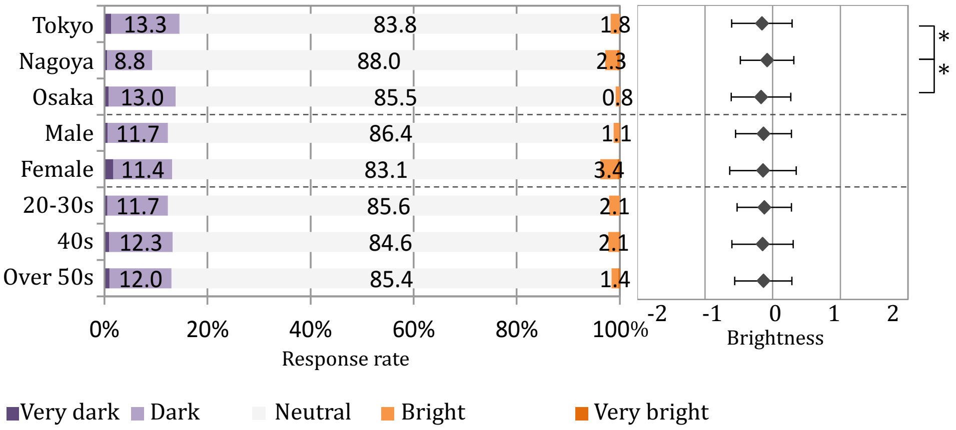


Figure 3-21. Level of brightness on the employees' desk.

(2) Thermal sensation/air dryness/air movement

Figure 3-22 shows thermal sensation, air dryness, and air movement in office environments by location. Thermal sensation was measured on the ASHRAE scale, with +3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, and -3 = cold.

The answers of “slightly cool,” “neutral,” and “slightly warm” constituted 65% of all answers in the three regions, and there were no significant differences in thermal sensation seen between regions. The respondents who chose “hot” made up about 15% of all answers, which may have been caused by excessively raising the setting of the room’s air temperature. Analyses of differences in the trends between genders and among age groups revealed that a higher proportion of female and younger people responded with “cold” ($p < 0.01$).

Regarding air dryness (+3 = very humid, +2 = humid, +1 = slightly humid, 0 = neutral, -1 = slightly dry, -2 = dry, and -3 = very dry), the largest number of answers in every region was “neutral,” followed by “slightly dry.” On the other hand, analyses of the differences between the genders and among the age groups revealed that a higher proportion of female and younger people responded with “dry” ($p < 0.01$).

Regarding air movement (+1 = feel no air movement, +2 = feel weak air movement, +3 = feel normal air movement, +4 = feel strong air movement), about 90% of every region’s respondents chose “feel no air movement” or “feel weak air movement.” There was a significant difference only between males and females, which showed that females found it easy to feel air movement.

3.5.2 Comparison with PMV and PPD

Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) were calculated and compared with thermal sensation responses and thermal environmental satisfaction to confirm the validity of the statements concerning the air temperature in the work space. For air temperature and radiation temperature, 27.3°C was used based on the questionnaire result shown in 3.4. It was assumed that the metabolic rate is 1.1 met, which is the standard assumption for office work. Moreover, they were assumed that relative humidity is 50% RH, and air velocity is 0.15 m/s. For the clothing value, questionnaire results from females fluctuated, so males' average clo value (= 0.53 clo) was used.

The average PMV was 0.57, a number close to 0.53 which was identified by the questionnaire as males' average thermal sensation. At the same time, the PPD was calculated at 11.8%. Of the male respondents, 8.7% chose "dissatisfied" with the thermal environment, and 29.3% chose "slightly dissatisfied," which meant that this PPD (= 11.8%) was nearly equal to the rate of the those who chose "dissatisfied" (= 8.2%); 10% of the respondents chose "slightly dissatisfied" (= about 2.9%) in this survey.

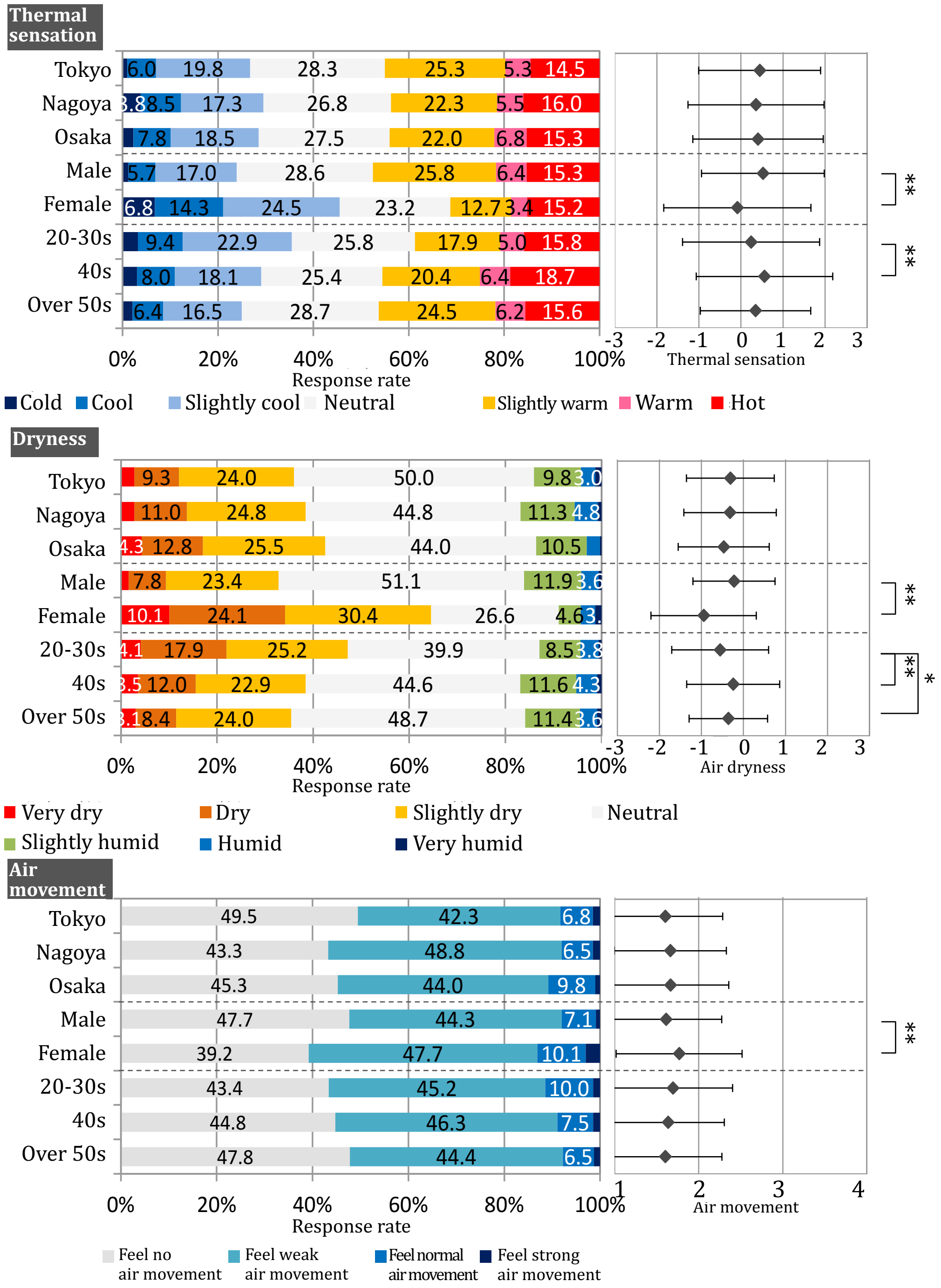


Figure 3-22. Thermal sensation, air dryness, and air movement in office environments by location.

3.5.3 Indoor environmental satisfaction

Figure 3-23 shows indoor environmental satisfaction, Figure 3-24 shows satisfaction with air temperature/relative humidity/air velocity, and Figure 3-25 shows reasons for dissatisfaction with lighting/thermal/indoor air environment.

We defined the satisfaction rate as the proportion of “satisfied: +2” or “slightly satisfied: +1” answers to the total number of answers; the dissatisfaction rate is the proportion of “dissatisfied: -2” or “slightly dissatisfied: -1” answers to the total number of environmental satisfaction questionnaires. Note that Figure 3-24 only shows graphs comparing gender and age because significant differences in thermal sensation, dryness, and air movement were not shown in each region previously mentioned (Figure 3-22). We only asked for reasons of dissatisfaction (Figure 3-25) from the employees who answered that they were “dissatisfied” or “slightly dissatisfied” with the lighting/thermal/indoor air environment. It should be noted that where an analysis of satisfaction in each environment was carried out between males and females, a declaration of dissatisfaction on the part of females was significantly higher concerning the following aspects of the environment: thermal sensation, air quality, space, and the overall environment. It is not proper to discuss about the differences in each district by not distributing male and female; because there were differences in some environments according to gender. Thus, we compared the order of the average value of satisfaction in each environment in the case of all the respondents divided by gender or not. As a result, the order of the means concerning environmental satisfaction by region was almost the same: Tokyo > Osaka > Nagoya or Tokyo > Nagoya > Osaka. In particular, the declared rate of dissatisfaction among females in Osaka tended to be higher in all environments. Moreover, the environmental satisfaction differences due to age, among the over 50s in Tokyo was around 10% higher than in the other two regions. However, each environmental satisfaction rating in Tokyo was almost the same by age group. Thus, differences by region and the ranking of the three regions were investigated not by dividing all respondents by gender or age, although there are composite differences among the respondents by gender and age in each region. The satisfaction rating of each environment is described in the following section.

(1) Lighting environment

Many electricity-saving measures like “Daylight harvesting,” “Turning off lights after office hours,” “Turning off lights during lunch,” “Abstaining from using task lighting,” and

“Daylight shielding with blinds” were undertaken (Figure 3-9). In particular, many employees answered that “Turning off ceiling lights” was the most annoying measure although the percentage was less than 20% of the 1,200 total respondents (Figure 3-11). The dissatisfaction rates with the lighting environment were lower than other environmental measures (maximum 20%), and any significant differences were identified in the satisfaction ratings among regions, ages, and between genders. The most common reason given for environmental dissatisfaction with lighting was “Overall darkness.” In the main, the dissatisfaction with the lighting environment in the office due to electricity-saving measures, such as dimming of lighting was found to be relatively small.

(2) Thermal environment

The electricity-saving measure of “Increasing the set temperature point” was conducted most often in every region and was also the most annoying measure (Figures 3-9, 3-11). Thermal environmental satisfaction included satisfaction with air temperature, relative humidity, and air movement. The thermal dissatisfaction rate was the highest of all rates, at around 40%. Dissatisfaction with air temperature was especially high, and “Overall hotness” was the highest reason for dissatisfaction (70%), followed by “Temperature difference by location” at 30%. Although some significant differences in thermal sensation, dryness, and air movement were seen among different ages, they were not seen in the satisfaction expressed among regions and ages. However, between genders, the satisfaction of females was significantly lower than that of males ($p < 0.05$).

(3) Indoor air environment

“Less ventilation” was not indicated as an annoying measure in Figure 3-11; however, the dissatisfaction rate of indoor air quality was more than 30%, which was the second highest rate in all environments. Additionally, the significant differences in the dissatisfaction rate were seen among regions, ages and between genders; the dissatisfaction rate was higher in Tokyo than Nagoya or Osaka, higher in elderly than among younger people, and higher in females than males. “Stagnation of indoor air” was the highest source of dissatisfaction (over 65%), followed by “Dirtiness of the air.” As it is conceivable that there is deterioration in the perceived air quality due to the rise in temperature [9], thermal environmental improvements should be carried out at the same time as improvements to the air quality environment.

(4) Sound/Space/ICT/Overall environment

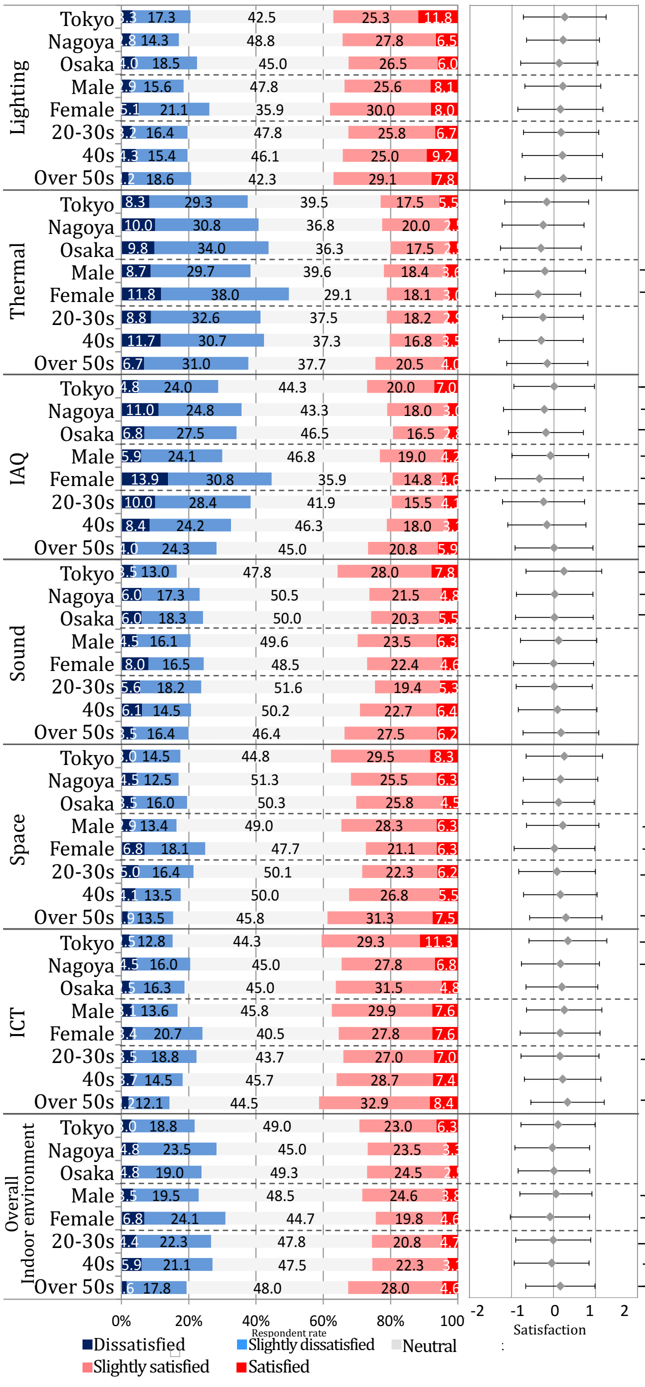
The dissatisfaction rate of these four environments (sound/space/ICT facilities/comprehensive) was lower than that of the other environments. The satisfaction rate of the usability of ICT facilities was the highest of all the environments. With regard to the sound environment, there were significant differences among regions, and the dissatisfaction rate in Tokyo was the lowest among the three regions. Females and younger people had higher dissatisfaction rates concerning space and overall environments, whose reason can be assumed due to business content and occupations. Several electricity-saving measures for the ICT facilities such as “Saving PC energy” and “Turning off the switch of the PC” and so on were practiced; however, not too many complaints were reported. Significant differences were seen between respondents from Tokyo and Nagoya, between people in their 20–30s, and among the over 50s; younger people had more dissatisfaction with the usability of ICT facilities.

Overall, the answer of “neutral” was the major rating except for females’ thermal rating of environmental satisfaction. Moreover, it can be concluded that there were large differences in satisfaction rate and dissatisfaction rate by environment. Among them, the dissatisfaction rate for thermal environment was the highest and accounted for about 40% of responses, followed by ratings for indoor air environment. Regarding the satisfaction rate, the usability of ICT facilities and the lighting environment were rated highly (about 40%). On the other hand, the thermal environment and indoor air quality rating were each around 20%.

In the context of electricity saving in the office since the Great East Japan Earthquake, this study reconfirmed that the acceptable range for changing the lighting environment is broad compared to changing the indoor thermal environment and indoor air quality, as shown in previous research [7]. Moreover, the dissatisfaction rate in all the environments except for lighting and the spatial environment in Tokyo, was the lowest (= satisfaction rate was the highest), although statistically significant differences were not identified. Although it may be that the ratio of differences in respondents’ attributes affected the differences in indoor environmental dissatisfaction rates, the differences in electricity-saving target numbers, and differences in employee awareness of saving electricity in each region can be affected by the differences in those target numbers.

3.5.4 Effects of indoor environmental quality on work performance

Figure 3-26 shows the effects of each indoor environment on work productivity; the scale ranges from -2 (worsened) to +2 (improved). As a result, the answer of “No effect” constituted the majority or more than 50% of all answers. In addition, the rate of respondents who answered “worsen” or “slightly worsen” compared to the entire answers showed almost the same percentage trends as the environmental dissatisfaction rates shown in Figure 3-22. The ratio of the thermal environment answers “worsen” and “slightly worsen” to the rate of work productivity was the highest of all. On the other hand, the ratio of answers “improved” or “slightly improved” made up only a few of all the responses to the environments. Among them, the ratio of ratings of the usability of ICT facilities as “improved” and “slightly improved” in relation to work productivity in Tokyo especially was a little higher overall. The significant difference was seen in the rate at which the lighting environment worsened the work productivity between Tokyo and Osaka. Regarding the thermal environment, it was seen as the same across all age groups. The significant differences were seen in indoor air environment by gender, sound environment by gender, the usability of ICT facilities between Tokyo and Nagoya, and comprehensive indoor environment by gender and age (i.e., the 40s and over 50s groups).



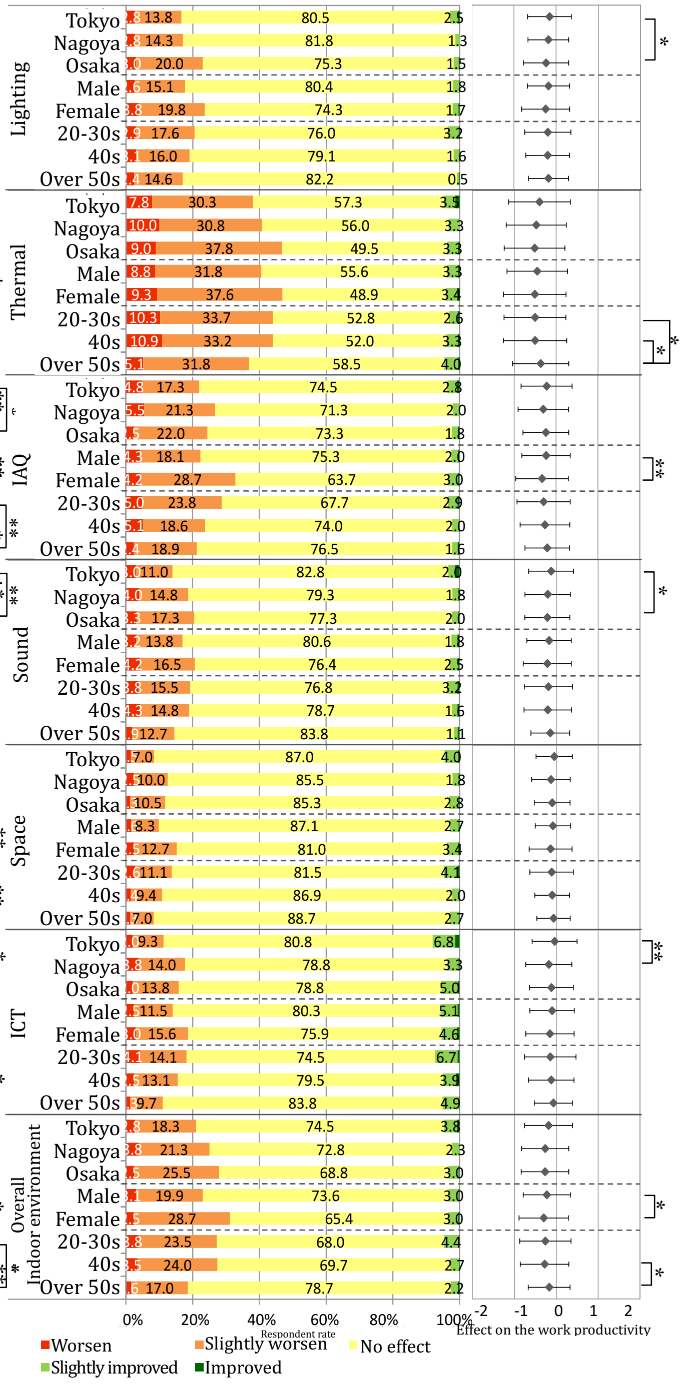


Figure 3-23. Indoor environmental satisfaction. (left)

Figure 3-26. Effects of each indoor environment on work productivity. (right)

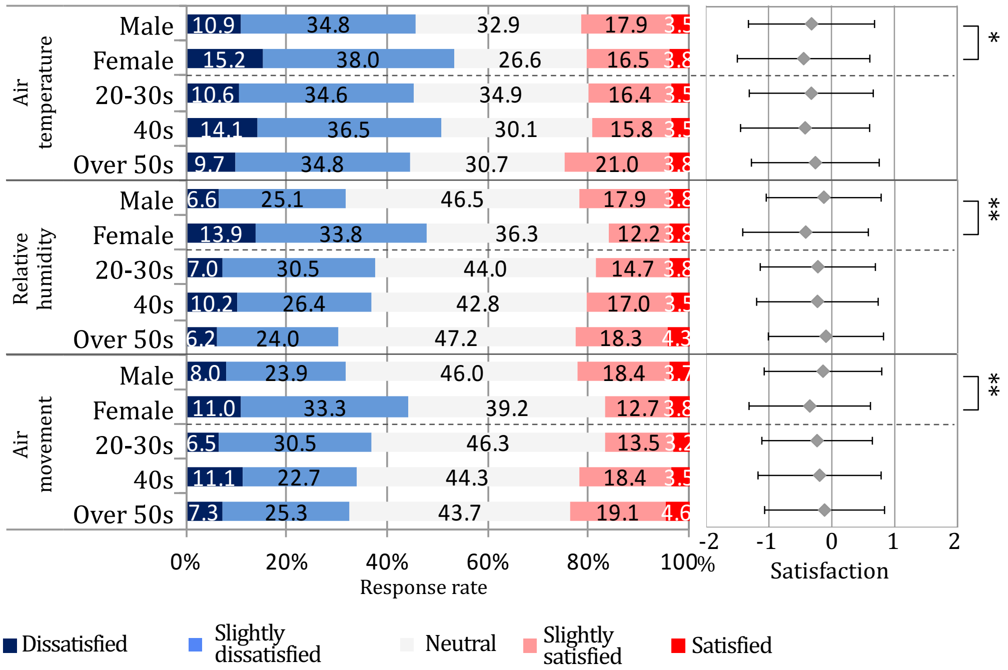


Figure 3-24. Satisfaction with air temperature/relative humidity/air velocity.

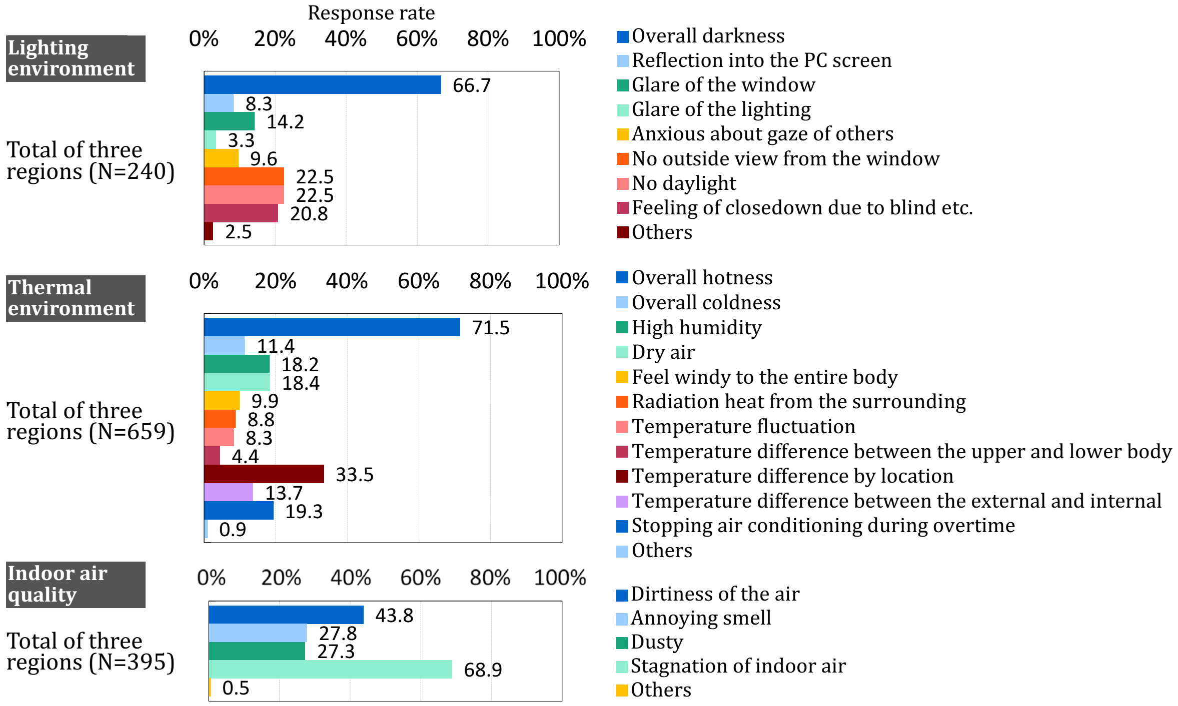


Figure 3-25. Reasons for dissatisfaction with lighting/thermal/indoor air environment.

3.6. Results and discussion of indoor environmental quality by awareness of electricity-saving

The averages of each environmental dissatisfaction rate were ranked in the following order: Osaka > Nagoya > Tokyo or Nagoya > Osaka > Tokyo, though there were no significant differences (5.3). This is the same order and magnitude of the negative feelings about electricity-saving measures in each region, which were discussed in the survey questions concerning awareness of electricity-saving. The reason that can explain this is that the differences in the electricity-saving target values and employee awareness of electricity-saving, which could be affected by those target values, are reflected in satisfaction with the office environment of each region. Additionally, there is also the possibility that raising the electricity price had reduced the employee awareness of electricity-saving; TEPCO raised 8.46% of electricity price in September 2012. Therefore, we analyzed the results of indoor environment surveys by the awareness of electricity-saving measures expressed; this is especially apparent in Figure 3-15 (positive or negative attitudes to saving electricity) where difference of awareness about electricity saving appear remarkable. The answers were classified into two categories: negative (in total 265 respondents, who chose “negative” and “slightly negative”) and positive (in total 935 respondents, who chose “positive” or “slightly positive”). The results are indicated in section 3.6. The negative answers were particularly identified by men in their 20s in Osaka: 43%, and men in their 30s in Nagoya: 37%. We undertook the same analysis and show the results in Figure 3-17 (Acceptability of decreasing comfort because of electricity-saving measures) and Figure 3-18 (Agreement or disagreement with continued measures to save electricity in the upcoming fiscal year), and obtained similar results as the analysis shown in Figure 3-15. Note that the answers of Figure 3-18 were classified into two categories as following: disagree (the respondents who chose “disagree” and “slightly disagree”) and agree (the respondents who chose “agree” or “slightly agree”).

3.6.1 Perception of working environment

Figure 3-27 shows assessments of brightness/thermal sensation/dryness/air movement. The more “negative” feeling people had for power-saving measures, the higher the rate of answers that were on the “dark side” with respect to the amount of available light (brightness) with a significance level of 1%. In addition, people who had “negative” feelings toward power saving declared more “hot side” thermal sensations with a significance level of 1%; this may be the reason that there were many males who rated this condition negatively. On the other hand, “positive” side respondents felt more air dryness and air movement, with a significance level of 5%. Furthermore, the declared air temperature in respondents' work spaces were recalculated with the same way (by dividing respondents into the positive side and negative side for electricity-saving) as shown in 3.3.4. Table 3-2. The result was 27.5±1.4 ℃ for those who were positive, and 27.2±1.5 ℃ for those who were negative; this range did not show the large differences between the two.

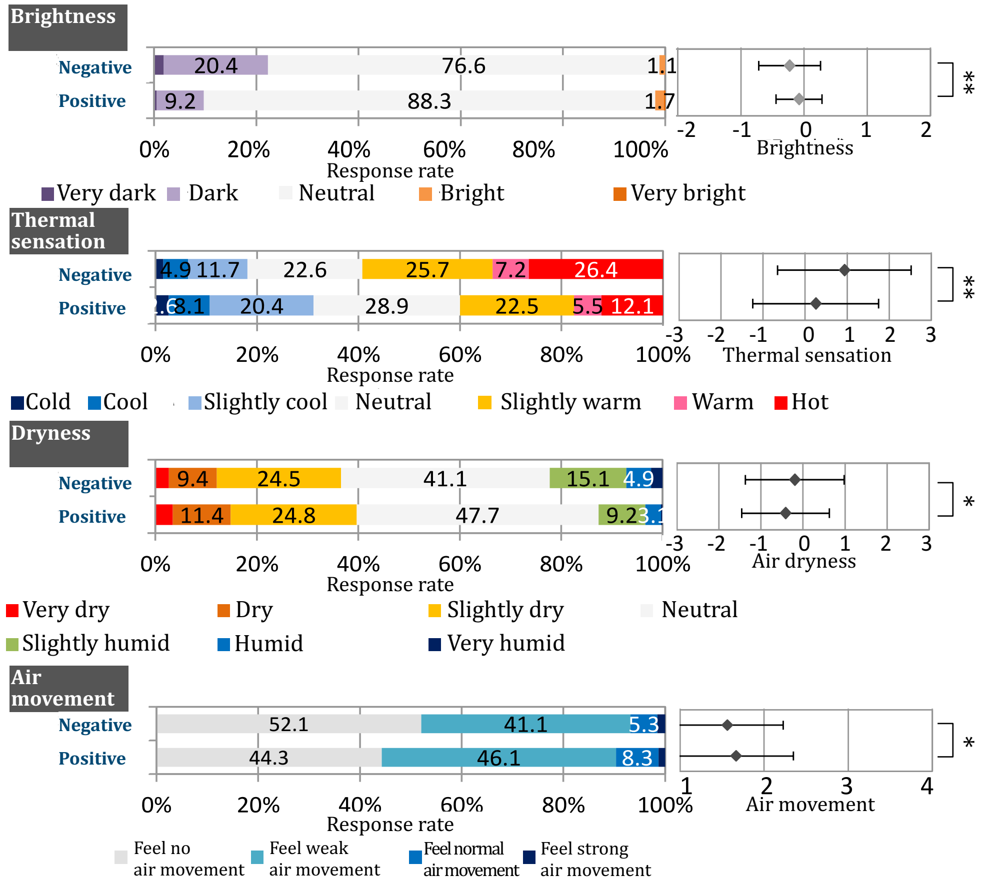


Figure 3-27 Brightness/thermal sensation/dryness/air movement.

3.6.2 Indoor environmental satisfaction

Figure 3-28 shows satisfaction levels for each environmental condition. In all environments, the dissatisfaction rate of the "negative" side was significantly higher than that of the "positive" side ($p < 0.01$). The largest difference seen between the two sides is the thermal environmental dissatisfaction rate (25%). When the data on awareness of the power savings were analyzed by classifying it into two categories: negative and positive sides, a similar rate and trend are also seen in the "worsened" side effects of each indoor environment on work productivity.

The more employees a region has who are positive about saving electricity, the lower the thermal dissatisfaction rate appears to be in the region, although the thermal indoor environment of the office was almost the same in the three regions, as shown in Figure 3-22 and Table 3-2. The following facts in Figure 3-28 may show the reasons why thermal environmental satisfaction as well as other environmental satisfactions of the "positive" group were significantly higher than those of the "negative" group. It was suggested in the results that there is the possibility that differences in electricity-saving awareness affected environmental satisfaction levels.

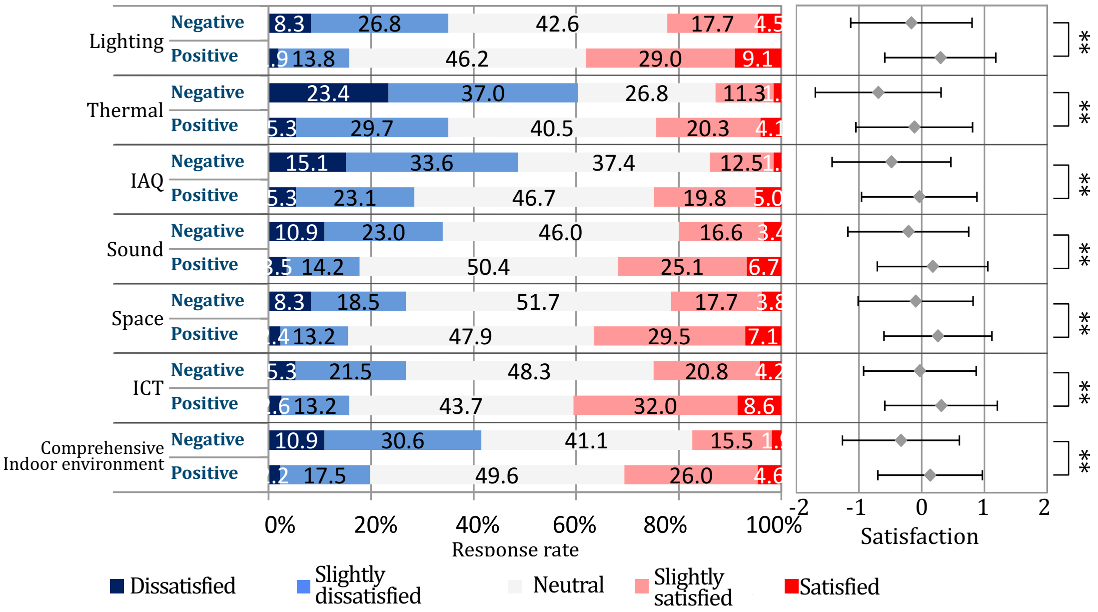


Figure 3-28. Satisfaction levels for each environmental condition.

3.7 Conclusions

In this study, web-based questionnaire for 1200 employees in Tokyo, Nagoya, and Osaka was conducted to investigate their awareness, measures for saving electricity, and the effects of these on indoor environmental quality. Indoor environmental quality was analyzed by employee gender and age as well as by region.
The following conclusions were obtained:

1. Similar electricity-saving measures were implemented in three areas in the summers 2011 and 2012. The measures that were practiced the most were “Adoption of Cool Biz,” followed by “Increasing the set temperature point”; more than 60% of employees found the latter the most annoying measure. The average change rate for all measures of electricity saving practiced from the summer of 2011 to the summer of 2012 were -1.7% for Tokyo, +0.4% for Nagoya, and +2.3% for Osaka. The change rate decreased in Tokyo; however, electricity-saving measures were conducted at the same level as other regions, although clear electricity-saving target values had not been determined in the 2012 summer. Therefore, it was found that saving electricity has been established in Tokyo.
2. The difference concerning awareness of electricity-saving among regions was confirmed. A higher percentage of awareness about electricity saving was found with Osaka having higher awareness than Nagoya, which in turn had higher awareness than Tokyo, from 2011 to 2012. On the other hand, respondents’ expressed inconvenience caused by the measures, and the unacceptability of decreasing comfort due to electricity saving was the highest in Osaka, followed by Nagoya, then Tokyo. It was suggested that backgrounds where electricity-saving measures were undertaken and the electricity-saving target values of each region could have affected awareness of saving electricity to no small extent.
3. Regarding environmental satisfaction, the dissatisfaction rate with the thermal environment (“turning up the set point of the air conditioning”) was the highest although electricity-saving measures relating to lighting environment (e.g., lowering illumination) were mostly conducted in offices. Employees generally expressed discomfort relating to air temperature and humidity, but widely accepted the decrease in illumination among the range of electricity-saving measures described. Moreover, the rate at which the environment worsens employee productivity showed

almost the same percentage values as the dissatisfaction rate with the environment, which implies the possibility that dissatisfaction with the environmental quality reduces work performance.

4. The more employees who were positive about power-saving in a region, the less thermal dissatisfaction rate the region showed, although the indoor thermal environment of the office was almost the same in the three regions. The reason for this may be that thermal environmental satisfaction as well as other environmental satisfaction of the "positive" group were significantly higher than those of the "negative" group. It was revealed that employee satisfaction with the office environment was affected to a large degree not only by the indoor environment or their gender and age, but also by their attitudes.

Out of the many efforts undertaken on global environmental issues, it is fundamentally important to increase people's awareness.

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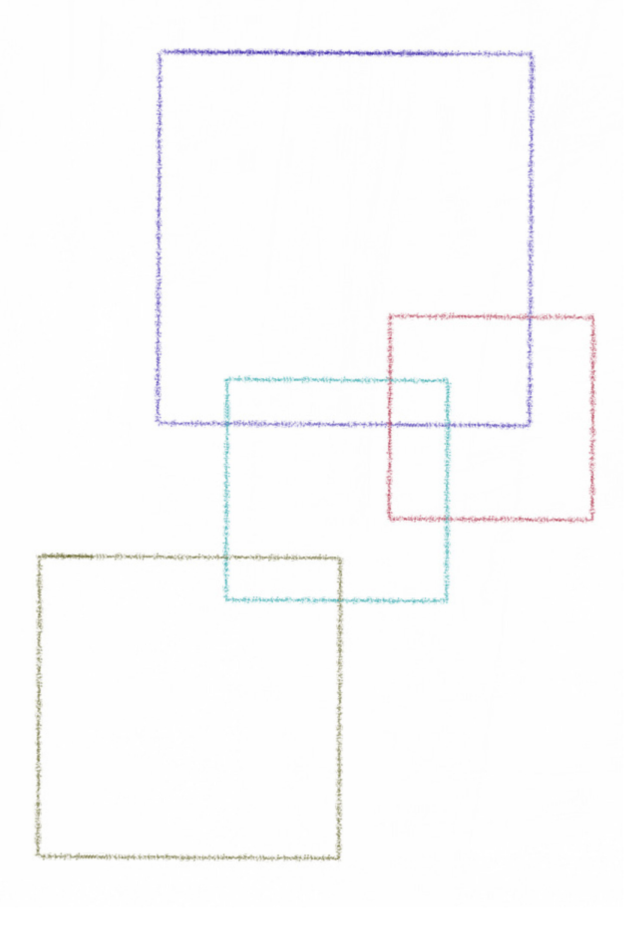
Outline

Chapter 4

Changes in the behavior of workers and indoor environmental quality based on the post-earthquake electricity-saving experiences



4.1 Objective and general approach

This research aimed to reveal the extent to which employee behaviors had changed regarding energy consumption and productivity since the impact of the earthquake disaster. No study to date had investigated such behavior changes caused by the mandatory electricity-saving experiences in the workplace.

Energy-saving measures have been promoted in offices in Tokyo for both environmental and safety reasons, especially after the Great East Japan Earthquake. Mechanical power-saving is definitely important; however, building devices that induce the occupants' energy-saving actions are vital. This research would be considerably useful to other countries, whether or not they experience a natural disaster.

The author had conducted continuous field and questionnaire surveys in seven electricity-saving office buildings in the summers of 2011–2013. Additionally, the past research data of our laboratory was collated, and in total, 60 cases with 3692 questionnaires were analyzed.

4.2 Methodologies

Surveys in electricity-saving offices were conducted from 2011 to 2013 in order to investigate how these offices may have changed; in particular, how the indoor environment and employee awareness have changed was the target for the investigation. Continuous field and questionnaire surveys were conducted in seven electricity-saving office buildings in the summers of 2011–2013. Also, our laboratory's past research data (15 buildings, 17 cases: 2003–2012) were collected, and analyzed together with our field data. All buildings have not been continuously measured for many years. This means that the measured buildings and measurement period of the data are almost all different, and, of course, respondents are different, too. However, the measurements, questionnaire items, and survey methods were almost the same throughout all investigations. We only used the data to investigate the indoor environmental quality (IEQ) and employee feelings toward the IEQ at that time, and to compare that data to the other measurement period.

4.2.1 Outline of buildings

Table 4-1 lists the characteristics of these buildings. All cases were studied in the Kanto area comprised of seven adjacent prefectures, including Tokyo, which plays a key role in the politics and economy of Japan. This area is 32,423.90 km^2 in total, and about one-third of the total population of Japan (42,598,300 people) is concentrated there. The GDP in the Kanto area was 199,993,380 million yen in 2011 [1], making it a huge economic zone. All buildings we surveyed are located in this area, where a 15% peak-power reduction was carried out in the summer of 2011. All buildings had functioning air conditioning systems (HVAC), as the studies were carried out during the hot and humid summer season. The surveyed periods are from 2003 to 2013, and each study case is numbered, from No. 1 to No. 60, in chronological order.

The seven electricity-saving office buildings surveyed are labeled as follows: Building L, M, N, O, P, Q, and R. In the 2011 study of case Nos. 16–19, 20–23, 24–27, 28–31, and 32–35, as mentioned above, we varied the temperature, illuminance, and ventilation rate of the target office floors in order to find relationships between each environmental parameter and employee awareness of saving electricity. Each environmental condition was counted as one case. In case Nos. 52 and 60, only the questionnaire survey was conducted and asked the occupants for their overall feelings about saving electricity without taking any physical measurements or carrying out satisfaction assessments. Further, the energy data of Building N, which is equipped with the Building Energy Management System (BEMS) was analyzed.

Office plans and measurement points of each floor are shown in appendix.

4.2.2 Physical measurements and representative days

Physical conditions were recorded in each investigated building. Table 4-2 shows the variables measured over long time periods and the representative days. For analysis, representative days was selected depending on the number of questionnaire respondents and outdoor air temperature. Data from Tokyo meteorological stations close to these buildings were used to represent outdoor conditions. Air temperature and relative humidity were recorded at several points on each floor of the buildings depending on the size of the floor. Average values for these variables during office hours (namely 9:00–17:00) were calculated for analysis. Detailed measurements of vertical temperature distribution, air velocity, noise level, occupancy rate, and occupants' behavior were also conducted on the representative day as a part of these cases. The percentage of occupants participating was high in almost all cases.

4.2.3 Questionnaires

Questionnaire surveys for office employees were conducted to investigate the employee comfort and productivity. In the studies of Buildings L–R, which were surveyed from 2011 to 2013, we also asked employees about means and awareness of saving electricity.

(1) Satisfaction and productivity

Center for the Built Environment (CBE) at the University of California, Berkeley. The survey implemented CBE research measures occupant satisfaction and self-reported productivity in nine IEQ categories in an invite-style web-based questionnaire, as described in Abbaszadeh et al. [2]. The present study uses a similar questionnaire for assessment of visual comfort, air quality, and thermal comfort. In Japan, the Japan Sustainable Building Consortium (JSBC) proposed SAP [3], which measures productivity based on web questionnaires. In contrast, Humphreys and Nicol say that workers' environmental satisfaction is related to their productivity [4]. In our study, we placed special focus on workers' satisfaction with the IEQ. Workers' satisfaction-dissatisfaction levels were measured on or modified as follows: +2 = satisfied, +1 = slightly satisfied, 0 = neutral, -1 = slightly dissatisfied, and -2 = dissatisfied.

Thermal sensation was measured on the ASHRAE scale, with +3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, and -3 = cold. Questionnaires were delivered directly to occupants' desks; we requested that occupants place the completed questionnaires in a sealed box. Table 4-3 shows the questionnaire contents used for this analysis and the number of questionnaire answers. These 60 cases were classified into three categories using the earthquake year (2011) as a boundary; (pre-earthquake, year of the earthquake, and post-earthquake) and compared. Table 4-4 shows each categorical questionnaire's answers by gender and age. No large differences were seen in each categorical rate.

Table 4-1. Outline of buildings for the investigation.

Building	Place	Completion Year	Total Floor Space [m^2]	Air Conditioning System	Number of Stories*	Target Floor	Survey Number	Survey Period										
								2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
A	Ibaraki	2003	13,741	Underfloor supply	10F/–**	3F	1	●										
B	Tokyo	2003	28,220	Ceiling supply	14F/B2	6F	2		●									
C	Tokyo	1979	–	Ceiling supply	6F/–	3F	3			●								
D	Tokyo	1983	101,301	Ceiling supply	26F/B3F	23F	4,7				●	●						
E	Kanagawa	2006	8,645	Underfloor supply	3F/–	2F	5–6					●						
F	Kanagawa	1961	–	Ceiling supply	2F/–	–	9					●						
G	Kanagawa	2007	69,472	Underfloor supply	7F/B2F	6F	10						●					
H	Tokyo	1982	3,776	Ceiling supply	3F/B1F	3F	11								●			
I	Tokyo	1992	4,475	Ceiling supply	3F/B1F	2F	12								●			
J	Tokyo	1999	7,300	Ceiling supply	3F/B1F	2F	13								●			
K	Tokyo	2010	5,535	Underfloor supply	3F/–	–	14									●		
L	Kanagawa	1996	5,645	Ceiling supply	4F/–	3F	15,40,52									●	●	○
M	Tokyo	2007	15,163	Ceiling supply	14F/B2F	7F	44										●	
N	Tokyo	2007	33,517	Ceiling supply	15F/B2F	8F	16–19									●		
						10F	20–23,45,53									●	●	●
						2F	24–27,46,54									●	●	●
						8F	8					●						
						9F	28–31,47,55									●	●	●
O	Tokyo	1989	29,468	Ceiling supply	9F/B1F	4F	32–35,48,56									●	●	●
P	Tokyo	1988	11,187	Ceiling supply	10F/B1F	3F	36,49,57									●	●	●
						5F	58											●
Q	Tokyo	1993	43,320	Ceiling supply	18F/B2F	7F	37,50,59									●	●	●
R	Tokyo	1984	14,741	Ceiling supply	40F/B3F	26F	38–39,51									●	●	
						–	60											○
S	Tokyo	2011	12,537	Ceiling radiation panel	6F/B2F	5F	41										●	
T	Tokyo	2011	104,000	Ceiling radiation panel	27F/B5F	27F	42										●	
U	Ibaraki	2012	14,777	Underfloor supply	6F/–	2F	43										●	

*Number of stories: above ground floor/basement floor
*●: conducted both field and questionnaire surveys
○: conducted only questionnaire survey

Table 4-2. Physical parameters measured over a long time period.

Building	Survey Number	Representative Day (mean outdoor temperature [°C])	Air Temperature and Humidity			Illuminance			CO_2 concentration		
			Level [m]	Point [number]	Interval [min]	Level [m]	Point [number]	Interval [min]	Level [m]	Point [number]	Interval [min]
A	1	Aug. 26 (29.0)	0.6	9	0.5	1.1	1	0.5	return air	4	60
B	2	Aug. 11 (28.9)	1.1	21	1	–	–	–	–	–	–
C	3	Aug. 22 (29.3)	1.1	18	1	1.1	4	1/6	1.1	1	10
D	4,7	Aug. 31 (29.4), Aug. 8 (29.1)	at desk level	30,36	10	0.7	1	10	1.1	1,1	10
E	5–6	Aug. 21･24 (30.4)	1.1	12	5	–	–	–	1	2	10
F	9	Jul. 27 (29.8)	at desk level	18	5	at desk level	7	5	1.1	1	–
G	10	Jul. 31 (29.7)	at desk level	6	5	at desk level	6	5	1.1	1	5
H	11	Aug. 27 (31.9)	1.1	20	10	at desk level	3	10	1.1	1	10
I	12	Aug. 27 (31.9)	1.1	14	10	at desk level	2	10	1.1	1	10
J	13	Aug. 27 (31.9)	1.1	1	10	at desk level	1	10	–	–	–
K	14	Aug. 24 (29.1)	1.1	41	10	at desk level	8	10	1.1	2	10
L	15,40,52	Jul. 27 (28.4), Aug. 7 (29.5), –*	1.1	16,16,–	10	at desk level	9,9,–	5	1.1	1,1,–	10
M	44	Aug. 7 (31.1)	1.1	4	10	–	–	–	1.1	1	1
	16–19	Aug. 2･5･8･11 (30.6)	1.1	4	10	at desk level	1	1	at desk level	1	1
	20–23,45,53	Jul. 19･22･25･28 (26.9), Aug. 7 (31.1), Jul. 30 (29.6)	1.1	2,2,4	10	at desk level	1,1,2	1	at desk level	1,1,1	1
N	24–27,46,54	Jul. 19･22･25･28 (26.9), Aug. 7 (31.1), Jul. 30 (29.6)	1.1	3,3,4	10	at desk level	1,1,2	1	at desk level	1,1,1	1
	8	Aug. 22 (34.8)	1.1	42	5	1.1	7	1/6	–	–	–
	28–31,47,55	Jul. 19･22･25･28 (26.9), Aug. 7 (31.1), Jul. 30 (29.6)	1.1	5,4,4	10	at desk level	1,1,2	1	at desk level	1,1,1	1
O	32–35,48,56	Aug. 2･5･8･11 (30.6), Aug. 7 (31.1), Jul. 30 (29.6)	1.1	5,12,12	10	at desk level	1,1,2	1	at desk level	1,1,1	1
P	36,49,57	Aug. 11 (33.6), Aug. 28 (31.9), Jul. 30 (29.6)	1.1	3,3,4	10	at desk level	1,1,2	1	at desk level	1,1,1	1
	58	Jul. 30 (29.6)	1.1	2	10	at desk level	1	1	–	–	–
Q	37,50,59	Aug. 9 (32.3), Aug. 7 (31.1), Jul. 30 (29.6)	1.1	1,1,2	10	at desk level	1,–,2	1	at desk level	1,1,1	1
R	38–39,51	Aug. 5･11 (31.6), Aug. 1 (31.2)	1.1	1	10	at desk level	1,1	1	at desk level	1,3	1
	60	–	–	–	–	–	–	–	–	–	–
S	41	Aug. 7 (31.0)	1.1	12	10	–	–	–	1.1	1	10
T	42	Aug. 8 (28.0)	1.1	32	5	at desk level	10	5	1.1	1	10
U	43	Aug. 24 (32.2)	1.1	4	10	at desk level	2	10	1.1	1	10

*– : measurement was not conducted.

Table 4-3. Physical parameters and questionnaire answerers.

Building	Survey Number	Questionnaire Item				
		Thermal Environment		Visual Environment		IAQ
		Thermal Sensation	Satisfaction	Brightness Sensation	Satisfaction	Satisfaction
A	1	70	–	–	–	–
B	2	84	–	–	–	–
C	3	44	–	–	–	–
D	4,7	115,141	118,142	–	–	115,140
E	5–6	46/42	–	–	–	–
F	9	33	33	33	32	32
G	10	60	40	–	40	40
H	11	28	28	26	28	27
I	12	22	22	21	22	22
J	13	31	31	30	31	31
K	14	117	119	119	119	119
L	15,40,52	128,116,–	127,114,–	128,114,–	128,110,–	127,117,–
M	44	44	44	44	42	44
N	16–19	31/38/36/35	29/38/36/36	31/38/36/36	29/38/36/33	31/38/36/36
	20–23,45,53	37/38/44/45,41,22	37/38/44/44,41,22	37/38/44/45,41,22	37/38/42/44,41,22	37/38/44/45,41,21
	24–27,46,54	50/51/48/53,46,53	49/50/47/50,46,52	50/50/47/53,46,53	50/46/44/49,44,53	49/51/48/53,44,53
	8	86	–	–	–	–
O	28–31,47,55	73/76/73/88,86,88	72/74/74/87,87,88	73/76/74/88,87,88	72/75/71/87,84,86	73/76/74/88,87,88
	32–35,48,56	98/98/92/96,83,96	97/97/90/95,83,96	98/98/91/94,83,96	94/93/91/92,80,95	98/98/92/95,83,96
P	36,49,57	50,34,35	50,34,35	50,34,35	47,34,35	50,34,35
	58	22	22	22	22	22
Q	37,50,59	68,32,35	66,35,35	68,32,35	67,32,35	68,32,35
R	38–39,51	73/53,43	71/53,43	44/44,56	43/43,55	73/53,43
	60	–	–	–	–	–
S	41	29	29	–	28	29
T	42	126	126	–	126	126
U	43	96	96	96	96	96

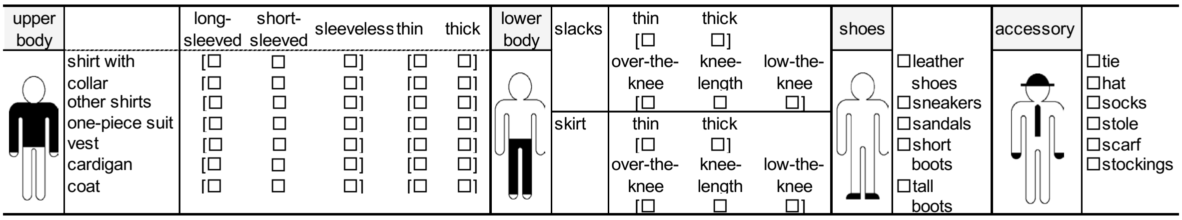
*– : questionnaire was not conducted.

Table 4-4. Attributes of the questionnaire respondents of each classification.

Survey Period	Gender		Age						Total
	Male	Female	10s	20s	30s	40s	50s	60s	
Pre-earthquake	446	159	3	145	196	149	104	9	749
(2003–2010)	74%	26%	0%	24%	32%	25%	17%	1%	
Earthquake year	1194	479	0	258	298	527	314	160	1693
(2011)	71%	29%	0%	17%	19%	34%	20%	10%	
Post-earthquake	872	394	0	229	271	373	227	84	1250
(2012–2013)	69%	31%	0%	19%	23%	32%	19%	7%	

(2) Clothing value

To evaluate thermal comfort, it is important to determine the clothing characteristics of respondents. Figure. 4-1 illustrates the questionnaire used to assess clothing ensembles. Each part of clothing (clo) value was calculated based on ISO9920 [5] and summed up to calculate overall clothing value. In this study, we did not include chair insulation in the calculation of overall clothing value.



upper body		long-sleeved	short-sleeved	sleeveless	thin	thick
	shirt with	[☐	☐	☐]	[☐	☐]
	collar	[☐	☐	☐]	[☐	☐]
	other shirts	[☐	☐	☐]	[☐	☐]
	one-piece suit	[☐	☐	☐]	[☐	☐]
	vest	[☐	☐	☐]	[☐	☐]
	cardigan	[☐	☐	☐]	[☐	☐]
	coat	[☐	☐	☐]	[☐	☐]

lower body				
	slacks	thin [☐	thick ☐]	
		over-the-knee [☐	knee-length ☐	low-the-knee ☐]
	skirt	thin [☐	thick ☐]	
		over-the-knee [☐	knee-length ☐	low-the-knee ☐]

shoes	
	☐leather shoes ☐sneakers ☐sandals ☐short boots ☐tall boots

accessory	
	☐tie ☐hat ☐socks ☐stole ☐scarf ☐stockings

Figure 4-1. Questionnaire for clothing ensembles.

4.3 Results

4.3.1 Energy consumption

Energy consumption levels for the ninth floor of Building N on representative summer days from 2007 to 2013 are shown in Figure. 4-2 (per day) and Figure. 4-3 (per hour). Building N was completed in 2007 and equipped with the Building Energy Management System (BEMS). The representative days were selected by the average outdoor temperature (about 30 °C) and maximum temperature (about 34 °C) excluding the first day of the week. Then, we analyzed the BEMS data.

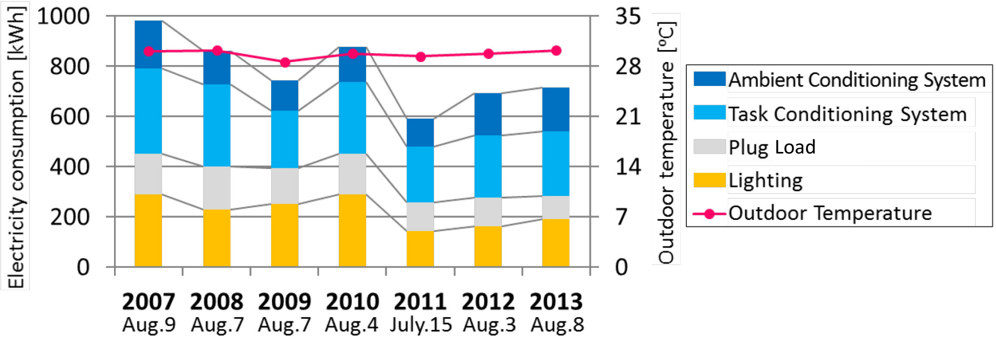


Figure 4-2. Electricity consumption of Building B (9F) on representative summer days (per day).

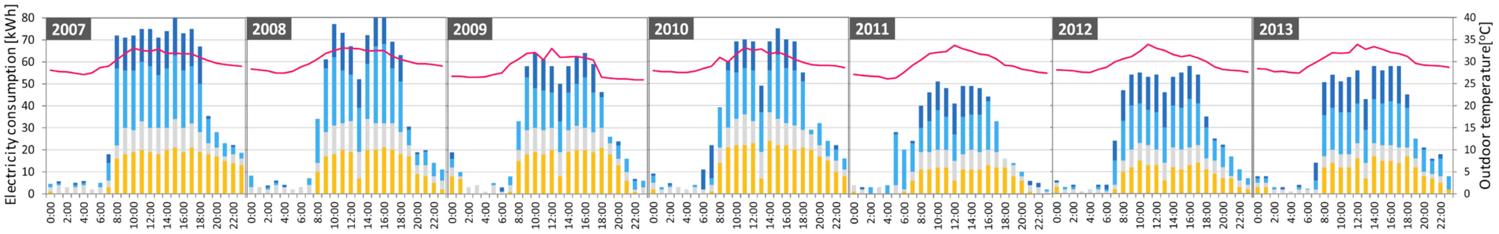


Figure 4-3. Electricity consumption of Building B (9F) on representative summer days (per hour).

The results show that electricity consumption decreased substantially during the year of the earthquake (2011). In 2011, total electricity consumption decreased by over 30% compared with 2010. Especially, electricity consumption by plugs and lighting has decreased by about 45%. These electricity consumption rates remained at lower levels after the earthquake; however, electricity consumption by the air conditioning system reverted back to the pre-earthquake level. Incidentally, energy consumption in 2009 is less than that in 2007, 2008, and 2010. It can be assumed that the bankruptcy of Lehman Brothers*1 on September 15, 2008 influenced the electricity consumption of offices. When the bankruptcy of Lehman Brothers, called the "Lehman shock," broke out, a lot of funds had problems and the Japanese company was affected, too. In general, however, the average post-earthquake energy consumption of the ninth floor of Building N decreased over 20% compared with that of pre-earthquake.

4.3.2 Means of saving electricity

The target employees of the investigation were asked to rate the measures taken to save electricity and to indicate which caused the most annoyance; they were allowed to check multiple answers (Figure. 4-4).

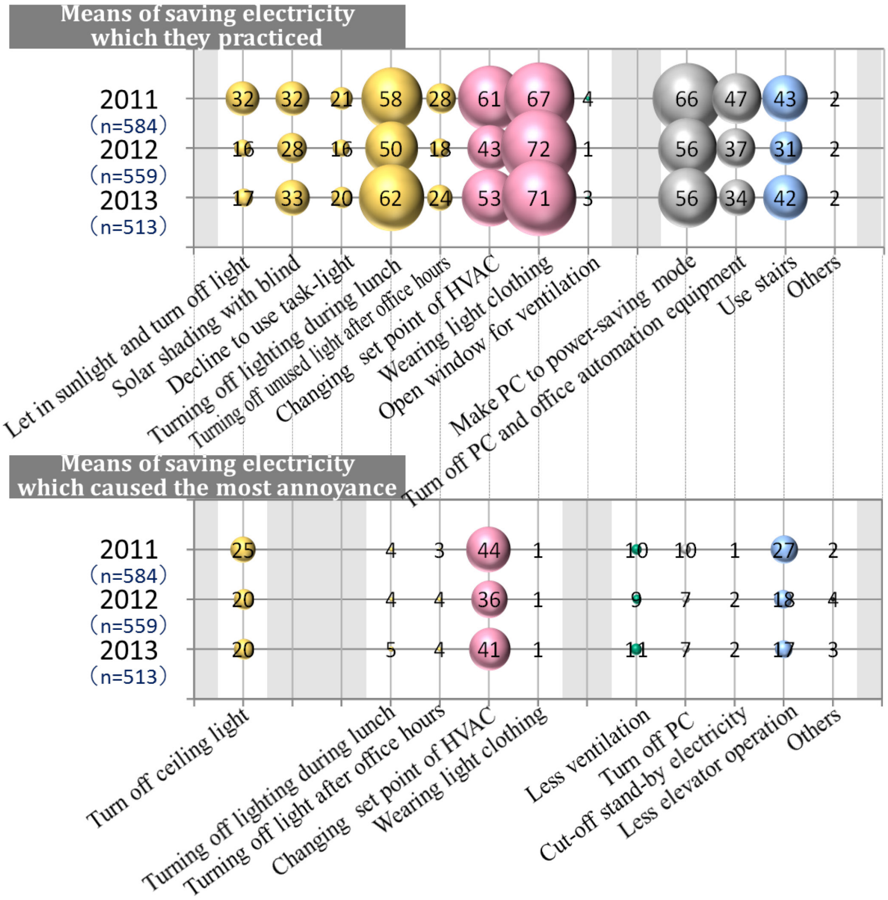


Figure 4-4. Measures taken to save electricity and which of them caused the most annoyance.

In 2011 the ratios of the practice of “Turning off lights during lunch break” and “Adoption of Cool Biz; wearing light clothing” were at a high rate, around 60%, compared with other practices, and these ratios were maintained for three years, from 2011 to 2013. Moreover, almost all respondents did not feel annoyed about these means of saving electricity. Conversely, “Increasing the set temperature point” occurs in over half the building now, even with most of the respondents feeling annoyed about it. These results show that raising the room set-point temperature of HVAC as a means of saving electricity should be reconsidered. Also, the practice rate of “Daylight harvesting”, which means reducing electric light in building interiors when daylight is available, was over 30% in 2011; however, it declined to under 20% after the earthquake. The annoyance response rate for this means of saving electricity had been relatively high; therefore, good utilization of daylight should be investigated in the future.

4.3.3 Awareness of electricity-savings

To investigate the attitudes of office employees toward saving electricity in the five buildings (Building L, M, N, O, and P) discussed above and in two additional buildings (Building Q and R), we asked the following questions: “How did your awareness of electricity-saving change after the Great East Japan Earthquake?” and, “How do you think about electricity-saving?”

The average answer to the question of awareness of electricity-savings was low side before the earthquake. It increased into the high side significantly in 2011, the year of the earthquake (Figure. 4-5, left). After the earthquake it declined, but remained on the high side. Approximately 90% of employees are on the positive side of saving electricity in 2013 (Figure. 4-4, right).

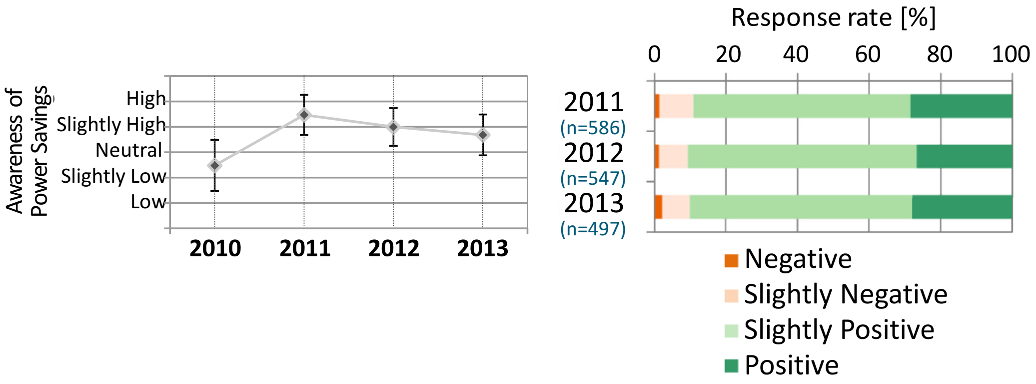


Figure 4-5. Changes in the awareness of electricity-saving (left); positive or negative feelings towards electricity-saving (right).

Moreover, the employees were asked the following questions: "How do you feel about the measures taken by your office to save electricity today?" and, "Do you accept the decrease in comfort caused by the energy savings?" Over half of the respondents noted some degree of inconvenience caused by energy-saving measures (Figure. 4-6, left). Employees who cannot accept the decline in level of comfort due to energy saving have increased since the earthquake, and now the rate has reached about 50% (Figure. 4-5, right). That is to say, most employees feel positive about saving electricity, though some also feel inconvenience.

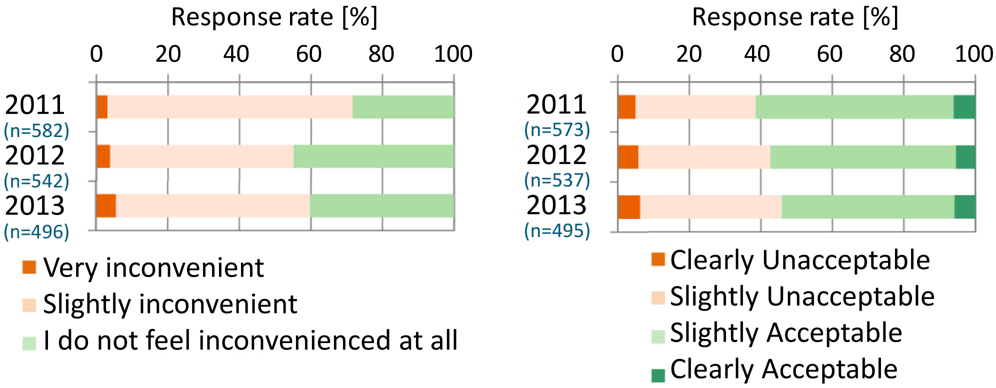


Figure 4-6. Perceived degree of inconvenience caused by electricity-saving measures (left); acceptability of decreased comfort caused by energy saving (right).

4.3.4 Changes in self-estimated productivity

The employees were also asked to rate their own loss in productivity by asking them the following question: "compared with the summer in 2010, how much would you estimate you have lost or gained in terms of productivity in the summers of 2011, 2012, and 2013?" (Figure 4-7). Humphreys and Nicol (2007) evaluated productivity in the office environment through self-assessment, with methods similar to those employed in this experiment [4].

When considering the average productivity of the 474 responses provided in 2011, we found that loss in productivity was 6.6%. Although the answer of 0%, indicating no change in productivity, accounted for most of responses, a 10% decrease of productivity was indicated by about 30% of respondents in 2011. This represents a notable reduction in productivity, with considerable economic impacts. However, it cannot be claimed that such changes in productivity are purely a result of environmental conditions and thermal comfort: office employees in Tokyo may have had other reasons such as the mood of depression for their reduced productivity during the summer of earthquake year. We intend to further investigate this in a future study. On the other hand, the perceived change in productivity in 2012 and 2013 increased back to around 0%. Thus it is considered that productivity returned to an almost normal level (i.e. back to pre-earthquake levels) one year after the earthquake.

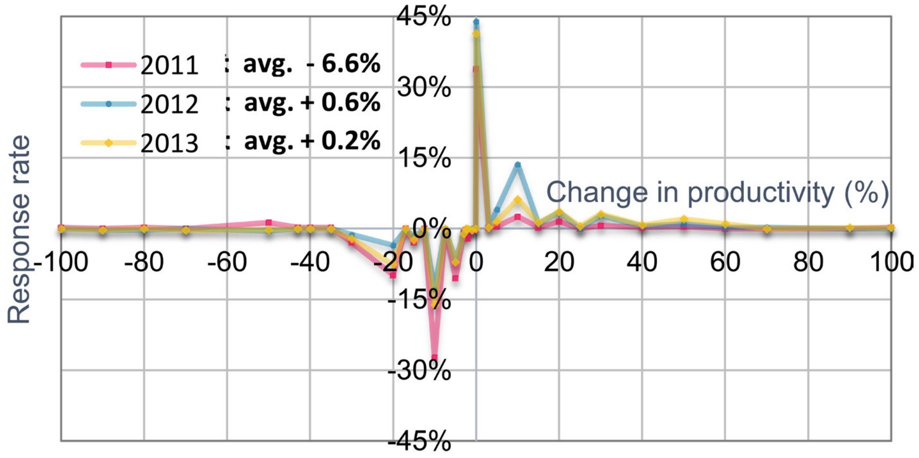


Figure 4-7. Productivity changes under electricity-saving in 2011, 2012 and 2013.

4.3.5 Change of IEQ and employee satisfaction through the earthquake

To investigate the change of IEQ and employee satisfaction through the earthquake, we collected our past research data (15 buildings, 17 cases: 2003–2012) and analyzed it together with our field data (2011–2013).

The relationship between the mean desk level illuminance and mean visual satisfaction is shown in Figure. 4-8, and the relationship between mean room air temperature and mean thermal satisfaction is shown in Figure. 4-9. The cases of loss and non-measurement are left blank.

For the lighting environment, desk level illuminance decreased substantially, from 751 lux to 390 lux. This is because actions such as “Let in sunlight and turn off light” and “using task-lighting system” as well as turning off light during unnecessary time such as “turning off lighting during lunch break” have been conducted since after the earthquake. About 80% of mean lighting satisfaction showed satisfaction, and there was not a difference seen in mean lighting satisfaction by the mean desk level illuminance.

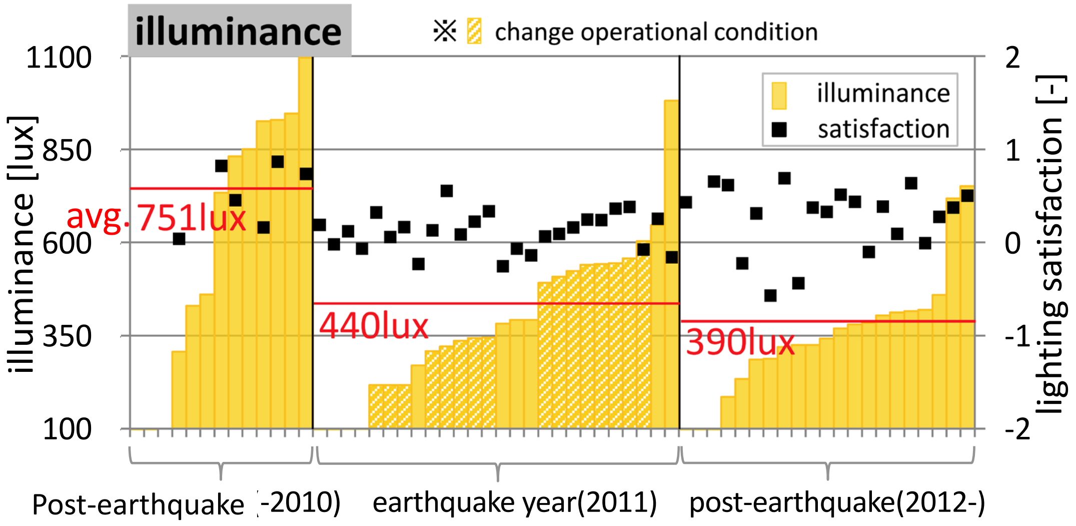


Figure 4-8. Mean desk level illuminance and mean visual satisfaction.

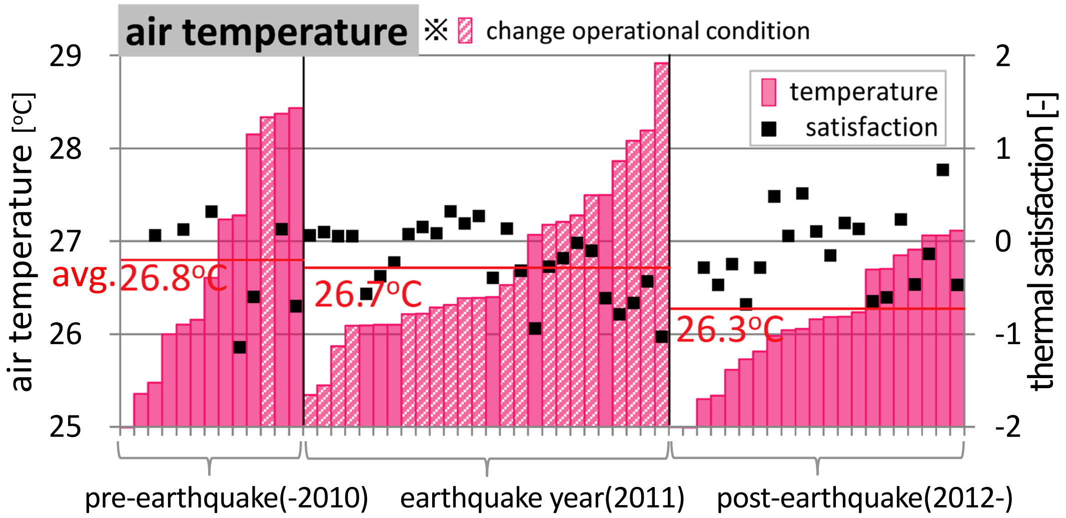


Figure 4-9. Mean room air temperature and mean thermal satisfaction (right).

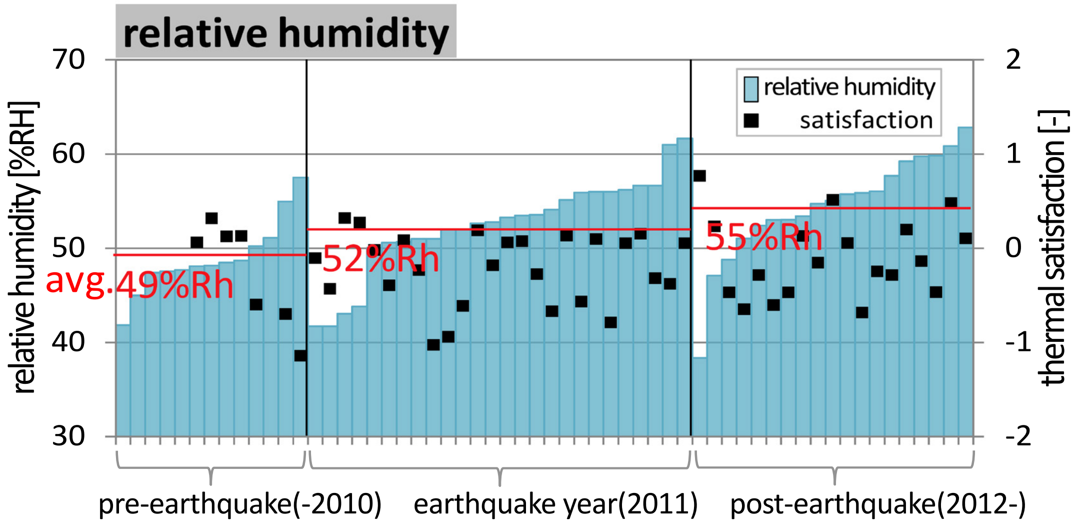


Figure 4-10. Mean room relative humidity and mean thermal satisfaction.

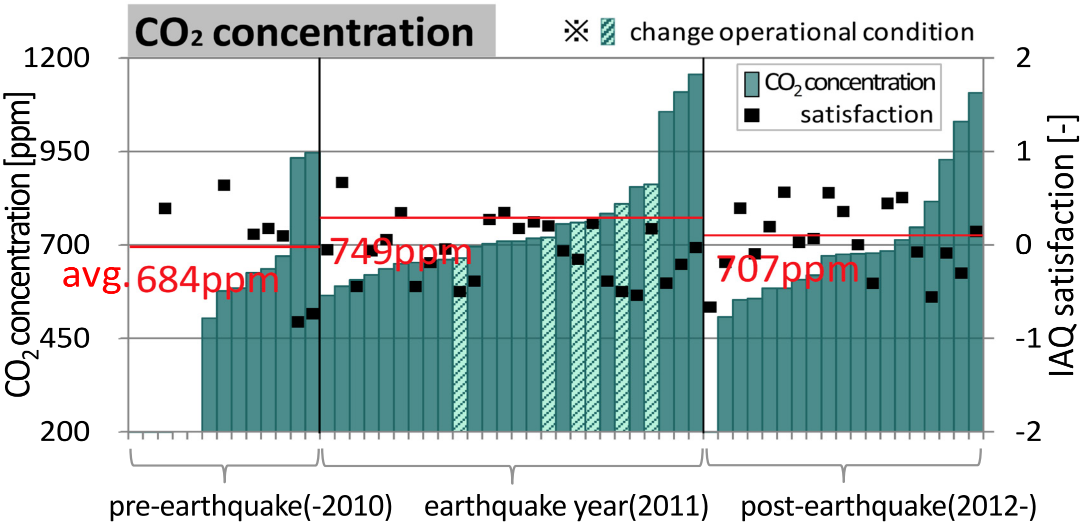


Figure 4-11. Mean CO_2 concentration and mean IAQ satisfaction.

For the thermal environment, the mean temperature exceeded 28 °C in one case, which was the upper limit determined by the building hygiene method. It can be assumed that there are two main reasons for this. One is simply the effects of changing indoor environment setting conditions, such as the indoor temperature experimentally in 2011. The other is the "COOL BIZ" campaign, an initiative led by the government from 2005 onwards that recommended raising the room set point temperature of the work space to 28 °C, and wearing light clothing and using items like folding fans for employees [6]. In the year of the earthquake (summer of 2011), the Japanese government promoted the urgent electricity saving measures and strongly demanded raising the room set point temperature. However, after 2012, we realized from the summer of 2011 experience that we could cope with the saving electricity by decreasing illumination, internal load reduction, and wearing further light clothing, like polo shirts, as part of the "Super COOL BIZ" Campaign [7] without reducing productivity by raising the room set point temperature excessively. So, after the earthquake disaster, mean air temperature became almost 26–27 °C, and excessive indoor air temperatures, like 28 °C, were avoided. The satisfaction varied by indoor temperature and half of the mean satisfaction value was on the "dissatisfaction" side.

The CO_2 concentration and relative humidity did not change largely between pre-earthquake and post-earthquake as shown in Figure. The relative humidity was in the range of mostly between 40–60%RH. The CO_2 concentration was in the range of 500–1200 ppm. 4-10 and Figure. 4-11. The average CO_2 concentration was about 700 ppm.

There was temperature distribution in office floors. We assigned a value of temperature and relative humidity that was measured at the nearest measurement point to the seat of each questionnaire respondent (shown in appendix). These values were used to calculate of Standard New Effective Temperature "SET*," which is the general thermal environment evaluation index consisting of six elements: air temperature, relative humidity, radiation temperature, air velocity, clothing value, and metabolic rate. SET* is defined as the equivalent air temperature of an isothermal environment at 50% RH (relative humidity) in which a subject, wearing clothing standardized for the activity concerned, has the same heat stress and thermoregulatory strain as in the actual environment [8]. We assumed that radiation temperature is equal to ambient air temperature and the metabolic rate is 1.1 met, which is the assumption for office work. For the air velocity, the actual measured value was used, but in the non-investigation case (No.8, 11–13, 16–19, 36–40, 45–51, 59), 0.15 m/s was used as an undetectable air velocity. For the clothing value, questionnaire results were used, but in non-investigation cases (Nos. 1, 5–7), 0.5 clo was used as the mean of all investigations. Additionally, we classified SET* every 0.5 °C, grouped it, and calculated an average report level of each group more than n = 10. Then, we analyzed relationships between SET*, thermal sensation, and thermal satisfaction by three chronological divisions: pre-earthquake, year of the earthquake, and post-earthquake.

Relationships between SET* and thermal sensation are shown in Figure. 4-12 (left). There was no significant difference in mean thermal sensation votes between SET* 25.5–27.5 °C by chronological division. However, in the post-earthquake group, mean thermal sensation votes showed more neutral side values below SET*25.5 °C or above SET*27.5 °C than the pre-earthquake group and the earthquake year group. Relationships between SET* and thermal satisfaction are shown in Figure. 4-10 (right). All mean thermal satisfaction rates of the pre-earthquake group were on the dissatisfaction side; however, the rate of the satisfied votes became high in the earthquake year group and the post-earthquake group. Particularly, mean thermal satisfaction did not decrease much, even above SET* 28 °C, in the post-earthquake group. People came to be able to set proper indoor temperatures, and their acceptability zone of thermal environment extended slightly, too.

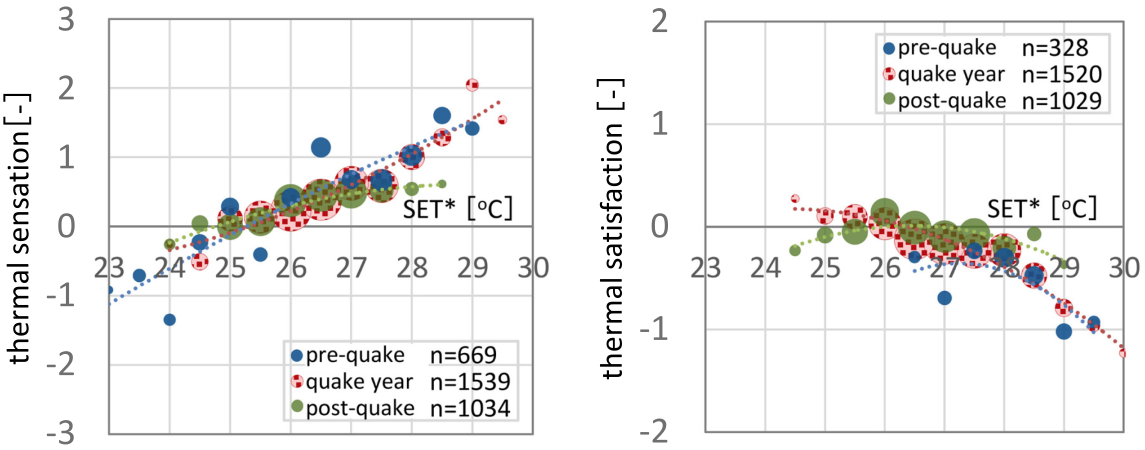


Figure 4-12. SET* and mean thermal sensation (pre-earthquake: $y = -0.014x^2 + 1.18x - 20.7$, $R^2 = 0.85$, $n = 669$; earthquake year: $y = 0.032\,x^2 - 1.34\,x + 13.1$, $R^2 = 0.92$, $n = 1539$; post-earthquake: $y = -0.033x^2 + 1.91x - 27.1$, $R^2 = 0.94$, $n = 1034$) (left); SET* and mean thermal satisfaction (pre-earthquake: $y = -0.052x^2 + 2.76x - 36.5$, $R^2 = 0.65$, $n = 327$; earthquake year: $y = -0.043\,x^2 + 2.08\,x - 25.1$, $R^2 = 0.98$, $n = 1520$; post-earthquake: $y = -0.133x^2 + 7.22x - 98.7$, $R^2 = 0.60$, $n = 1029$) (right).

4.3.6 Environmental satisfaction of each classification

Even as the office environment significantly changed after the earthquake, nearly all of the employees are satisfied with IEQ today. However, there are still a certain number of employees who are unsatisfied with their office environments, as described above.

Thiel (1997) said that individual differences in the way environmental information is perceived can be classified into three categories: (1) physiological parameters (e.g., by gender or age); (2) characteristic traits of information choice (e.g., by a standard of education, culture, or lifestyle); and (3) psychological set (e.g., by appetite or awareness at the time) [9]. No conclusive study that compare individual differences in the way environmental information are perceived has been conducted so far. Given these individual differences, we categorized five of the results obtained from the questionnaires in this research and compared them with the level of environmental satisfaction (with lighting, thermal, indoor air quality, sound, space, and IT environment). The five questions were as follows: (1) gender, (2) age, (3) positive or negative feelings about electricity saving, (4) acceptability of decreased comfort caused by energy saving, and (5) business content satisfaction. We classified each of the answers to these questions into two or three categories: (1) male or female, (2) 20s, 30–40s, or 50–60s, (3) positive or negative, (4) acceptable or unacceptable, and (5) satisfied or dissatisfied. The Mann-Whitney U test was performed to identify the significant difference between two items. To find a significant difference among three items, the Kruskal-Wallis test was first performed. The Mann-Whitney U test was then performed along with the adjustment of the Holm–Bonnferoni method by one set for significant differences identified by the Kruskal-Wallis test.

The results, shown in Figure. 4-13, indicate that the levels of environmental satisfaction differed with the employees' gender, age, and awareness of saving electricity. Particularly, differences in the employee's awareness of saving electricity and work satisfaction had a systematic effect on their satisfaction with IEQ. This indicates that employees who were supportive of saving electricity experienced and reported greater satisfaction with IEQ.

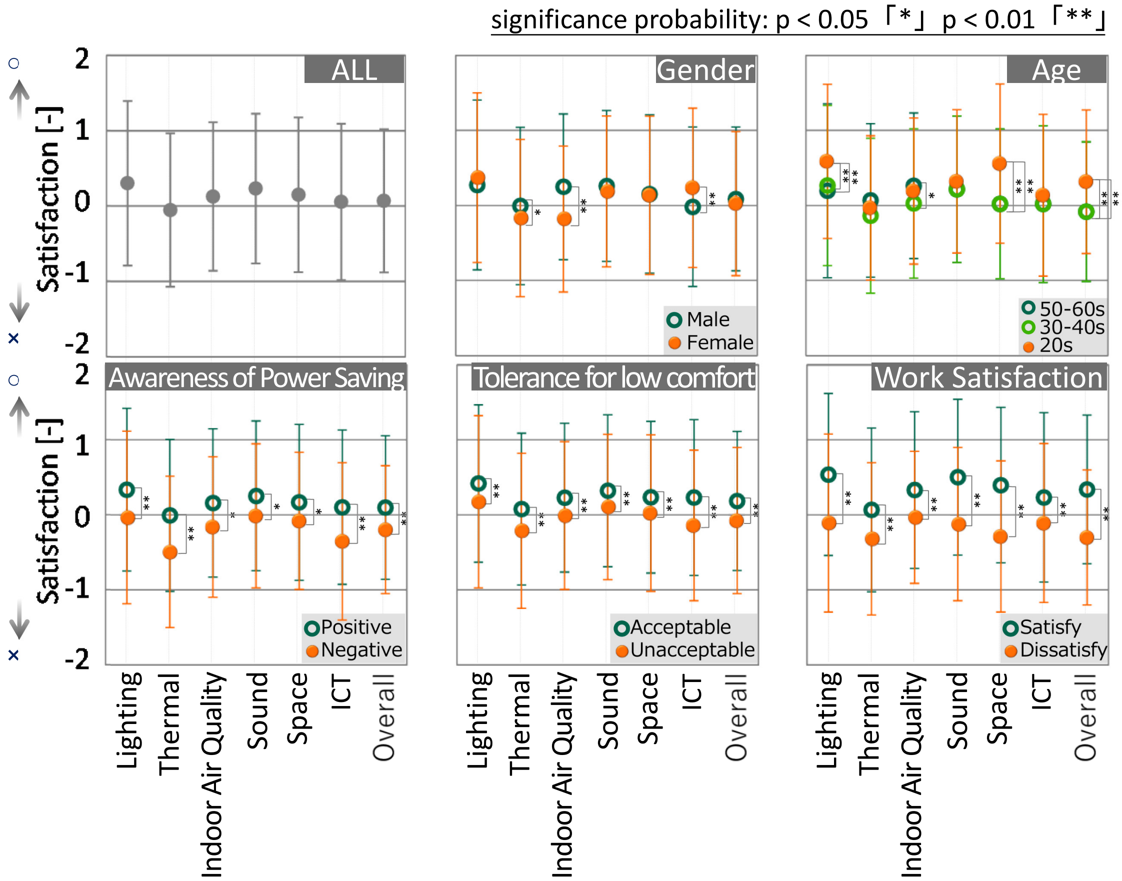


Figure 4-13. Environmental satisfaction levels for each classification.

4.3.7 The environmental factors related to comprehensive environmental satisfaction

For the purpose of prioritizing indoor environmental improvements, the Customer Satisfaction (CS) Portfolio analysis was used to reveal the importance of the factor items (which equal each environment satisfaction) for the comprehensive indoor environment satisfaction. The post-earthquake (2012 and 2013) data was used for analysis. First, we calculated the number and percentage of respondents to each environmental satisfaction's question and divided them into the three categories: the group that indicated they were "dissatisfied" and "slightly dissatisfied," the group that indicated they were "neutral," and the group that indicated they were "slightly satisfied" and "satisfied." Second, a cross analysis between comprehensive indoor environmental satisfaction and each environmental satisfaction metric was conducted, and the qualitative correlation coefficient was calculated. We scored each environmental satisfaction and qualitative correlation coefficient in order of the priority improvement, as shown in the scatterplot with a vertical axis representing the satisfaction deviation value (which represents satisfaction) and a horizontal axis representing the independent factor deviation value (which represents importance). Table 4-5 shows the satisfaction rate and qualitative correlation coefficient of each environment, and Figure. 4-14 shows the classification of the indoor environment satisfaction structure.

Respondents' satisfaction with both thermal and indoor air quality had a weak correlation with comprehensive indoor environmental satisfaction (qualitative correlation coefficient =0.26, 0.31); they had high expectations of, but low satisfaction with, some attributes. In contrast to this, concerning lighting they had low expectations but high satisfaction. We found that there was a need to focus on improving the thermal and air quality environment in the offices after the earthquake.

Furthermore, we asked respondents to check the factors that they felt dissatisfied with, allowing them to check multiple answers (Figure. 4-15). As a result, 39% of respondents felt that they suffered from overall hotness, and 37% of respondents felt that they suffered from the stagnation of indoor air. Hot and humid thermal environment may have affected to the perceived air quality to some extent [10]. Office IEQ is improving following the experience of mandatory electricity-saving; however there is still room for improvement in IEQ.

Table 4-5. Satisfaction rate and the qualitative correlation coefficient of each environment.

	Satisfaction rate* (%)	Qualitative correlation coefficient (-)	Deviation value of satisfaction rate	Deviation value of qualitative correlation coefficient
Lighting	42.0	0.21	68.7	42.2
Thermal	30.0	0.26	41.2	51.3
IAQ	30.0	0.31	41.2	58.8
Sound	33.0	0.18	48.1	37.9
Space	37.0	0.36	57.2	66.4
ICT	31.0	0.22	43.5	43.4
Number	877	877		
Average	33.8	0.26		
Standard deviation	4.37	0.06		

*Satisfaction rate: the percentage of respondents who were “slightly satisfied” or “satisfied”

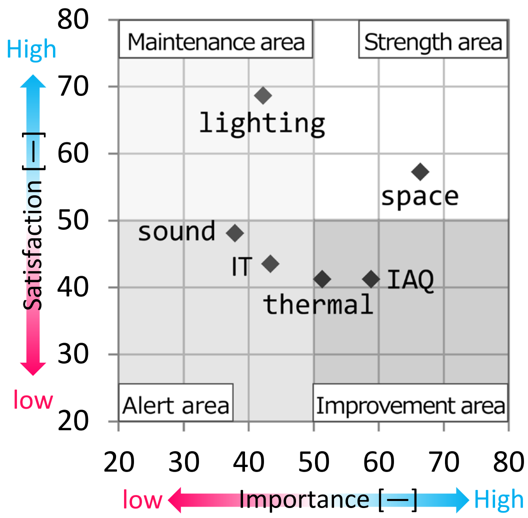


Figure 4-14. Classification of the indoor environmental satisfaction structure.

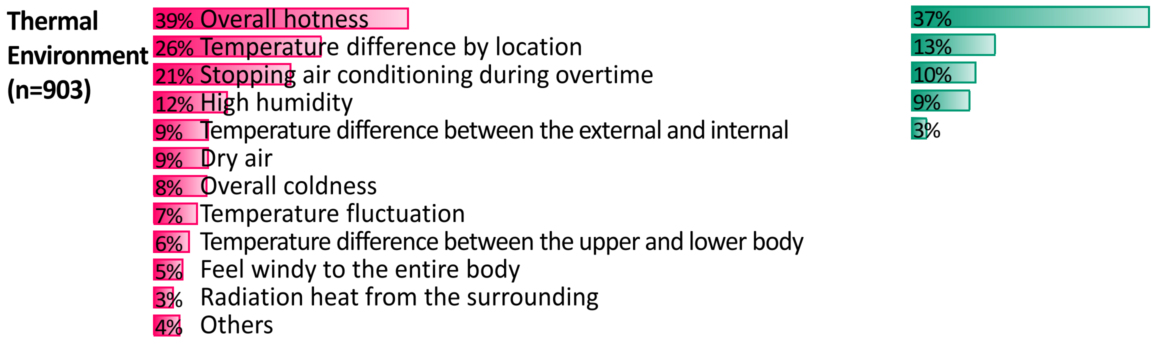


Figure 4-15. Factors of environmental dissatisfaction.

4.4 Discussion

The comfort and productivity of occupants in offices before and after the 2011 earthquake in the Kanto area in Japan were investigated.

Light environment changed the most in office environments after the earthquake. The standard of desk level illuminance in the offices before the earthquake was 750 lux [11], and it was the brightness of the top-class conventionally in the world. However, though various methods to save lighting electricity have been being conducted since the Great East Japan Earthquake, employees did not feel dissatisfied and it was mostly accepted. Moreover, it made energy consumption in office buildings decrease significantly. A supplement of the Japanese Industrial Standards was published after the great earthquake disaster, and an illuminance range of 500–1000 lux was added as the recommended desk level illuminance in the office [12]. We should continue saving lighting electricity in the future; however, the concrete method to decide illuminance in a real illumination design is not specified as of now. An effective way to use daylight and LED light will be needed for the future office.

For the thermal environment in offices, a 28 °C setting had been recommended by the COOL BIZ campaign, where it was encouraged by the government since 2005 [7]. However, after this policy was enforced, much research against a 28 °C setting was conducted in Japan and concluded that a high temperature environment reduced productivity [13, 14]. Immediately after the earthquake, a 28 °C setting was widely conducted as an emergency measure; however, excessive indoor air temperatures, like 28 °C, were avoided later after the earthquake, as mentioned earlier. In fact, it was found that lowering illuminance reduced energy consumption to a greater degree than turning up the temperature of air conditioning units [15]. Moreover, indoor temperature has a significant influence on perceived air quality. Fang et al. (1999) found that, compared with the direct impact of temperature and humidity on the perception of air quality, the impacts of temperature and humidity on chemical emissions from building materials have a secondary influence on perceived air quality [11]. In order to raise employee productivity and reduce personnel expenses, we should work to make the environment as healthy as possible, especially the environmental elements that have a big influence on productivity, like thermal and IAQ.

Moreover, it was thought that individual differences in gender and age have a large effect on environmental opinions. There is much research that focused on these differences [16, 17, 18, 19]. However, this study showed that differences in the employees awareness of saving electricity and work satisfaction had a more profound effect on their satisfaction with IEQ than did employees gender and age. The most affecting factor in improving employee comfort and productivity is raising their awareness. That is to say, mechanical power-saving is important; however, building devices that induce occupants' energy-saving actions are more important.

4.5 Conclusions

This chapter aims to reveal to what extent employee awareness of saving electricity has changed since the Great East Japan Earthquake had an impact on energy consumption and productivity. We have conducted continuous field and questionnaire surveys in seven electricity-saving office buildings in the summers of 2011–2013. We also collected our past research data (15 buildings, 17 cases: 2003–2012), and analyzed it together with our field data. The following conclusions were obtained:

1. After the earthquake disaster, most mean air temperatures were lowered to 26–27 °C, and excessive indoor air temperatures, like 28 °C, were avoided. In contrast, the desk level illuminance greatly decreased from 750 lux (pre-earthquake) to around 400 lux (post-earthquake) and this decreased the electricity consumption of office buildings. The coexistence of comfort and energy saving came to be required more in Japanese offices after the earthquake disaster.
2. Employees awareness of saving electricity hardly diminished after peaking in 2011. Most employees feel positive about saving electricity; however, some also feel inconvenience.
3. The average change rate of self-estimated productivity, as compared with that in 2010 (before the earthquake), improved from -6.6% in the earthquake year to almost 0% after the earthquake.
4. Employees lighting satisfaction did not decrease, even though the desk level luminance greatly decreased from about 751 lux to 390 lux. Moreover, post-earthquake thermal satisfaction was higher than pre-earthquake under the same

thermal environment. Employees acceptability zone for the indoor environment was extended slightly by the experience of electricity saving.

5. Nearly all of the employees are satisfied with the IEQ after the earthquake, but this differed with the employees' gender, age, and awareness of saving electricity. Particularly, differences in the employee awareness of saving electricity and work satisfaction had a profound effect on their satisfaction with the IEQ. The employees who were supportive of saving electricity experienced and reported greater satisfaction with the IEQ. Differences in the employee's awareness of saving electricity had a more profound effect on their satisfaction with the IEQ than those in the employees' gender or age.
6. By using the Customer Satisfaction (CS) Portfolio analysis, we have shown that the indoor air quality and thermal environment are the two environments that need to be improved for increasing employee satisfaction.

It was shown by this research that changes in employee awareness of saving energy largely affect their productivity and energy saving in buildings. Smart energy saving practices that pay careful attention to employees is vital for future sustainable office buildings. It is important not only to seek technological innovation, but to also take action about changing people's awareness.

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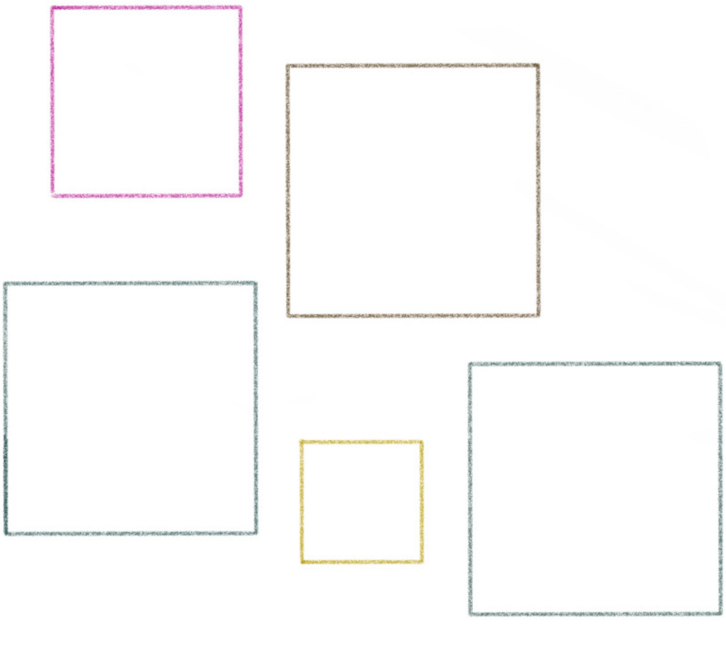
Outline

Chapter 5

Effects of varying air conditioning operation on comfort and energy consumption in an office after the earthquake



5.1 Objective and general approach

Chapter 5 presents the post-earthquake electricity-saving experience caused employee behavioral change i.e. the average desk level illuminance decreased, energy-efficient office automation (OA) equipment was introduced and implemented as well as excessive indoor air temperatures were avoided that resulted in a decrease in the internal heat load, as explained in Chapter 4. However, this decrease is considered to have reduced the efficiency of Heating, ventilation and air conditioning (HVAC) systems because these systems were already equipped with excess capacity to manage the previous internal heat loads.

It has been more than 30 years since the development of the multisplit type air-conditioning system and its adoption in offices. It has become the most common air-conditioning system in nonresidential buildings including large-sized buildings in the last ten years, although it was originally introduced in small- and medium-sized buildings. This system consists of an outdoor unit with several indoor units and the outdoor unit uses a heat pump. This arrangement allows it to operate individually with less conveyance energy and in a small space, in contrast to a conventionally used central air-conditioning system, which consists of heat sources such as chillers and boilers, a water-conveying system, and an air-conditioning system.

Past research has indicated that multisplit type air-conditioning systems have to be operated with low efficiency owing to their excess capacity for the actual internal heat loads [1, 2]. Normally, systems with about 200 W/m^2 capacity are introduced in buildings. However, they are too large considering that 120 W/m^2 capacity systems are normally used for central air-conditioning. Accordingly, it is assumed that the recent decrease in the internal heat load should have reduced the efficiency of heating further [3].

In this study, the internal heat load and operation of the multisplit type air-conditioning systems were investigated in an office after the earthquake in order to point out problems and provide some improvements.

5.2 Methodologies

5.2.1 Investigated office

Table 5-1 shows the building investigation summary details. Completed in August 2012 after the earthquake, the KD building is designed as an environmentally conscious office. It acquired the S rank in the comprehensive assessment system for built environment efficiency (CASBEE) [4] in Japan. The KD building uses natural energy technologies such as solar power generation and night purging (passive cooling at night), and maximizes the use of natural daylight. The third floor workrooms used for the investigation consist of three offices: room 1, room 2, and room 3. Office hours are from 8:50 to 17:30. During the investigation period, there were 36 full-time employees and few part-time employees in room 3, which itself has a volume equal to 439.9 m^3.

Table 5-1. Details of the summary of the building for the investigation.

Location	Toyonaka-city, Osaka, Japan	
Completion	August 2012	
Structure	RC	
Construction area	4368.49 m^2	
Total floor space	12282.46 m^2	
Number of floors	6 aboveground floors	
Building applications	Offices	
Target floor space	433.9m^2	

5.2.2 HVAC system and BEMS (Building Energy Management System)

Multisplit type air-conditioning systems for indoor-air conditioning and outdoor-air processing have been introduced in the building. In room 3 of the third floor office, seven indoor units of ceiling-embedded indoor-air conditioners connected with one outdoor unit that uses variable refrigerant flow control developed by Daikin (=VRV: Variable Refrigerant Volume) have been introduced. In addition to VRV a dedicated outdoor air system (DOAS) has been introduced, which consists of two parallel systems: a dedicated system for delivering outdoor air ventilation, and a parallel system to handle the (mostly sensible heat) loads generated by indoor/process sources and those that pass through the building enclosure. In the third floor office, six indoor units of DOAS with a total heat-exchanger unit connected with one outdoor unit have also been introduced for ventilation. Three of the six indoor units are located in room 3. Figure 5-1 shows the layout of the installed HVAC systems on the third floor. Figure 5-2 shows the conceptual scheme of the indoor HVAC system. Outdoor air is cooled and dehumidified by a cooling coil after it is processed by a total heat exchanger of the DOAS.

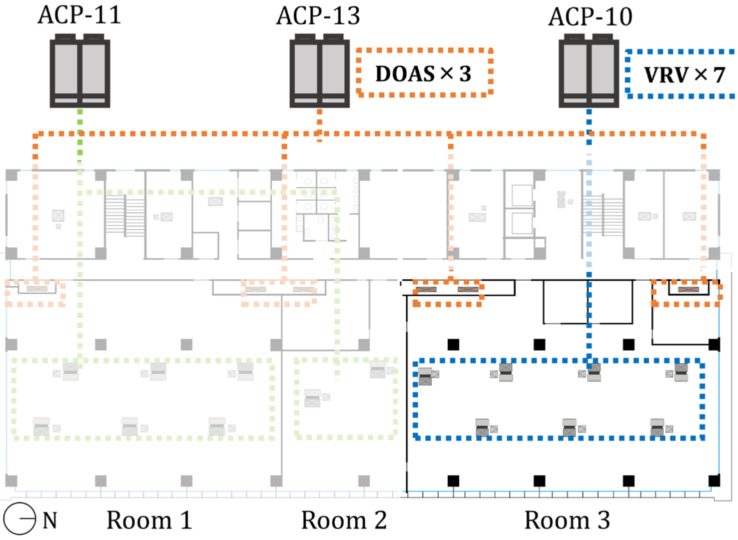


Figure 5-1. Layout of the third floor with the installed HVAC systems.

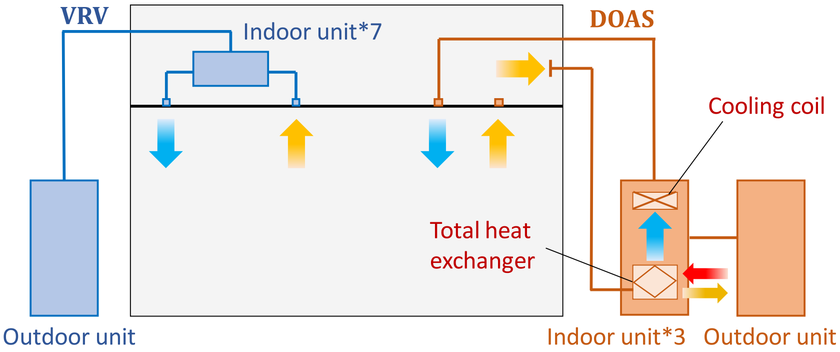


Figure 5-2. Conceptual scheme of indoor HVAC system.

High efficiency control is carried out while both the VRV and DOAS are in operation. When the room air temperatures are less than standard (±1°C for VRV, ±1.5°C for DOAS), the operation of the outdoor units is regulated. In detail, the outdoor unit of the DOAS attains the thermo-off state when the internal heat load becomes less than 20% of the designed value, and attains the thermo-on state when the room air temperatures are beyond the temperature range. On the other hand, the capacity of the cooling coil of the DOAS outdoor unit fluctuates based on the controlled temperature range.

The calculated loads of the outdoor and indoor air were 30.7 W/m^2 and 89.9 W/m^2, respectively. However, the DOAS cooling capacity of the surveyed floor was 45.5 W/m^2 and the VRV cooling capacity was 112.0 W/m^2; in total, it was 157.5 W/m^2. The capacities were respectively larger by 33% and 25% to secure the margins of the instruments. The rated coefficient of performance (COP) is 3.6 for VRV and 4.3 for DOAS. Table 5-2 shows the installed cooling capacity.

The COP of the outdoor units was obtained through BEMS from the data log of the Daikin units. It was calculated by dividing the air conditioning load, obtained by the compressor curve method, which estimates the cooling capacity based on the refrigeration cycle characteristics, with the estimated electricity consumption assumed from equipment power factor and voltage. Moreover, the load factor was calculated in order to confirm the actual load balance of the VRV and DOAS by dividing the product of the electricity consumption per unit time (hour) and COP by the rated cooling capacity.

Table 5-2. Installed cooling capacity.

	DOAS		VRV	
	Outdoor unit	Indoor unit	Outdoor unit	Indoor unit
Rated cooling capacity [kW]	45	9.35 *3 units	50	7.1 *7 units
Rated COP [-]	4.3	4.4	3.6	53.4
Rated electricity consumption [kW]	10.5	0.832	13.9	0.133

5.2.3 Measuring conditions

To observe the actual internal heat load, BEMS data for the entire year of 2015 was obtained. In addition, to see the relationship between the internal heat load and the operation of a multisplit type air-conditioning system, the settings of the DOAS were changed. Two indoor air temperature settings, 26°C and 27°C, were chosen to investigate the changes in the operation number of the DOAS and the control settings of the DOAS. The changes were investigated in summer 2016 using field and questionnaire surveys, and by an energy consumption analysis within the survey area of the KD building. The preset air conditioning temperature in the investigated office during regular hours in summer was 27°C.

Table 5-3 shows the schedule and settings of the HVAC system. Six conditions were created, i.e., two types of indoor air temperature settings (26°C and 27°C) and three types of air conditioning operation (A, B, and C). The description of the air conditioning operation is as follows.

A: Normal operation in the target building
B: Reduction in the number of DOAS units from three to two; which further results in less outdoor air intake
C: Change in the control setting of the DOAS towards less operation by changing the standard DOAS temperature from "±1.5°C" to "(+0.5)–(+3.5)°C" and relative humidity from "50-55%" to "no control"; which can change the operational balance of the VRV and DOAS.

Table 5-3. Schedule and settings of HVAC systems.

condition code _temperature _operation of DOAS units	VRV	DOAS			Period	The number of questionnaire respondents
	Air temperature		Relative humidity	Outside air		
	Settings [°C] (Operation range)	Settings [°C] (Operation range)	Settings [%RH] (Operation range)	The number of units in operation		
A_27_3 units	27 (26–28)	27 (25.5–28.5)	55 (50–55)	3	June 25-June 29, 2016	34
A_26_3 units	26 (25–27)	26 (24.5–27.5)	55 (50–55)	3	Aug. 1-Aug. 5, 2016	34
B_27_2 units	27 (26–28)	27 (25.5–28.5)	55 (50–55)	2	Aug. 22-Aug. 26, 2016	30
B_26_2 units	26 (25–27)	26 (24.5–27.5)	55 (50–55)	2	Aug. 8-Aug. 12, 2016	31
C_27_3 units with less operation	27 (26–28)	27 (27.5–30.5)	no control	3	Aug. 29-Sep. 2, 2016	-
C_26_3 units with less operation	26 (25–27)	26 (26.5–29.5)	no control	3	Sep. 5-Sep. 9, 2016	-

5.2.4 Physical measurements

Table 5-4 shows a list of measurements and Figure 5-3 shows measurement points. On the north side of the third floor of the KD building, physical environmental measurements were conducted from July 25 to September 9, 2016. The measured elements included indoor air temperature and humidity, indoor radiation temperature, desk level illuminance values for optimal lighting, and CO_2 concentrations for indoor air quality. In addition, the outlet air temperature and humidity of the VRV as well as DOAS were measured. Energy consumption was measured and logged by the BEMS every hour.

Table 5-4. List of measurements.

Legend	Parameter	Equipment	Position	Interval
●	Indoor air temperature (AT) and relative humidity (RH)	TR-74Ui	1.1m above floor	10 min
○	Supply AT and RH of indoor-air conditioning	RSW-20S		
○	Supply AT and RH of outdoor-air processing unit	RSW-20S		
○	Return AT and RH of indoor-air conditioning	RSW-20S		
◆	Globe temperature	RSW-30S		
✦	Illuminance	TR-74Ui		
■	CO_2 (1,2)	LX-1128SD		1 min
	CO_2 (3,4)	TR-76Ui		5 min
🛸	-	Fan	-	10 min

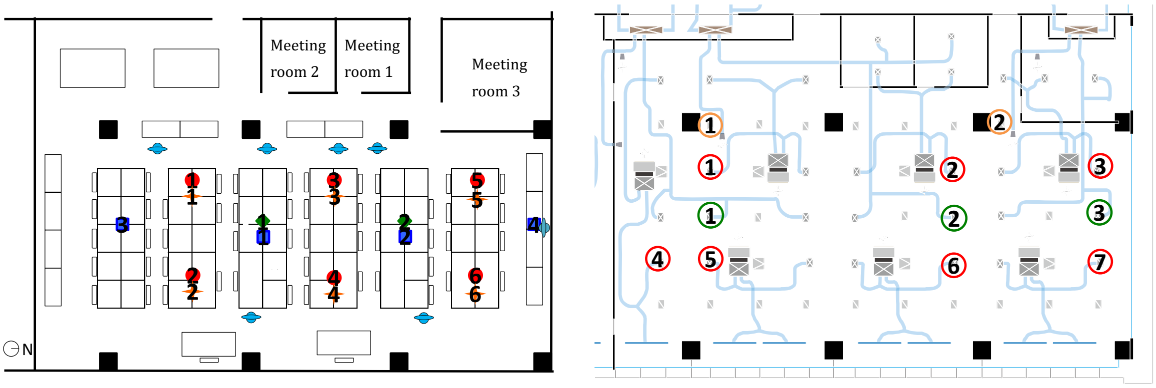


Figure 5-3. Measurement points at desk level (left) and at ceiling level (right).

5.2.5 Questionnaire survey

The questionnaire period was from July 25 to September 9, 2016; 36 surveys were distributed, and 90% of the copies were collected. The questionnaire was conducted to research the level of satisfaction with the indoor environment and its influence on employee productivity. The questionnaire was based on the subjective assessment of workplace productivity (SAP) 2013 [5]. In addition, a survey was conducted regarding the odour intensity, employee concentration, and awareness and measures of energy saving. Respondent demographics of each condition are shown in Table 5-5.

Table 5-5. Questionnaire respondents.

Conditions	Number of respondents	Gender			Age					
		Male	Female	NA	20s	30s	40s	50s	60s	NA
A_27_3 units	34	23	10	0	3	3	21	5	1	1
A_26_3 units	34	19	10	5	2	2	19	5	1	5
B_27_2 units	30	15	10	5	2	0	18	5	1	4
B_26_2 units	31	17	10	4	2	2	18	4	1	4
C_27_3 units with less operation	No questionnaire	-	-	-	-	-	-	-	-	-
C_26_3 units with less operation	No questionnaire	-	-	-	-	-	-	-	-	-

5.3 Results

5.3.1 Annual Energy Consumption

Figure 5-4 shows the annual energy consumption of the target building (left) and that of conventional buildings (right) [6]. Lighting, OA equipment, total energy consumption, and cooling capacity are obtained and shown in Table 5-6. The results showed that the primary energy consumption of the OA equipment was approximately 95 MJ/m^2 and 235 MJ/m^2 per year for lighting. The average desk-lighting illuminance was 520 lux. These values are relatively small compared to the officially published average energy consumption value of 369 MJ/m^2 for OA and 363 MJ/m^2 for lighting. The cooling capacity settings were 158 W/m^2, which is relatively small considering the conventional cooling capacity of 200 W/m^2.

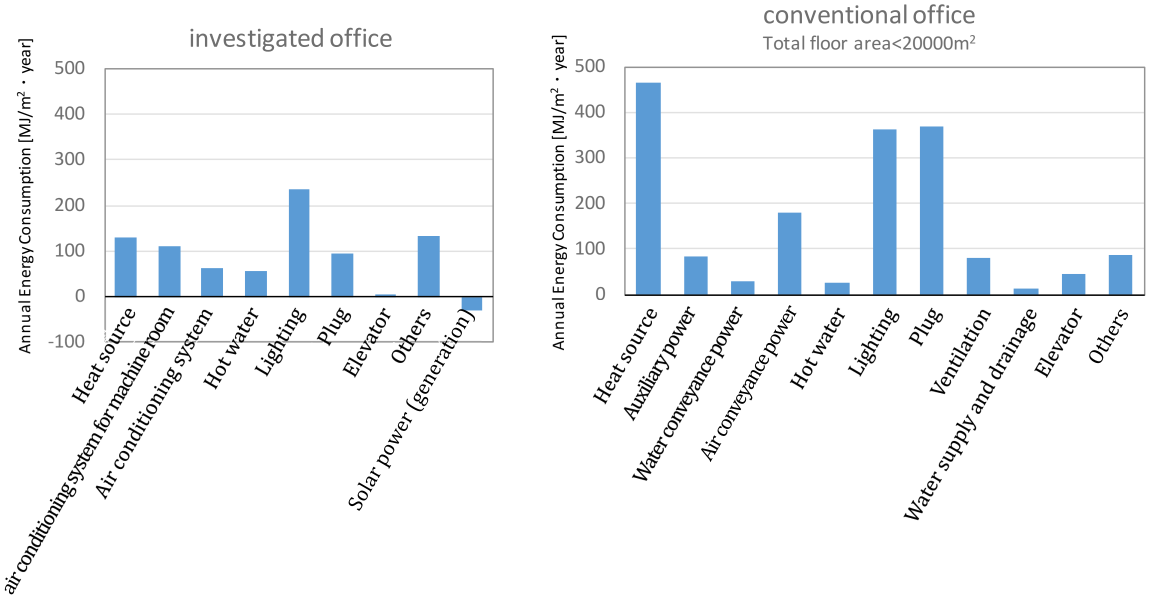


Figure 5-4. Annual energy consumption of the target building (left) and average of conventional buildings (right).

Table 5-5. Comparison of annual energy consumption and cooling capacity.

	Annual energy consumption [MJ/m^2 year]			Cooling capacity [W/m^2]
	Lighting	OA	TOTAL	
Conventional office [6]	363	369	1737	ca. 200 [7]
Investigated office	235	95	803	157

5.3.2 Indoor environment and satisfaction

Table 5-7 shows the measurements of the indoor and outdoor environmental factors and the calculated difference of the indoor-outdoor air enthalpy for the six conditions investigated in the present survey. Mean values and standard deviation (SD) are shown together. Table 5-8 shows the questionnaire result regarding the indoor environmental quality for the four conditions investigated in the present survey.

The actual indoor air temperature was controlled as desired. Surveys conducted to assess employee comfort and satisfaction showed that respondents tended to reply that they were more on the “cool side” of a sliding scale of thermal sensation after the temperature was lowered and their satisfaction with the indoor environment improved. Changing the set-point temperature from 27°C to 26°C reduced the actual mean indoor air temperature by 1.3°C and the employee dissatisfaction rate by 15%.

When the indoor enthalpy was 58.1 kJ/kg or more, occupants complained about the thermal environment. The indoor mean relative humidity was between 50 and 60%. The mean clothing (clo) value for males was 0.50 and that for females was 0.48. Varying the intake rate of outdoor air, by stopping one of the three indoor units of DOAS, increased the indoor CO_2 concentration only by around 50 ppm and did not substantially affect the indoor air quality. Employees were generally satisfied with the resulting indoor environment.

Table 5-6. Measurements of indoor and outdoor environmental factors and calculated difference of indoor-outdoor air enthalpy with mean value and SD.

	Indoor air										Outdoor air				Difference of indoor-outdoor air enthalpy	
	AT		RH		Globe temperature		CO_2 concentration		Interior Desk level illuminance		AT		RH			
A_27_3 units	26.9	±0.6	61	±2	26.8	±0.6	710	±52	508	±95	30.6	±2.9	63	±11	75.9	±6.9
B_27_2 units	26.6	±0.4	58	±4	26.3	±0.5	753	±60	498	±127	32.9	±1.9	52	±7	76.1	±6.0
C_27_3 units with less operation	27.0	±0.6	54	±7	26.8	±0.7	702	±51	527	±135	28.9	±3.6	62	±21	61.0	±5.7
A_26_3 units	25.4	±0.5	59	±3	25.3	±0.4	712	±56	532	±120	33.7	±1.6	53	±6	79.4	±5.3
B_26_2 units	25.4	±0.5	56	±3	25.1	±1.5	736	±61	533	±104	33.5	±1.5	47	±7	71.9	±8.3
C_26_3 units with less operation	25.6	±0.4	59	±4	25.3	±0.5	702	±56	521	±101	29.5	±3.0	57	±10	71.2	±8.8

Table 5-7. Questionnaire result regarding indoor environmental quality.

	Thermal environment								IAQ		Lighting environment	
	Thermal sensation	AT satisfaction	Dry or humidity	RH satisfaction	Air flow from HVAC	Air flow from fan	Air flow satisfaction	Thermal satisfaction	Odour Intensity	IAQ satisfaction	Desk level brightness	Lighting satisfaction
A_27_3 units	1.09	-0.81	0.39	-0.38	1.35	2.50	-0.41	-0.69	7.50	-0.25	3.63	4.24
B_27_2 units	0.50	-0.40	0.07	-0.07	1.60	2.14	0.17	0.03	14.50	0.00	-	-
C_27_3 units with less operation	-	-	-	-	-	-	-	-	-	-	-	-
A_26_3 units	-0.24	-0.32	-0.12	0.15	1.59	2.39	0.00	-0.06	10.79	0.00	-	-
B_26_2 units	-0.53	0.14	-0.27	0.38	1.77	2.14	0.31	0.24	9.50	0.13	-	-
C_26_3 units with less operation	-	-	-	-	-	-	-	-	-	-	-	-

5.3.3 Operation of HVAC systems

Figure 5-5 shows the results of the outlet temperature fluctuation of both DOAS and VRV in each condition on representative days having similar outdoor air condition. Both VRV and DOAS were operated as desired in almost all operating hours. That is, one of the three DOAS indoor units stopped in condition B. In condition C, all cooling coils of DOAS indoor units stopped and outdoor air, after passing through the total heat exchanger, was introduced into the room without cooling.

However, all such stoppings of the DOAS cooling coils were also seen in conditions A and B. It was found that the humidity setting of the system was the main cause for the change in operation. Specifically, when the relative humidity after the total heat exchanger is less than 55%, the cooling coil of the DOAS stopped at 89% of the observation time at the set temperature 27°C, and 73% at the set temperature of 26°C. Stoppage or excessive operation of the DOAS could cause the collapse of the operational balance between the DOAS and VRV, resulting in energy wastage.

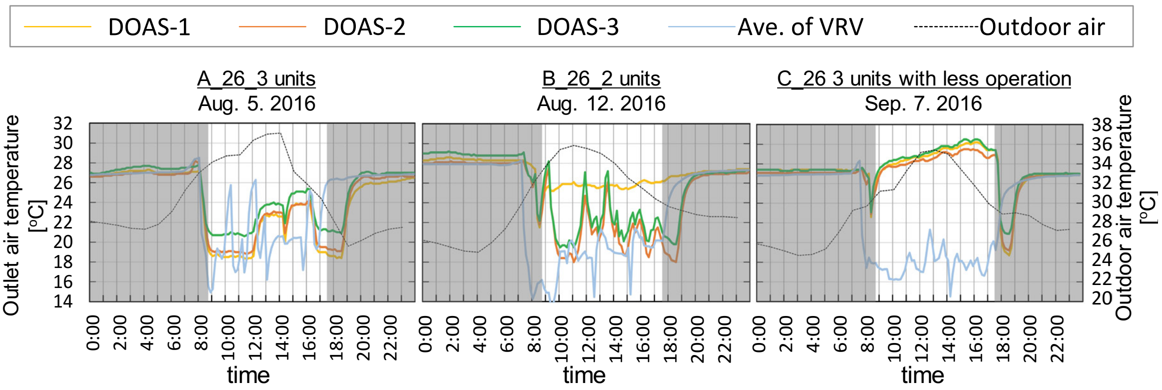


Figure 5-5. Outlet temperatures fluctuation of DOAS and VRV in each condition.

5.3.4 Load factor, COP and Electricity consumption

The load factor, COP, and energy consumption of the VRV and DOAS were analyzed in each operating condition. It has been reported in past studies that the COP usually improves the most around 50% load factor and decreases as the load factor decreases [7].

Figure 5-6 shows the load factor and COP including the rising time for which the temperature rose (7:00–19:00) at regular condition A. The average load factor for both VRV and DOAS under normal operation was small, below 30%. Mainly, the VRV processed the rising air and the load factor was over 70% during most of that period. There were many periods of COP exceeding the rated value of 3.6. The operation ratio at low COP increased when the load factor was about 40%, which confirmed that high COP can be obtained even at a partial load of around 50% of the rated capacity. For some time, the DOAS operated with a load factor of 80% or more; however, the time for which the operation stopped occupied a large portion. In case of the VRV, the low COP ratio significantly increased at a load factor of around 40%. When the DOAS operated at an excess capacity of 100%, the VRV almost stopped, and vice versa. It was confirmed that the operational balance of the VRV and the DOAS collapsed due to stoppage or excessive operation of the DOAS.

Figure 5-7 shows the load factor and COP by condition, excluding the rising time (10:00–16:00) as well as the beginning of the week. The VRV operated at a load ratio of around 35% on an average, and the COP remained at around 4.0 in the normal stable condition. The average loading factor of the DOAS during the operation of condition A and B was 41%. On the other hand, the cooling coils of DOAS almost stopped at condition C. As the investigated building was completed after the earthquake, it was expected to have a low internal load. Hence, a smaller cooling capacity was selected. However, the average load factor was somewhat lower, resulting in a low COP.

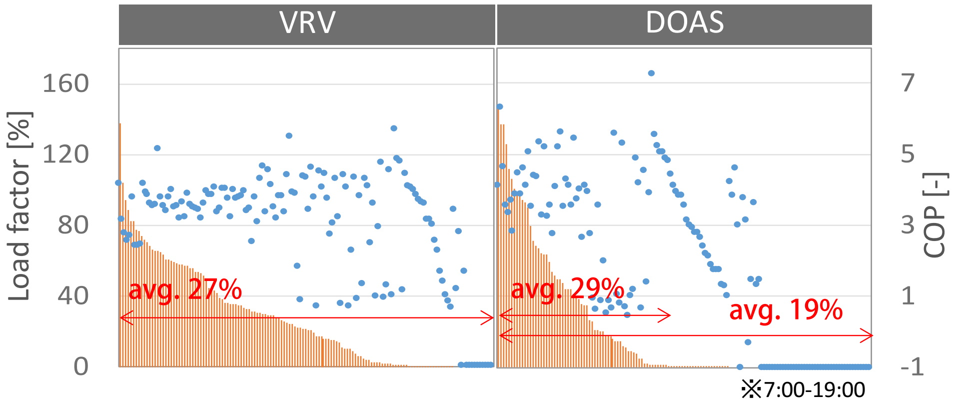


Figure 5-6. Load factor and COP including the rising time of temperature in regular condition A.

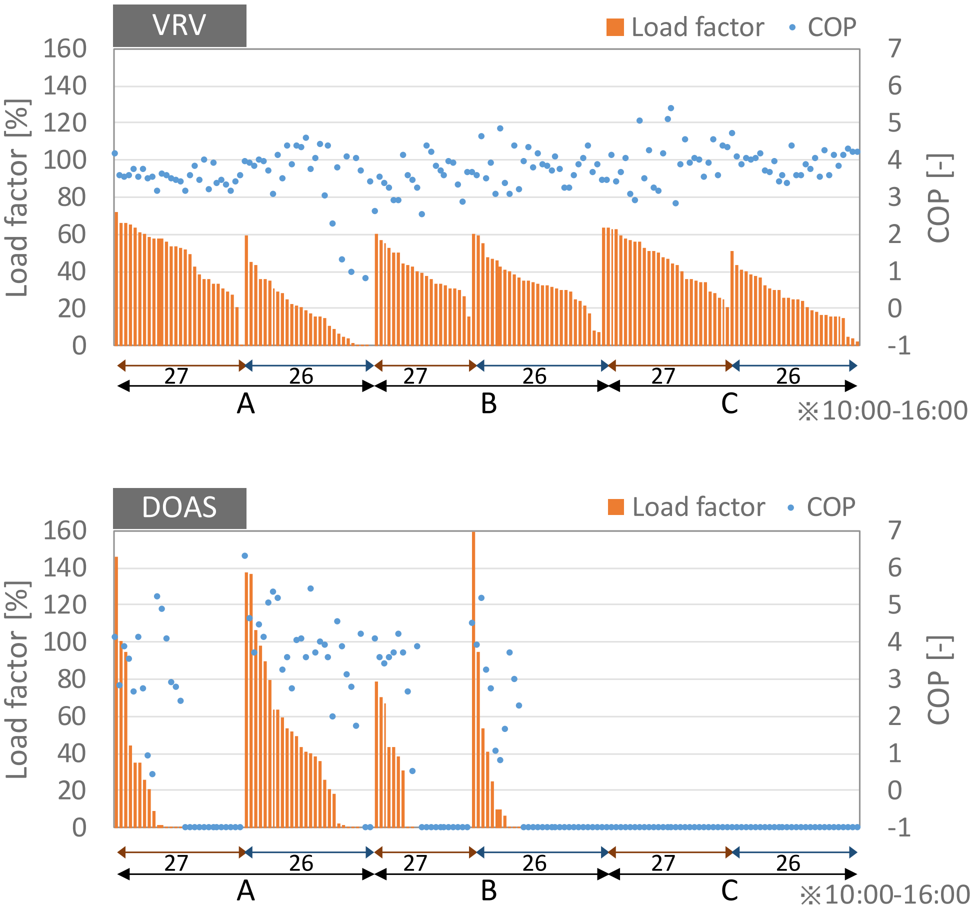


Figure 5-7. Load factor and COP by condition excluding the rising time and beginning of the week.

Figure 5-8 shows the relationship between the COP and the electricity consumption of the heat source of both VRV and DOAS, respectively. VRV had many COPs around the rated value of 4.0. At lower COP, the energy consumption slightly increased. The COP of the DOAS was uneven, and even with the same COP value, the energy consumption varied. In condition B, with two DOAS indoor units operating, the energy consumption was slightly smaller than in the conditions A and C with three DOAS indoor units operating. It is considered that the reduction in the air transportation energy caused this result.

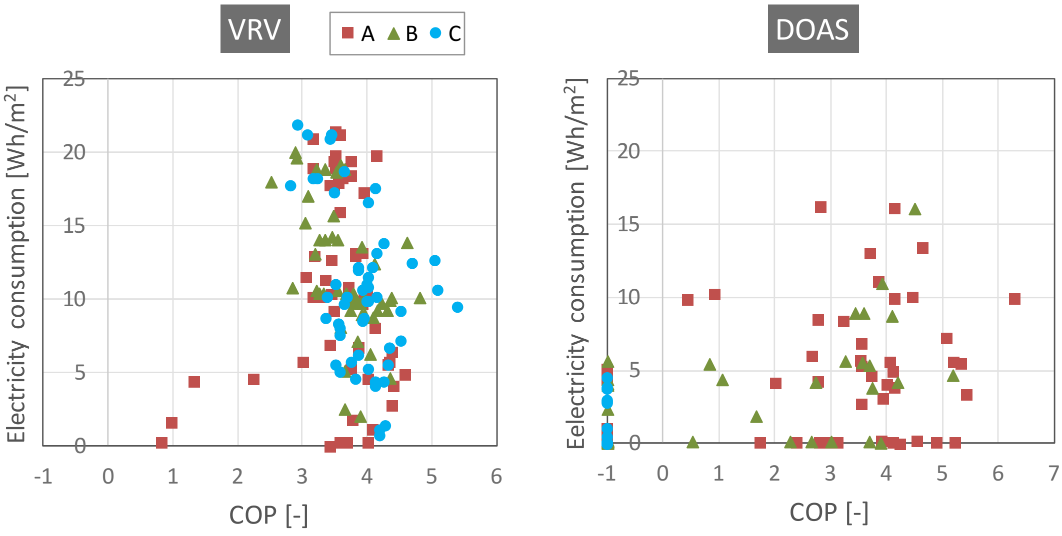


Figure 5-8. Relationship between COP and electricity consumption.

Figure 5-9 shows the relationship between the difference of the indoor-outdoor air enthalpy and the electricity consumption with three and two DOAS indoor units operating, respectively. Analysis was conducted based on whether the cooling coil, after passing through the total heat exchanger, was in operation. The horizontal axis shows the difference between the indoor air enthalpy and outside air enthalpy after the total heat exchanger. The vertical axis shows the total energy consumption of the heat source of both DOAS and VRV, and the heat conveyance. In the case where the enthalpy difference was small, only the VRV operated and processed the air, resulting in low energy consumption. When the enthalpy difference was large, the power consumption was small, with both DOAS and VRV being operated. However, as mentioned above, even in the case where the enthalpy difference was large, the cooling coils of the DOAS stopped, because the relative humidity fell below the control set value, and the load was processed only by the VRV, resulting in an increase in the energy consumption. Energy consumption also increased when the enthalpy difference was large in condition C with less DOAS operations. It was found that the humidity setting of the system was the main cause for the change in operation. The operational method of the DOAS had a large influence on the total electric energy consumption in offices practicing internal load reduction.

In this connection, if the temperature is raised by 1°C from 26°C to 27°C at 55% relative humidity, the enthalpy decreases by 2.85kg/kJ. Furthermore, it was shown by simulation, by using a dynamic heat load program (New HASP) and Life Cycle Energy Management System tool (LCEM), that more energy would be saved by adopting a well-balanced operation of the VRV and DOAS, than by raising the setting indoor air temperature by 1°C at relative humidity under 55%. However, the enthalpy difference was large.

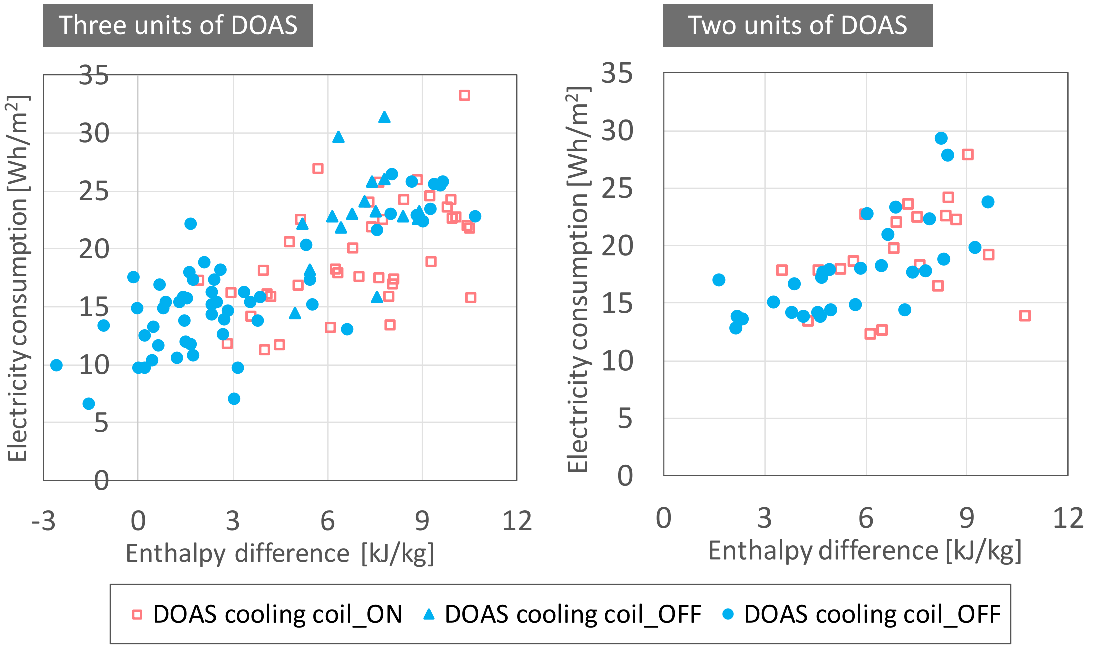


Figure 5-9. Relationship between difference of indoor-outdoor air enthalpy and electricity consumption with operation of three indoor units of DOAS and two indoor units of DOAS respectively.

5.4 Discussion

In case of high enthalpy difference, greater energy saving is achieved by both VRV and DOAS by performing load processing. At present, the air-conditioning control settings are set respectively for both air temperature and relative humidity. The DOAS stopped merely due to humidity even when the enthalpy difference was high, which led to inefficient operations. Although, in this chapter, only the summer measurement result was shown, it was reported that the DOAS excessively operated in order to meet the relative humidity setting in winter, resulting in VRV stoppage and increased energy consumption [8]. Even, in the office, where radiant air conditioning was introduced, survey results showed that the DOAS operated too much in winter to meet the relative humidity setting, resulting in the stoppage of the radiant air conditioning operation.

The operational method of the DOAS would greatly influence the total energy consumption in offices, practicing internal load reduction, because the DOAS also processes the internal heat load. It would save more energy to adopt a well-balanced operation of the VRV and DOAS, rather than a partial optimization of each device.

It is important how to treat outside air and introduce it indoor. Appropriate air-conditioning system capacity and a comprehensive energy saving operational method, such as control by indoor-outdoor air enthalpy difference, rather than a partial optimization of each device, would be beneficial for total energy saving.

5.5 Conclusions

1. The results showed that the primary energy consumption of the OA equipment was approximately 95 MJ/m^2 per year and 235 MJ/m^2 per year for lighting. The average desk lighting illuminance was 520 lux. These values are relatively small compared to the officially published average energy consumption value of 369 MJ/m^2 for OA and 363 MJ/m^2 for lighting.
2. The cooling capacity settings were 158 W/m^2, which is relatively small considering the common cooling capacity of 200 W/m^2. However, the average load factor for both the VRV and the DOAS, under normal operation, was small; below 30%.
3. The actual indoor air temperature was controlled as desired and the 1.3°C temperature drop reduced the employee dissatisfaction rate by 15%. Varying the intake rate of the outdoor air by stopping one of the three indoor units of the DOAS did not substantially affect the indoor air quality, and employees were generally satisfied with the resulting indoor air quality.
4. The relaxation of the air-conditioning setting temperature and the improvement in the control of the air conditioning operation reduced the energy consumption. However, it was confirmed that the operational balance of the VRV and the DOAS collapsed due to stoppage or excessive operation of the DOAS. Furthermore, it was found that the humidity setting of the system was the main cause for the change in operation.
5. When the processing enthalpy difference (the difference between the indoor and outdoor air) is small, it is better to introduce, into the room, outdoor air, which has passed only through the total heat exchanger. The VRV, then, processes the air from the view of saving energy. When the processing load is large, the energy consumption was smaller, when both the VRV and the DOAS process the air that is to be cooled.
6. The operational method of the DOAS had a large influence on the total electric energy consumption in offices practicing internal load reduction. Thus, appropriate capacity of the air-conditioning systems and a comprehensive energy saving operation method, such as control by the indoor-outdoor air enthalpy difference, rather than a partial optimization of each device, would be beneficial for total energy saving.

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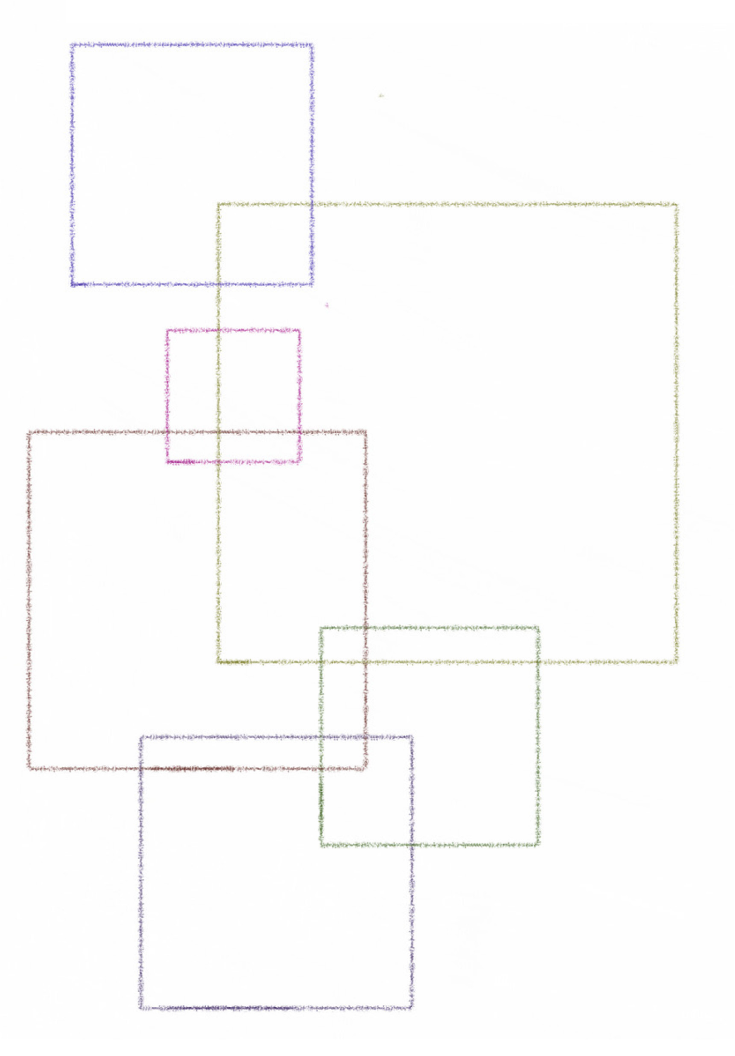
Outline

Chapter 6

Sensory evaluation and chemical analysis of exhaled and dermally emitted bioeffluents



6.1 Objective and general approach

Chapter 6 attempts to identify the under-researched problems of perceived air quality stated in Chapter 2. Effective improvement measures are needed for the indoor environment especially indoor air quality and thermal environment as Chapter 4 showed that the satisfaction of the workers depended on the indoor air quality and thermal environment more than the other environmental factors such as lighting, sound, space, and ICT, however, the post-earthquake satisfaction in these areas was still poor.

Since the focus on human bioeffluents and their contribution to indoor air quality exposures has increased again recently, an experiment to investigate the difference between the effects of dermal-emitted (through skin) and exhaled (by breathing) bioeffluents on perceived air quality at typical indoor setting was conducted as the first attempt in Chapter 6.

Chemical analysis and sensory evaluation of humans bioeffluents were made. Exposures with dermally-emitted, exhaled and dermally-emitted+exhaled bioeffluents were created. Human subjects dressed lightly sat in a ventilated stainless steel low-polluting climate chamber. They exhaled air through a mask to the twin chamber ventilated at the same outdoor air supply rate or to the chamber where they were sitting. Carbon dioxide concentration in the chamber containing exhaled air was 2,000 ppm. Chambers were set at 23^{o}C and 28^{o}C and ozone was removed or not from the supplied air.

6.2 Introduction

Body odour originates from sweat and sebaceous secretions from skin, and from foul breath. The latter includes the pollutants emitted when breathing including gases from the digestive tract. Although considered generally as nontoxic, body odour may evoke a feeling of nausea and even reduced appetite in some people [1]. Recently published work shows that exposure to human bioeffluents can increase sleepiness, fatigue, headaches and difficulty in concentrating [2, 3, 4], and reduce cognitive performance, including the ability to take decisions [5]. There is substantial evidence on how body odour is perceived by humans [6, 7, 8, 9]. This research provided the basis for contemporary ventilation standards [10, 11].

The connection between body odour and ventilation goes back to the 19th Century when Pettenkofer (1858) [12] associated discomfort with emission from humans, rejecting the earlier theories that associated discomfort with the presence of carbon dioxide (CO_2) or lack of oxygen (O_2). Pettenkofer proposed to use CO_2, the main human inorganic bioeffluent, as a marker of the quality of air polluted by human bioeffluents, and assumed that other indoor pollutants not emitted by humans would be eliminated at source. CO_2 at a concentration of 1,000 ppm was proposed as a level above which indoor air quality would be unacceptable; 700 ppm was proposed for bedrooms. CO_2 has subsequently been used universally as a proxy for indoor air quality. Pure CO_2 at the levels normally occurring indoors was not considered by Pettenkofer to constitute a risk for occupants. Recent studies by Zhang et al. (2016) [3, 4] and Liu et al. (2016) [13] show that pure CO_2 below 5,000 ppm does not produce sensory discomfort, increase self-reported acute health symptoms or reduce the performance of cognitive tasks. Two recent experiments suggest however that pure CO_2 at concentrations as low as 1,000 to 2,500 ppm can reduce the ability to take decisions in a stressful situation [14, 15], and one experiment reported that a pure CO_2 concentration of 4,000 ppm reduced perceived air quality (PAQ) and increased acute health symptoms, and that the performance of a proof-reading task was reduced in one of the two series of experiments that were reported [16].

Humans emit many different volatile organic compounds (VOCs). Recently, Liu et al. (2015) [17] reported that the compounds associated with the presence of humans contribute up to 40% of the measured daytime VOC concentration in indoor spaces. In another recent study, Tang et al. (2016) [18] reported that human-emitted VOCs were the dominant source during occupied periods in a well-ventilated classroom (57%), with ventilation supply air the second most important source of pollution (35%). The types of pollutants emitted depend on the nutrition and hygienic standards of the occupants, on their health condition and even their addictions, such as alcohol or cigarette smoking [19]. Some studies measured whole-body bioeffluents (e.g. [20, 21, 22]), others analysed bioeffluents emitted when breathing (exhaled bioeffluents) and through skin (dermally-emitted bioeffluents) or bioeffluents from a particular part of the body, for example the oral cavity (e.g., [23, 24]), skin excluding the head (e.g., [25, 26, 27, 28]), axillae (e.g., [29, 30, 31, 32, 33, 34, 35, 36, 37]), scalp (e.g., [38]), hand (e.g., [27, 39, 40, 41, 42, 43, 44, 45, 46]), feet (e.g., [37, 47, 48]) and intestines (e.g., [49, 50]). Different sampling procedures and approaches to determining the composition of bioeffluents were used. A summary of the main compounds identified as emissions from humans and their different body parts is given in Table 6-1.

Krotoszynski and Dravnieks (1995) [20] sampled vapors from the whole-body by placing subjects on a Teflon-lined stretcher in a glass tube. Five compounds were found to be common to White, afro-American and Indian males and to White females. These were acetone, butanol, ethanol, lactic acid and pyruvic acid. Ellin (1974) [21] sampled compounds in the headspace surrounding a person. Forty-six semi-nude males were placed, one at a time, in a sealed chamber made of glass, stainless steel and teflon. Around 330 compounds were detected and 135 compounds were identified. Five compounds with the highest concentration and found commonly for all subjects were acetone, butanol, ethanol, isoprene, and toluene. Wang (1975) [22] investigated bioeffluents in an auditorium. Samples were taken from the inlet and exhaust of the air conditioning system. Sixteen compounds were considered as bioeffluents, and acetone, acetic acid, butyric acid, ethanol and methanol, were found in high concentrations. The main compounds measured in bedrooms and associated with the presence of human bioeffluents are according to Hanihara et al. (2013) [51] C2-10 fatty acid, C6-10 aldehydes, 6-methyl-5-hepten-2-one (6-MHO), (E)-6,10-dimethyl-5,9-undecadien-2-one (geranylacetone) and 2-ethyl-hexanol.

VOCs in human breath were identified by Chen et al. (1970) [52] who concluded that the intensity of the odour is directly related to the amount of dimethyl sulfide in the breath. At that time, oral bioeffluents were used as a non-invasive indicator of health. In the study of

Sun et al. (2014) [53], the air exhaled by 111 subjects was sampled using a specially developed experimental system, and 645 VOCs were detected; on average over fifty different types of VOCs from each subject were detected. In a summary of studies measuring human bioeffluents, Bluyssen (1990) [23] reported that hydrogen sulfide, methyl mercaptan and dimethyl sulfide were believed to be the main sources of poor PAQ caused by human exhalation. Fenske and Paulson (1999) [24] reported that the major VOCs in the exhaled breath of healthy individuals were isoprene, acetone, ethanol, methanol and other alcohols; minor components included pentane and higher aldehydes and ketones.

Zhang et al. (2014) [25] measured emissions from 30 healthy subjects wearing gas masks in a sealed chamber with almost no ventilation. Organic pollutants emitted from the skin were identified. In all, 893 VOCs were detected and an average of 71 VOCs (SD=21.2, range=19–101) from each subject. Logan et al. (2008) [60] analysed the organic pollutants emitted by human volunteers, who were placed in individual plastic bags lined with aluminum with only their heads outside the bag. They identified 24 volatile compounds that were additionally shown to attract Aedes mosquitoes. The dermally-emitted bioffluents that were found to play a key role in attracting insects were 6-MHO, decanal, nonanal, octanal and geranylacetone. Dormont et al. (2013) [26] noted that only a few families of compounds are represented among dermal emissions and that these include carboxylic acids of various chain lengths and derivative esters, aldehydes, alkanes, short chain alcohols, and some ketones. Harraca et al. (2012) [27] collected dermally-emitted bioeffluents by placing volunteers in customised heat-sealed oven bags; their heads were kept outside the bag as in the studies reported by Logan et al. (2008) [60]. Six main compounds were observed, including 6-MHO, decanal, geranylacetone, heptanal, nonanal, and octanal. Gallagher et al. (2008) [28] reported that the dermally-emitted amounts of some dermally-emitted compounds can vary with age. Three compounds were found to be biomarkers of increased age: dimethylsulphone, benzothiazole and nonanal. No significant differences related to age or locus were found for octanal or decanal.

The axillary region is a particularly important source of diverse volatile compounds [29]. The source strength in this region is a result of interactions between secretions of eccrine, sebaceous and apocrine glands and the resident bacteria. Compounds contributing to the profile of the PAQ of air from the axillary region include androstenol, which has a musky smell [30], androstenone which is a ketone with a urinelike smell [31] and isovaleric acid [32]. In particular, lipophilic corynebacteria, which dominate the commensal bacterial community in the axillary region of the skin, are largely responsible for the production of malodorous volatile products [33, 34, 35]. In some studies, volatile profiles have been reported to be dominated by two key odoriferous compounds, 3-methyl-2-hexenoic acid and 3-hydroxy-3-methylhexanoic acid [36, 37].

The scalp is rich in lipids, owing to the high density of sebaceous glands [54]. The source strength of the scalp is a result of the propionbacterium acnes in the hair follicles. The major scalp population is pityrosporum ovale, which metabolises lipid substances to fatty acids and glycerol that undergo ring closure to the volatile ɤ-lactones. Labows (1979) [38] indicated that ɤ-decalactone could be responsible for the smell of unwashed hair.

Odors from hands have been largely investigated in the context of forensic sciences [39, 40, 41, 42]. The profiles of volatile compounds emitted by the hands are often dominated by aldehydes and ketones, and particularly by 6-MHO, decanal, geranylacetone, nonanal and undecanal [39, 41]. The same compounds have also been regularly found to be the major components of compounds emitted from the forearm together with some alkanes and carboxylic acids [28, 43, 44]. Comparing hand odours from 10 subjects, Curran et al. (2010b) [41] identified 24 main compounds that can be considered to be a part of the “primary odour” profile of human scent. Six compounds were found to be highly frequent among the emissions from hands and they include 2-furancarboxaldehyde, 2-furanmethanol, decanal, dimethyl hexanedioate, nonanal and phenol. Among them only decanal, nonanal and and some carboxylic acid-methyl esters have been isolated regularly from hand emissions in other studies [55, 39, 41, 46, 42].

Brevibalterium (b.epidermidis) is resident on human skin, especially in areas such as toewebs. This organism produces methanethiol gas, which accounts for a large part of the characteristically cheesy smell from unwashed feet [47]. Other gaseous substances for example hydrogensulfide [47] and isovaleric acid [38], also contribute to the source strength of the feet. Ara et al. (2006) [48] reported several short-chain fatty acids in solvent extracts of foot sweat and considered that isovaleric acid was most likely responsible for strong foot odour.

Intestinal gas comprises five major compounds: N_2, O_2, CO_2, H_2 and CH_4 that represent 99% of bowel gas. A wide variety of gases, e.g. ammonium, hydrogensulfide, volatile amino acids and short chain fatty acids are also emitted from the intestines in trace concentrations, less than 1%, but can easily be detected by humans [49]. Kirk (1949) [49] sampled excreted intestinal gases (flatus) from 45 normal subjects and found an average concentration of hydrogensulfide (H_2S) of 0.00028%; it was excreted at an average rate of 1.47 ml per minute after an ordinary diet.

In addition to the emissions that result from the physiological processes that occur in the human body, recent studies show that many compounds can be created when the compounds emitted by humans, mainly constituents of skin oils, participate in reactions with ozone. These reactions occur in the presence of humans and also in spaces that were previously occupied by humans, due to shedding of the skin and the soiling of surfaces with human skin flakes containing skin oils. The major reaction that occurs is between ozone and squalene, while acetone, geranylacetone, 6-MHO, decanal and nonanal are the major products [56, 57, 58]. Squalene and geranylacetone are the major primary precursors for acetone and 6-MHO, and acetone may also be formed by 2-methyl-2-docosene. Yang et al. (2016) [58] showed that the possible primary precursors of four major products could be the compounds contained in the skin-oil deposited in clothing. The formation of nonanal can be mainly attributed to reactions between ozone and unsaturated fatty acids such as 9-octadecenoic acid and (Z)-7-hexadecenoic acid and their derivatives, such as (Z)-13-docosenamide. 6-Hexadecenoic acid (the most abundant unsaturated fatty acid) and 8-Octadecenoic acid are the main reagents that contribute to the generation of decanal. Wax esters and triglycerides having similar structure to the above-mentioned fatty acids can also contribute to the formation of nonanal and decanal. Schwarz et al. (2009) [59] reported that formaldehyde can be measured in human breath and its emissions can be enhanced during the reactions between squalene and ozone. Liu et al. (2015) [18] showed that phenol is one of the human bioeffluents that can be detected in exhaled breath and is a product of surface oxidation of human skin lipids. Liu et al. (2015) [18] concluded that VOCs produced from ozonolysis of human skin lipids were positively correlated with the concentration of CO_2 and negatively with the concentration of O_3. These results show that ozonolysis of skin lipids takes place indoors in buildings and that humans are an important source of indoor VOCs and a sink for indoor O_3.

Occupants can also be a source of the constituents of bathing soaps, shampoos, lotions, deodorants, perfumes and other cosmetic products as a result of their hygienic routines [60]. These compounds can vary greatly between individuals depending on their cosmetic preferences and hygienic standards, and are associated with their behavior and preferences rather than with their physiology.

Among the many studies described above that examined human bioeffluents emitted from the whole-body, its parts and when breathing, we were not able to find any experiments carried out to determine whether the compounds emitted from different body parts and the breath are perceived differently by human subjects. The present research was undertaken to compare the sensory effects produced by human bioeffluents emitted through skin and by breathing, and to examine whether any of these sensory effects could be attributed to any specific compounds that are emitted by other humans.

Table 6-1. Summary of previous studies measuring volatile organic pollutants emitted by humans

* some volatile products of ozone/skin oil chemistry are not presented

Compound	Odour threshold [μg/m³] (Nagata)	Odour threshold [μg/m³] (Devos)	Measurements of whole-body bioeffluents (dermally-emitted and exhaled)	Measurements of bioeffluents emitted by breathing (exhaled)	Measurements of bioeffluents emitted through skin (dermally-emitted)					Measurements of bioeffluents from intestines
					Skin except head	axillae	scalp	Hand, forearm	feet	
Acetic acid	16.098	363.078	○*3							
Acetone (2-propanone)	108937.500	34673.685	○*1*2*3	○*5						
Ammonia	1138.393	4073.803								○*22
Androstanol	-	-				○*9				
Androstenone	-	-				○*10				
Butanol	125.705	1513.561	○*1*2							
Butyric acid	0.747	14.454	○*3							
Decanal	2.791	5.888			○*6*7*8			○*16*17*18		
dimethyl hexanedioate	-	-						○*18		
Dimethylsulfide	8.317	5.888		○*4						
Ethanol	1070.179	54954.087	○*1*2*3	○*5						
ɤ-decalactone	-	-					○*15			
Geranylacetone	-	-			○*6*7*8			○*16		
Heptanal	-	22.909			○*7					
Hydrogensulfide	0.624	25.704		○*4					○*19*21	○*23
Isoprene	145.929		○*2	○*5						
Isovaleric acid	0.356	10.471				○*11*12			○*20*21	
Lactic acid	-	-	○*1							
lilia	-	-						○*16		
Methanethiol	-	2.089							○*19	
Methanol	47142.86	186208.714	○*3	○*5						
Methylmercaptan	0.150	-		○*4						
Nonanal	2.158	13.490			○*6*7*8			○*16*17*18		
Octanal	0.057	7.244			○*6*7					
octanoic acid	-	23.988						○*17		
pentadecane	-	-						○*17		
phenol	23.528	426.580						○*18		
pyruvic acid	-	-	○*1							
Toluene	1358.304	5888.437	○*2							
2- furancarboxaldehyde	-	-						○*18		
2-furanmethanol	-	-						○*18		
3-hydroxy-3-methylhexanoic acid	-	-				○*13*14				
3-methyl-2-hexenoic acid	-	-				○*13*14				
6-MHO	-	251.189			○*6*7*8			○*16		

*1: Krotoszynski and Dravnieks (1995)
*2: Ellin (1974)
*3: Wang (1975)
*4: Bluyssen (1990)
*5: Fenske and Paulson (1999)
*6: Logan et al. (2008) [60]
*7: Harraca et al. (2012)
*8: Laurent et al. (2013)
*9: Brooksbank (1974)
*10: Bird and Gower (1981)
*11: Natsch et al. (2005)
*12:Barzantny et al. (2012a, b)
*13: Zeng et al. (1996)
*14: Natsch et al. (2006)
*15: Labows (1979)
*16: Prada and Furton (2008)
*17: DeGreef and Furton (2011)
*18: Curran et al. (2010b)
*19: Noble (1981)
*20: Labows (1979)
*21: Ara et al. (2006)
*22: Levitt and Bond (1980) [49]
*23: Kirk (1949)

6.3 Methodologies

6.3.1 Facilities

The experiments were performed in the twin stainless steel chambers that were described in detail by Albrechtsen (1988) [62]. Each chamber had a volume of 22.5 m^3 (floor area of 9 m^2 x 2.5 m height) but with recirculation ducts had a volume of 30 m^3. The air in each chamber was recirculated during experiments to ensure proper mixing. Additionally, a desk-top fan and a standing fan were in operation. Both chambers were furnished with the stainless-steel chairs and tables used by the subjects. The outdoor air change rate was kept at 1.5 h^{-1}. It was measured using a constant dosing tracer gas technique and an Innova 1302 gas analyzer; CO_2 was used as the tracer gas. The outdoor air supply rate was selected so that the CO_2 concentration with five persons sitting in the chamber would reach 2,000 ppm.

The principal elements of the experimental facility are presented in Figure 6-1.

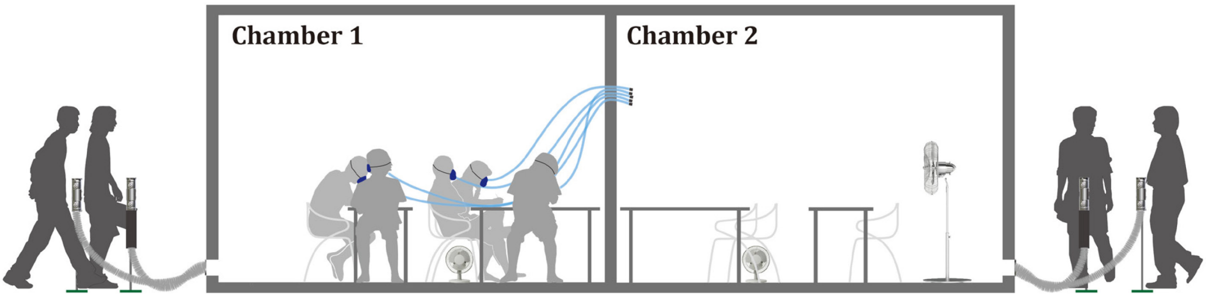


Figure 6-1. Experimental set-up in the twin chambers

6.3.2 Subjects

Five males were recruited to sit in one chamber as a source of bioeffluents. They were all Caucasian, non-smokers, and had no chronic diseases. Twenty-three additional subjects were recruited to perform sensory evaluations. Table 6-2 summarises information about the source subjects and the subjects who performed the sensory evaluations. This information was provided by the subjects themselves. No one was examined medically and no tests were performed to examine the ability of the subjects to perceive odours. Subjects with impaired hearing and those indicating that they considered themselves unable to discriminate odours or distinguish different intensities of odours were eliminated. The majority of subjects were students. The subjects were compensated financially for their participation in the experiments.

Table 6-2. Demographic data of recruited subjects.

Characteristic Description	Subjects sitting in the chamber	Subjects performing sensory evaluations
Total	5	23
Gender: males, females	5, 0	12, 11
Age (mean±sd) years old	24.4±2.0	24.5±3.0
Height (mean±sd) cm	174.6±4.8	-
Weight (mean±sd) kg	73.4±3.4	-
Occupation: students, faculty	5, 0	22, 1
Smokers	0	1
Subjects reporting to have allergy including hay fever	0	1
Subjects reporting to have asthma	0	0
Subjects reporting to have chronic disease	0	1 (Narcolepsy)
Subjects considering themselves more sensitive to odorous/pungent substances	4	16
Subjects reporting to adapt easily to most odorous/pungent substances	4	17
Subjects reporting to get alerted easily by odorous/pungent substances	4	17

6.3.3 Experimental conditions and procedures

Twelve experimental conditions of which nine were with bioeffluents were created by combining the following conditions (Table 6-3): chamber with dermally-emitted bioeffluents, chamber with exhaled bioeffluents, chamber with whole-body (dermally-emitted+exhaled) bioeffluents, the supply air with ozone naturally present or eliminated and the chamber temperature set at 23°C or 28°C.

Table 6-3. Measured temperature (T), relative humidity (RH), carbon dioxide concentration (CO_2) and ozone concentration (O_3) under 12 conditions created in the chambers and investigated in the present experiments; the numbers show average level (standard deviation). For ozone, the number in parentheses indicates the outdoor ambient concentration of ozone.

Conditions in the chambers	23°C with ozone present				23°C with ozone absent				28°C with ozone absent			
	T [°C]	RH [%]	CO_2 [ppm]	O_3 [ppb]	T [°C]	RH [%]	CO_2 [ppm]	O_3 [ppb]	T [°C]	RH [%]	CO_2 [ppm]	O_3 [ppb]
No bioeffluents (empty (unoccupied) chambers)	22.8 (0.2)	39 (2)	558 (2)	7.4 (16.0)	22.5 (0.4)	44 (6)	548 (22)	N/A (26.0)	28.2 (0.2)	30 (1)	504 (58)	N/A (31.9)
Exhaled bioeffluents (chamber with the air exhaled through masks)	24.0 (0.5)	34 (1)	1862 (8)	16.6 (24.4)	22.8 (0.1)	54 (5)	1763 (69)	0 (21.6)	27.7 (0.2)	32 (2)	1787 (179)	N/A (28.9)
Dermally-emitted bioeffluents (chambers with the pollutants emitted through skin when individuals were wearing the masks)	24.4 (0.1)	33 (0)	533 (2)	13.7 (24.4)	24.8 (0.1)	36 (0)	887 (22)	3.1 (21.6)	27.6 (0.4)	38 (4)	641 (49)	N/A (28.9)
Whole-body (dermally-emitted+exhaled) bioeffluents (emitted by individuals sitting and breathing normally in the chambers without masks)	22.7 (0.1)	43 (3)	2249 (31)	2.2 (16.0)	24.0 (0.1)	53 (1)	1960 (15)	N/A (28.0)	27.9 (0.2)	30 (0)	1880 (27)	4.8 (32.2)

Five lightly dressed male subjects occupied one chamber as the source of bioeffluents. They were instructed not to drink alcohol or eat spicy food or garlic on the day prior to an experiment or on the experimental day. They received fragrance-free soap and a shampoo that they used in the evening prior to each experiment instead of their usual hygienic products. They were additionally instructed not to use strong deodorants or perfumes.

To isolate dermally-emitted and exhaled bioeffluents, these subjects sat in one chamber and exhaled the air to the other chamber through breathing masks (Sperian ValuAir Plus 6100V series RP155). The masks were attached to tubes (diameter of 2.5 cm) that ran through a polyurethane plate separating the twin chambers. The plate replaced the door separating the chambers. A miniature fan was mounted on the other end of each tube. It was operated at a relatively low speed to facilitate the movement of the exhaled air through the tube and ensure that all of it entered the second chamber (Figure 6-1). Tracer gas measurements were performed to confirm that the exhaled air was delivered to the other chamber. The subjects were instructed to breathe normally through their masks and to avoid taking deep breaths or exhaling rapidly so that all the air that was exhaled could be drawn through into the second chamber. They breathed normally without the mask in the whole-body bioeffluents condition. The subjects breathed in the air in the chamber that they occupied.

To remove ozone from the supply air, charcoal filters were installed. In the “ozone present” condition, these charcoal filters were dismounted and the ozone concentration in the supply duct was then the result of the ozone occurring naturally outdoors and any ozone scavenging taking place in the duct itself; no ozone generators were used to increase the ozone concentration. It is worth mentioning that a large amount of ozone can be generated indoors by printers, PCs, etc. The emissions are indicated in standards i.e. in RAL-UZ122 [63] mentioning ozone emission rate should be below 1.5 mg/h for the black-and-white printer, and 3.0 mg/h for the color printer.

The two temperature conditions were maintained by the chamber ventilation system. Relative humidity was not controlled but was measured.

To reduce the time taken to reach steady-state conditions in the chambers in the ozone absent condition, once the subjects entered the chamber, the fans supplying outdoor air to the chambers were turned off. They were then kept off until the CO_2 concentration had reached 2,000 ppm. During this time, the recirculation and mixing fans were on. Upon reaching 2,000 ppm the supply fans were turned back on. In the “ozone present” condition, the fans supplying outdoor air to the chambers were operated continuously to ensure that ozone was continuously supplied to the chambers.

Experiments were carried out on four days in June 2016, each day lasting 180-205 minutes. On two experimental days, conditions with ozone present in the supply ducts were examined. The chambers were set to 23°C on both days. On these days the subjects entered the chamber and stayed there for 180 minutes. The following conditions were created on the first day: chamber without bioeffluents present (empty chambers); and chamber with whole-body (dermally-emitted+exhaled) bioeffluents. On the second day, the following conditions were created: chamber with dermally-emitted bioeffluents only; and chamber with exhaled bioeffluents only. On the two subsequent days, ozone was removed from the supply air. The chambers were set at 23°C on one day and at 28°C on another day. Each day the following conditions were created: chamber without bioeffluents present (empty chamber); chamber with exhaled bioeffluents only; chamber with dermally-emitted bioeffluents only; and chamber with whole-body (dermally-emitted+exhaled) bioeffluents. The order of the conditions was randomized to make it possible to analyse the results for a potential chamber effect. The details of the experimental procedures are given in Supplementary Material S1.

6.3.4 Measurements

Air temperature, relative humidity and CO_2 concentration were measured at two locations inside each chamber; these parameters were recorded every 10 or 30 seconds by each calibrated sensor and logged. Ozone was measured with a 2b Monitor Model 205 in the duct containing the air in the chamber. Outdoor ozone concentration was obtained from the nearest monitor station. The accuracy of measuring instrumentation, as provided by the producer, is shown in Supplementary Material S2.

Chemical measurements and sensory assessments began few minutes after the planned steady-state concentration of CO_2 in the chambers had been attained.

The air for the chemical analyses was sampled on pre-conditioned universal multisorbent tubes (containing Tenax and activated charcoal); the sampled volume was 5 L and 2 L and the sampling flow rate was 0.22 L/min. The air was also sampled on 2,4-dinitrophenylhydrazine (DNPH) silica cartridges; the sample volume was then 30 L. No duplicates were made. Blanks were taken. The analyses of the sampled air were performed by an external laboratory. The multisorbent tubes were analysed to identify and quantify VVOCs, VOCs and SVOCs (up to C22) by thermal desorption gas chromatography-mass spectrometry (TD-GC/MS). Analysis was performed using a slightly polar capillary column (RTX-624) for which the Retention Time is mostly a function of the boiling point/molecular weight. The concentrations of identified compounds were expressed as their Toluene equivalent concentration by assigning the calibration curve of Toluene and assuming that their response in GC/MS is similar to that of Toluene. This assumption is acceptable in the case of hydrocarbons without heteroatoms in the molecule in the range of C6–C16 (personal communication with the commercial laboratory performing chemical analyses). DNPH were analyzed for aldehydes and ketones in the range from C1 (formaldehyde) to C6 (hexanone, cyclohexanone, hexanal, methyl isobutyl ketone (MIBK)). The concentration of each of these substances was quantified individually using five-point calibration curves based on a standard solution of DNPH in acetonitrile by liquid chromatography with a diode array detector (HPLC-DAD). Only concentrations ≥ 5 $\mu g/m^3$ are reported following the recommendations of the German AgBB-scheme (AgBB, 2010 [64]). Supplementary Material S3 provides additional details of these chemical analyses.

The air for the sensory assessments was delivered to a test rig through mounting slots in the side walls of the chambers, just above the floor. A flexible duct attached to an axial fan was connected to the slot. The rig delivered the air from the chamber to the assessing subject outside the chamber at a height of about 1 m. Two dampers were installed in this duct. One was used to set the airflow in the duct to about 0.9 L/s. The other one was capable of closing off the airflow; it was only opened when the actual sensory evaluation by subjects was taking place. Two ducts delivered the air for sensory assessments. One of them delivered the air with the same temperature as in the chamber. The other one was equipped with a heating wire installed outside the duct and delivered the air from the chamber at a temperature of 28^{o}C; the heating effect was controlled with a transformer. The air presented for sensory assessments was heated to 28^{o}C to separate the effect of increased temperature in the chamber on emissions of bioeffluents from the effect of increased temperature on the sensory assessments; a similar approach was used by Fang et al. (1998 a,b) [65, 66]. The area outside the chambers, where the sensory assessments took place, was ventilated and the temperature and relative humidity of the air were measured, but they were not controlled. The subjects assembled and waited for their turn to make these sensory assessments in the adjacent hall.

Sensory assessments were performed in a random order balanced across all subjects. Three scales printed on the paper were used by the subjects for performing the assessments (Figure 6-2): an acceptability scale. an odor intensity scale and a Visual Analogue scale for assessing air freshness. The acceptability scale was presented first and the other two scales were presented on a separate sheet of paper. The scale for acceptability was preceded by the following sentence: “Imagine that during your daily life in non-industrial buildings you were exposed to this air. How do you assess acceptability of air quality (note the dichotomy of the scale)?”.

During the assessments, the subjects approached the tube delivering the air, opened the damper, took one sniff and made their assessment immediately. They were encouraged to take another sniff when assessing another scale should they consider it necessary. If they did they were asked to take at least 3 inhalations of ambient air before inhaling the air from the duct for the second time. When they completed their assessments, they closed the damper and went back to the waiting area, where they took a break of at least 1 minute before making the next assessment.

The subjects attended a practice session prior to the experiments to receive their instructions, become acquainted with the procedures and with the use of the measuring scales. They were instructed not to drink alcohol or eat spicy food or garlic on the day prior to experiments or on the experimental day. They were additionally instructed not to use strong deodorants or perfumes.

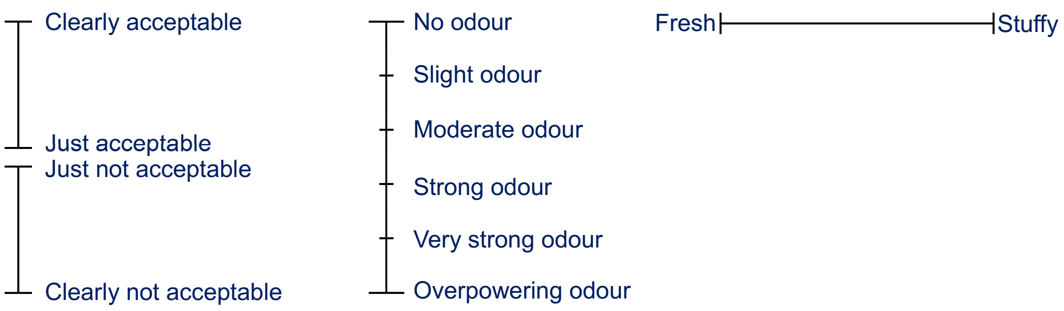


Figure 6-2. Visual Analogue scales used for the subjective assessments: acceptability scale (left), Yaglou's odour intensity scale (center) and an air freshness scale (right).

6.3.5 Data treatment and statistical analyses

The sensory ratings made by the subjects were digitized and the results were checked for transcription errors. The scales were coded as follows: clearly acceptable = +1, just acceptable = +0, just not acceptable = -0 and clearly not acceptable = -1; overpowering odor = +5 and no odor = 0, and fresh air = 0, stuffy air = 100. Measures of central tendency and variance were calculated for each condition under which sensory assessments were made.

Two-way ANOVA with a Bonferroni post-hoc test was applied to detect any significant differences between conditions with bioeffluents and conditions in the chamber, assuming that the residuals were Normally distributed. The analyses were made with IBM SPSS Statistics 23. In the present analysis, the significant differences were identified using p-values set at 0.01 and 0.05.

6.4 Results

All sensory assessments and the results of chemical analyses are shown in Supplementary Materials S4, S5 and S6. The present section shows selected results that describe the overall trends and directions identified by examining the measured data.

Figure 6-3 shows the ratings of acceptability of air quality and the ratings of odour intensity in the chambers under the different conditions examined in the experiments; the air delivered for these assessments had the same temperature as the temperature in the chamber. Univariate analyses were also made using one-way ANOVA with a repeated-measures design and Fisher's Least Significant Difference (LSD) post hoc test was used to compared sensory ratings made under different conditions (S7). Figure 6-3 shows that there were no statistically significant differences between sensory assessments of the air in the empty (unoccupied) chamber (without bioeffluents) and in the chamber with exhaled bioeffluents. The sensory assessments of the air in the chamber with dermally-emitted bioeffluents were significantly different from the assessments of air in the empty chamber and the chamber with exhaled bioeffluents. The sensory assessments of the air in the chamber with bioeffluents emitted by the whole-body (dermally-emitted and exhaled bioeffluents) did not differ significantly from the sensory assessments of air with dermally-emitted bioeffluents only but were statistically significantly different from the sensory assessments of air in the chamber with exhaled bioeffluents only and from those made in the empty chamber. Fig. 6-3 shows additionally that the presence or absence of ozone in the supply air did not significantly change the sensory assessments. However, it shows that when the temperature in the chamber was increased to 28^{o}C the sensory assessments of air in the chambers were significantly different from the corresponding sensory ratings made at 23^{o}C. Additional analysis was consequently made, which compared sensory ratings in the chambers with ozone absent when the temperature in the chamber was 23^{o}C or 28^{o}C, and the air presented for sensory assessment was 23^{o}C or 28^{o}C. Figure 6-4 shows the results of this analysis. It indicates that the reported odour intensity of the air with whole-body bioeffluents increased significantly at a temperature of 28^{o}C. This analysis shows additionally that a higher temperature of the air presented for sensory assessments reduced acceptability but had no effect on odour intensity assessments.

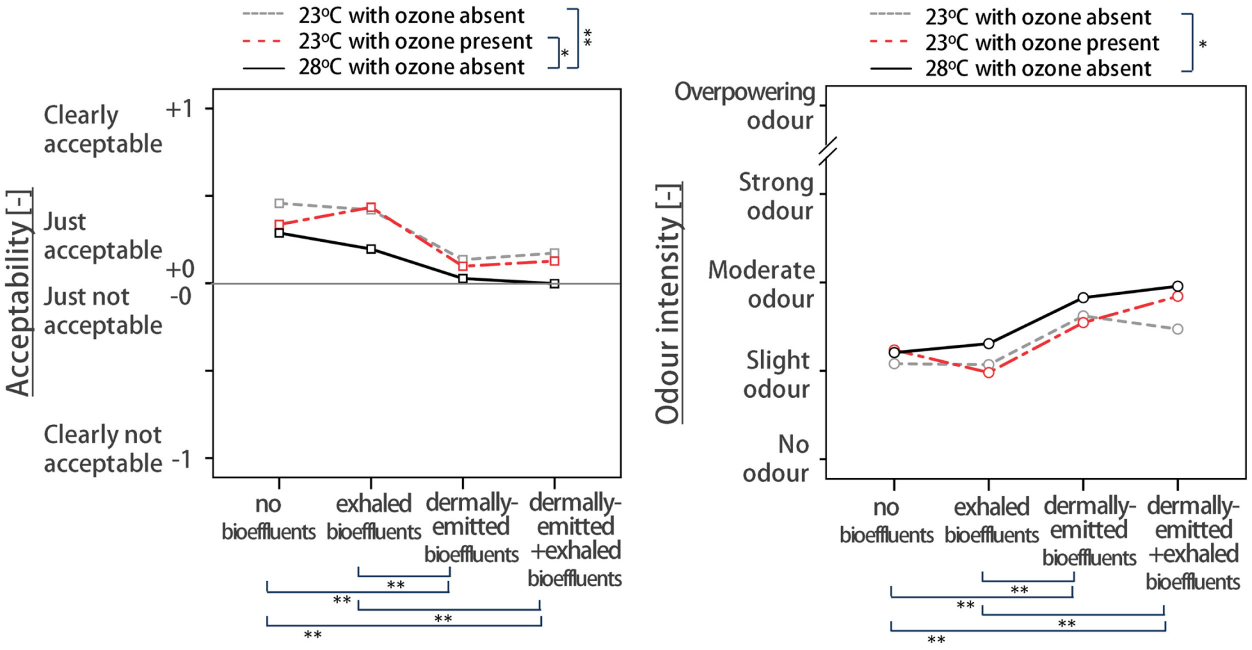


Figure 6-3. Acceptability of air quality (left) and odour intensity (right) in the chambers at different conditions investigated in the present experiments. The air presented for sensory assessments had the same temperature as the air in the chambers. Asterisks indicate the level of statistical significance: *: $0.01<p<0.05$, **: $p<0.01$

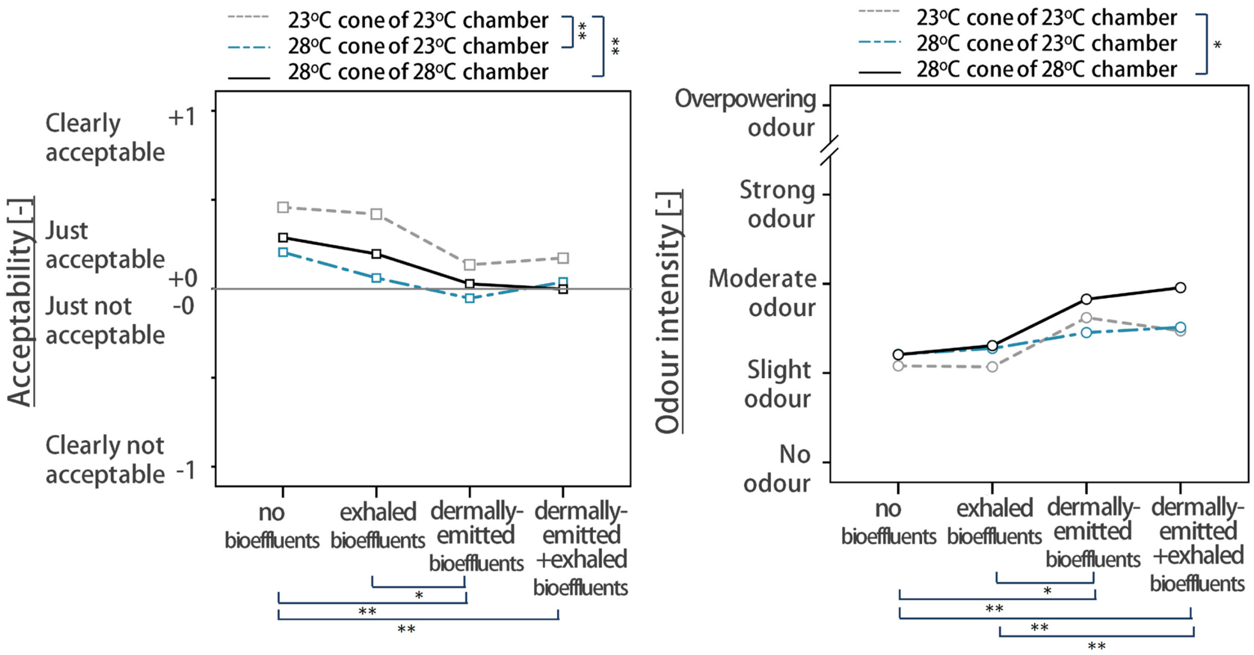


Figure 6-4. Acceptability of air quality (left) and odour intensity (right) in the chambers at different conditions investigated in the present experiments when ozone was absent in the supplied air. The air presented for sensory assessments had the same temperature as the chamber air but the air in an additional cone delivering the air from the chamber at 23°C was increased to 28°C. Asterisks indicate the level of statistical significance: *: $0.01<p<0.05$, **: $p<0.01$

In all, 51 substances were detected by GC-MS analysis and 7 substances were detected by HPLC-DAD. Figures 6-5 to 6-8 show some selected results of the chemical measurements. They were created by subtracting chromatograms representing chemical composition of the air under different conditions created during experiments. Major peaks are identified but a few that were not identified are left unmarked. Some of significant peaks could not be identified. When analyzing the results, the main focus was on whether there were any differences between the conditions in terms of the compounds that have previously been associated with human bioeffluents (Table 6-1).

Figure 6-5 shows the difference in chemical composition of the air with dermally-emitted and exhaled bioeffluents at 23°C when ozone had been eliminated from the supply air. The results show that greater amounts of geranylacetone, squalene, 6-MHO, nonanal and decanal were present in the dermally-emitted dermal bioeffluents, although less 6-MHO was present compared with geranylacetone, nonanal and decanal.

Figure 6-6 shows the difference in chemical composition of the air with dermally-emitted and exhaled bioeffluents at 23°C when ozone was present in the supply air. The figure shows very similar though larger differences in chemical composition than may be observed in Figure 6-5. Squalene was not detected to the same extent and here the 6-MHO peak was higher than those of nonanal and geranylacetone. Additionally, acetic acid was identified in the exhaled air, whereas the acetone in the dermally-emitted biofflluents was probably the result of the ozone-squalene chemistry that occurred in the chamber.

Figure 6-7 shows the difference in chemical composition of the air with whole-body (dermally-emitted+exhaled) bioeffluents when the chamber temperature was set at 28°C or 23°C. The results show more squalene in the chamber when the temperature was 28°C, as would be expected, and that there was more of an unknown hexanedioic acid ester at this temperature. More acetic acid was seen in the chamber when the temperature was 23°C. The other differences are unlikely to have been caused by the difference in temperatures.

Figure 6-8 shows the difference in chemical composition of the air with dermally-emitted bioeffluents when ozone was present and when it had been eliminated from the supply air, when the temperature was set at 23°C. The results show that when ozone was present there were more substances, including some higher molecular compounds and some aldehydes. More geranylacetone and squalene were found in the chamber when ozone had been eliminated.

The concentration of the compounds detected in the different conditions were compared with their odour thresholds. Although the concentrations were obtained as toluene equivalents, it is assumed that they approximate the actual concentration and at least maintain the relative differences between the reported concentrations. For 38 out of 59 substances detected in chemical analyses, the odour thresholds were obtained from the compilation of odour thresholds reported by Nagata (2003) [67], while for 33 out of 59 substances odour thresholds were found in the compilation reported by Devos (1990) [68]. The only substances for which the concentration was higher than the odour threshold in at least one of the 9 conditions examined in the experiments were decanal, hexanal, nonanal and octanal. A comparison of concentrations with odour thresholds for these and other compounds is presented in detail in the Supplementary Material S5 and S6.

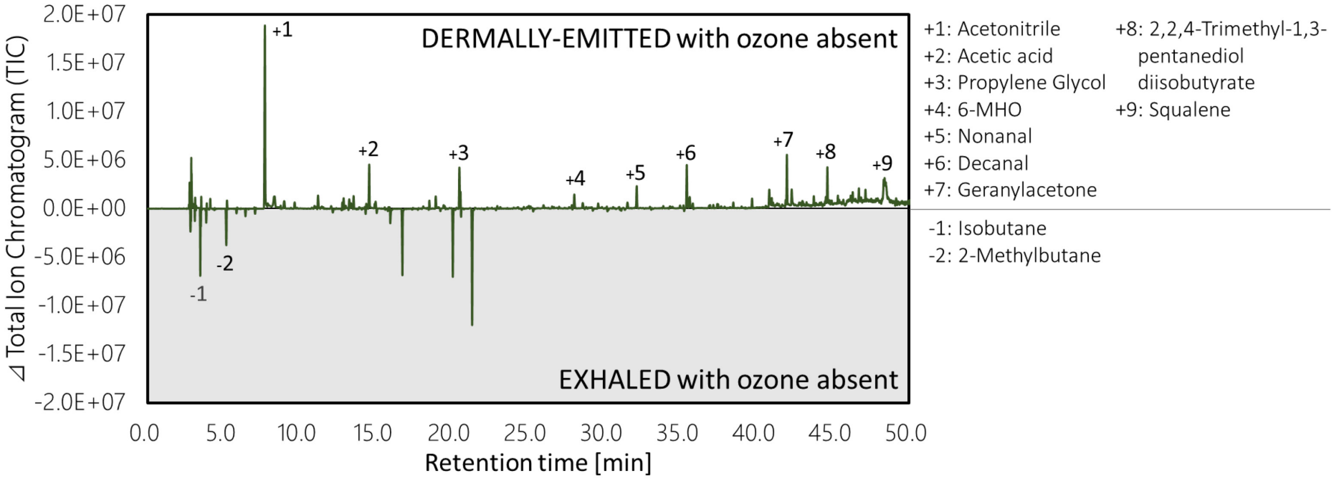


Figure 6-5. A comparison between chromatograms showing the chemical composition of the air with dermally-emitted and exhaled bioeffluents when the temperature in the chambers was 23°C and ozone had been eliminated from the supply air. The figure shows the result of subtraction of the chromatograms obtained for dermally-emitted and exhaled bioeffluents. The positive peaks indicate dermally-emitted pollutants with concentrations higher than were observed in the exhaled pollutants. The negative peaks show exhaled pollutants whose concentrations were higher than were observed in the dermally-emitted pollutants. No peak or peaks close to zero indicate either that the pollutant was not present or that the concentrations observed in the exhaled and dermaly-emitted bioeffluents were similar.

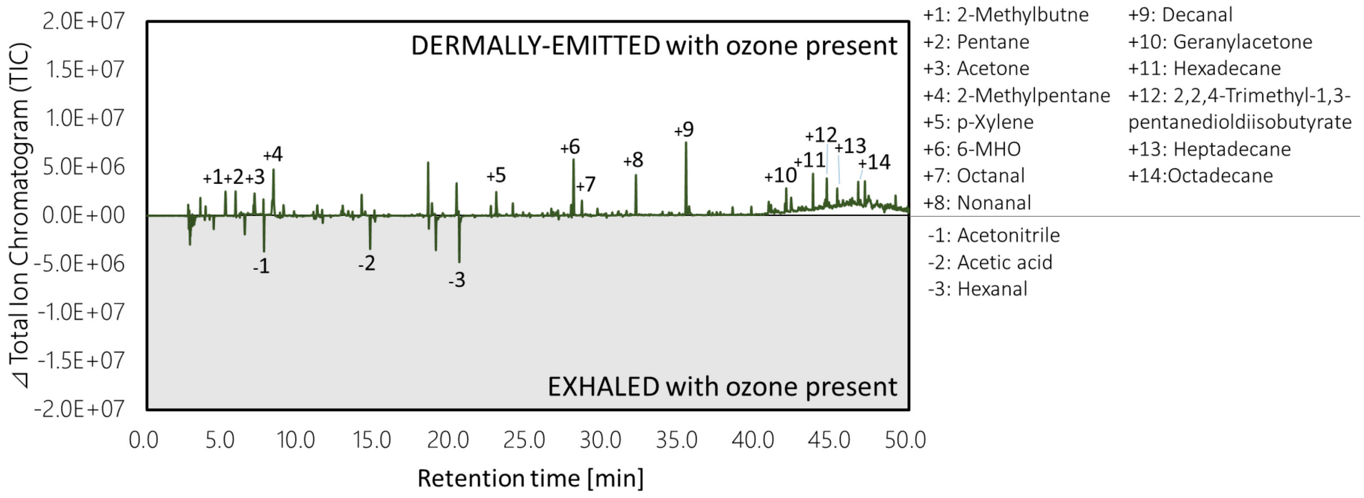


Figure 6-6. A comparison between chromatograms of dermal and oral bioeffluents at 23°C when ozone was not eliminated from the supply air. The figure shows the result of subtraction of chromatograms describing dermal emissions and exhaled emissions. The positive peaks indicate dermally-emitted pollutants with concentrations higher than they were in the exhaled bioeffluents. The negative peaks identify pollutants whose concentrations were higher in the exhaled bioeffluents than in the dermally-emitted bioeffluents. No peak or peaks close to zero indicate either that the pollutant was not present or that the concentrations observed in the exhaled and dermally-emitted emissions were similar.

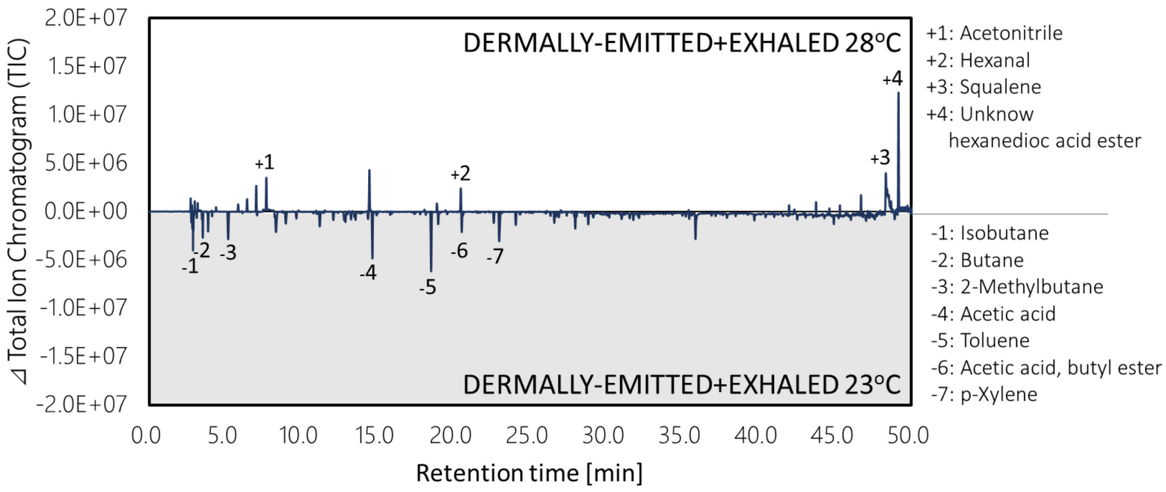


Figure 6-7. A comparison between chromatograms of whole-body (exhaled+dermally-emitted) bioeffluents at 23°C and 28°C when ozone had been eliminated from the supply air. The figure shows the result of subtraction of chromatograms describing emissions at 28°C and 23°C. The positive peaks indicate whole-body pollutants at 28°C with concentrations higher than were observed for whole-body pollutants at 23°C. Vice versa for the negative peaks. No peak or peaks close to zero indicate either that the pollutant was not present or that the concentrations in whole-body emissions at 23°C and 28°C were similar.

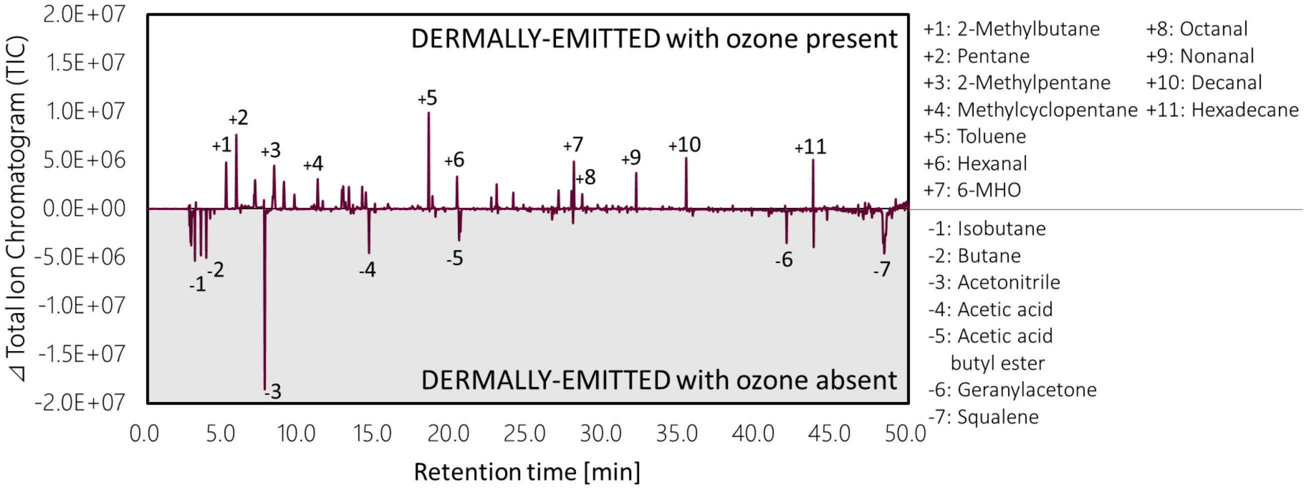


Figure 6-8. A comparison between chromatograms of dermally-emitted bioeffluents when ozone either had or had not been eliminated from the supply air at 23°C. The figure shows the result of subtraction of chromatograms describing emissions with and without ozone present. The positive peaks indicate dermally-emitted pollutants whose concentration was higher when ozone had not been eliminated than when ozone had been eliminated. Vice versa for the negative peaks. No peak or peaks close to zero indicate either that the pollutant was not present or that the concentrations with and without any ozone present were similar.

6.5 Discussion

The present results show that the perception of increased odour intensity and of unacceptable PAQ caused by human bioeffluents can be primarily attributed to dermally-emitted bioeffluents. As shown in Figure 6-3 the ratings of both acceptability of air quality and odour intensity differed significantly between exposures to exhaled and dermally-emitted bioeffluents. This finding supports the results of our pilot experiments, which also showed that the addition of pure CO_2 to air containing dermally-emitted bioeffluents did not significantly change the sensory ratings [69] , as has been reported by others [3, 4, 13].

One objective of the present research was to examine whether sensory responses can be associated with the chemical composition of the air. Figures. 6-5 show that among the compounds that were emitted dermally and from the whole-body there were aldehydes that have low odour threshold. These same compounds had been detected in the earlier studies that are summarized in Table 6-1. This suggests that the differences in sensory assessments shown in Figure 6-3 can be to a certain extent attributed to the presence of these compounds. Future studies should examine this hypothesis more closely, as the analytical measurements in the present experiment were limited (only Toluene equivalent concentrations were measured), as were the range and control of the ozone concentration.

The sensory evaluations of dermally-emitted and whole-body bioeffluents that were made when naturally-occurring ozone could enter the chambers with the supply air or when it had been eliminated were not significantly different (Figure. 6-3). The absence of an effect of ozone could be due to the low concentration of ozone leading to such small differences in the concentration of chemical compounds between the conditions with the ozone present or absent (Figure. 6-8) that they could not be detected by the sensory panel, which was also small. Figure. 6-8 shows that many compounds that would be expected to evoke sensory perception were at a slightly higher concentration when ozone was present - the peaks on chromatograms were higher; the differences were probably too small to be detected by the panel. Figure. 6-6 shows that squalene was present at lower concentration when ozone was present, as would be expected from the reaction of ozone with squalene (e.g. [57]). The occurrence of this chemistry is supported by elevated concentrations of the oxidation products expected from ozone/skin oil chemistry (e.g., acetone, 6-MHO, nonanal, decanal and geranylacetone). Table 6-3 shows that in the conditions with ozone present in the supply air, the ozone concentration measured in the chamber was lower than in the ambient air, suggesting that ozone was being scavenged in the chamber by reactions with skin oils.

Aldehydes, geranylacetone and 6-MHO were abundant in the dermal emissions, and they reduced PAQ and increased odour intensity. These results are in agreement with the published literature describing the processes that occur on human skin. Sebaceous glands consisting mainly of wax ester (25%), triglyceride (60%) and squalene (12%) and distributed over the entire body (except for the palms and soles of the feet) produce squalene [70]. Squalene has six double bonds that can be easily oxidized. This reaction produces nonanal, decanal, geranylacetone and 6-MHO. Geranylacetone is both produced by ozone (with squalene) and consumed by ozone after it is produced. In the present study, the consumption of geranylacetone seemed to dominate, as geranyl acetone was present at a lower concentration when ozone was present (Fig. 6-8). 6-MHO also reacts with ozone once it is formed but it apparently was not all consumed, as may be seen in Fig. 6-8. This is consistent with 6-MHO being produced both by ozone reacting with squalene and by ozone reacting with geranylacetone, whereas geranylacetone is produced only by ozone reacting with squalene (and then being consumed by ozone), which is in agreement with the measurements of gernalyacetone presented in Figure 6-8. The processes described above show that ozone and dicarbonyls react quickly in the upper layers of the skin, preventing from penetrating some potentially hazardous compounds deep into the skin and hence reaching the blood [71]. It is worth mentioning that sebaceous compounds mix with sweat on the epidermis and that this acid mantle has a bactericidal action on the horny cell layer (especially wax ester and squalene), promoting water retention [72, 73] (Schade and Marchionini, 1928; Hachem et al., 2003).

Absence of ozone will not completely eliminate the oxidation process but it may reduce the rate at which squalene is oxidized. The reason is that people may already have the oxidized substances on their skin because the process had occurred in places where ozone was present e.g. outside the building. Geranylacetone, nonanal and decanal have high molecular weights and hence are sticky. These molecules remain on the skin after they are produced; 6-MHO, on the other hand, is quite soluble in skin oil and not as sticky. This may explain why the aldehydes produced by ozone/skin oil chemistry were detected even when ozone had been removed from the supply air and that the concentration of 6-MHO was lower than that of geranylacetone, nonanal and decanal (Figure 6-5). The concentration of 6-MHO was higher than that of nonanal and geranylacetone with ozone present in the supply air, as indicated by the higher peak (Figure 6-6). This is consistent with its production in the ozone/squalene reactions that occurred in the chamber when ozone was present. For completeness, it should additionally be mentioned that the oxidation process can also be driven by other oxidative compounds such as oxygen, although this reaction is probably too slow to have had any effect in the present experiments.

It may also be seen that there were more compounds with a Retention Time higher than 40 in the condition with dermally-emitted bioeffluents compared with the condition with exhaled bioeffluents (Figs. 6-5 and 6-6). In general, compounds with a higher molecular weight have higher retention times. The compounds exhaled tended to be more volatile with a lower molecular weight than the compounds that were dermally-emitted (Table 6-1 and Nicolaides, 1974 [74]). Also, even if there had been compounds with a high molecular weight in the exhaled breath it is likely that they would have been sorbed on the breathing mask and on the tube delivering the exhaled air to another chamber.

There are other processes that may explain why body odour was present even when ozone was absent. Body odour is produced when the resident skin flora that are resident on the surface of the skin decompose the sebum and sweat through the process termed lipase action [69]. In particular, triglyceride is mainly hydrolysed to fatty acid by propionibacterium acnes and staphylococcus epidermidis, even when there is no ozone, although these compounds were not detected in the present experiment. Even if the skin had been wiped, staphylococcus epidermidis can return to its original concentration on the skin within 30 min to 2 hours. The analytical methods that were used were not capable of detecting fatty acids. Some of the undetected fatty acids may thus have been partially responsible for the observed body odour.

Although Figure 6-3 does not show clearly whether increased temperature increased the emission of human bioeffluents, Figure 6-5 shows that when the effect of temperature on perception was eliminated (the sensory ratings were made on air having the same temperature), the odour intensity of the air with whole-body bioeffluents at 28^{o}C was significantly different from the odour intensity when the temperature was 23°C. This result implies that the emission of bioeffluents increased with increasing temperature. A similar effect can be seen in Figure 6-7, especially for squalene and hexanedioic acid ester. The present results provide some support for the Australian ventilation standard [75] that imposes an increased ventilation requirement when ambient temperatures are higher than 27°C, to deal with the expected higher emission of bioeffluents. However, more studies are required to further investigate the effect of temperature on the emission of bioeffluents, taking into account the recent research reported by Luo et al. (2016) [76], which shows that metabolic rate can be significantly influenced by ambient temperature and clothing insulation.

To explain the results observed when the temperature in the chamber was 28°C, it should be noticed that the vapor pressure of squalene is higher at 28°C than at 23°C which means that it becomes more volatile (the melting point of squalene is -5°C so it is a liquid at indoor temperatures). Additionally, during periods with high temperatures sebum becomes soft and secretion increases, which would increase volatilization and consequently the emission of squalene. Moreover, the number of resident skin flora increases at higher temperatures; higher humidities, higher nutritional status of the skin and pH also increase this number. Consequently, when the temperature increases, more odorous substances will be produced as resident skin flora decompose triglyceride and contribute to any sensory effects [70]. Finally, higher temperature will increase the rate of the oxidation reaction with squalene according to the Arrhenius equation, which will again contribute to stronger sensory responses. The combined effect of higher temperature and elevated ozone concentration on emissions of bioeffluents that can reduce the PAQ warrants further attention. It should be taken into account in the design of ventilation for occupied spaces.

The temperature of the air should also be taken into account when setting ventilation requirements to achieve acceptable air quality. The sensory assessments of air quality performed during the present experiment confirm the previous work of Kerka and Humphreys (1956) [77], Woods (1979) [78], Cain et al. (1983) [8], Berglund and Cain (1989) [79] and Fang et al. (1999) [80]. They show that the air was perceived as less acceptable at an increased temperature and that there is either a very small or no effect of temperature on the perceived odour intensity (Figures 6-3 and 6-4).

Additionally, the effect of the occupants' age, body size, hygienic habits and health conditions should be considered in future studies. As mentioned above, Gallagher et al. (2008) [28] reported that some compounds, such as dimethylsulphone, benzothiazole and nonanal, were emitted from skin at a higher rate with increasing age. The number of colonies can differ from person to person depending on the composition of their skin and the composition of the sebum on the skin surface. Normally the volume of sebum secreted peaks around the age of 10 to 20 years for females and around the age of 30 to 40 years for males. In the present experiment, the source subjects' average age was 24.4±2.0, suggesting that the odour intensity would be higher if 30 to 40 year-old male source subjects had been used. If the source subjects had had a larger body surface area, it would also have been increased; their average height and weight were 174.6±4.8 and 73.4±3.4 in the present experiment, indicating that they were not overweight.

2,2,4-Trimethylpentanediol diisobutyrate, a low-temperature plasticizer commonly referred to as TXIB was detected when conditions with dermally-emitted bioeffluents were compared with the condition with only exhaled bioeffluents (Figures 6-5 and 6-6) but not when whole-body biofluents were compared (Figures 6-7 and 6-8). TXIB should not be considered as a dermally-emitted bioeffluent. It is an additive present in inks, plastisols, coatings, urethane elastomers, and nail polish lacquers and its presence was probably because the source subjects had touched something that was coated with TXIB prior to the experiments.

One of the limitations of the present experiments was that only one "blend" of bioeffluents was examined. There could be external factors, including the diet, stress level, hygiene habits, personal care products etc. of the source subjects, which could have affected the emission of chemical compounds and consequently the air quality. Their clothing could also affect the emissions; in the present experiments the source subjects were lightly dressed. Another limitation of the present work could be the experimental procedure. On the two experimental days when ozone was being eliminated the break between different conditions was 10-30 min. and the fans supplying outdoor air were turned off in order to reduce the time needed to achieve a steady-state condition. Sensory assessments showed however that the impact of these procedures on the final results was negligible. For example, the background sensory assessments on the days when the outdoor air supply was not turned off at 23°C did not differ significantly from those on the days when it was turned off.

Finally, the source subjects breathed air containing dermally-emitted bioeffluents when wearing the masks. This will have caused some dermally-emitted bioeffluents to be drawn into the chamber together with the exhaled bioeffluents.

Future studies should avoid these limitations. They should also extend the present results by examining the higher ozone levels that occur in other parts of the world with higher outdoor ozone levels than in Denmark, as well as the effect of indoor emitted ozone from printers and PCs. Additionally, the combined impact of ozone and temperature, different concentrations of bioeffluents, different production rates of bioeffluents (by manipulating the activity level of the source subjects) and the impact of clothing, laundering of clothing and bathing habits.

6.6 Conclusions

1. The presence of exhaled bioeffluents did not cause any significant change in the sensory ratings of odour intensity or the acceptability of the chamber air quality.
2. The presence of dermally-emitted bioeffluents (either alone or with exhaled bioeffluents) caused significant changes in the sensory ratings of both odour intensity and the acceptability of the chamber air quality.
3. Increasing the temperature from 23°C to 28°C significantly increased the odour intensity of bioeffluents emitted by the whole body.
4. Eliminating ozone from the supply air did not cause any change in sensory ratings of odour intensity or the acceptability of the air quality when dermally-emitted, exhaled or whole-body bioeffluents were present.
5. The chemical composition of air with dermally-emitted and exhaled bioeffluents was different. The air with dermally-emitted bioeffluents present contained aldehydes, geranylacetone and 6-MHO. Increasing the air temperature to 28°C increased the emission of squalene and other compounds with high molecular weight. Eliminating ozone from the supply air reduced the levels of aldehydes, geranylacetone and 6-MHO. When ozone was not removed the concentration of squalene was lower.
6. The present results are particularly relevant to the development of effective methods for improving the air quality when pollutants emitted by humans are present. They indicate that dermally-emitted bioeffluents may be the primary cause of any sensory effects.

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Outline

Chapter 7

Conclusive summary

7 Conclusive summary

The COOL BIZ campaign, which started in 2005, has been widely introduced in office buildings and has changed workers' behavior. The campaign recommends the room temperature to be set at 28°C and a relaxed business dress code in offices during summer. However, after the March 2011 Great East Japan Earthquake caused the accident at the Fukushima No. 1 nuclear power plant, mandatory electricity saving was forced on customers having large contracts, including office buildings in the Greater Tokyo region. The main objectives of this thesis were to quantitatively examine behavior change as a result of post-earthquake energy shortages and the consequences for indoor environment and comfort of office employees.

The thesis is composed of seven chapters and the main findings of each chapter are explained as follows.

In Chapter 1, the objectives of the research are stated and the relevant previous researches are summarized.

In Chapter 2, the field and questionnaire surveys conducted in five buildings with seven floors under mandatory electricity saving to investigate the energy efficient electricity-saving measures that did not decrease the comfort and productivity of the occupants are discussed. In five out of seven floors, the temperature, illumination, and ventilation rate settings were changed with a total of 22 environmental conditions surveyed. Further, we investigated three additional office buildings, only asking the occupants about their views on electricity saving without taking any physical measurements or carrying out satisfaction surveys. A total of 2046 questionnaires from employees were collected. A strong correlation was found between dissatisfaction and room temperature; in particular, thermal satisfaction decreased steeply at temperatures over 27°C. On the other hand, employees widely accepted the suggested decrease in illumination from 650 to 200 lux; the lowered illumination reduced energy consumption to a greater degree than the turning up of the temperature in the air conditioning system. A gradual increase in dissatisfaction was found with an increase in the concentration of carbon dioxide (CO_2) in the range of 600–1200 ppm. The perception of the indoor air quality was also affected by the thermal environment. According to the questionnaire results on electricity saving, increased awareness regarding electricity saving was observed, with more than 90% of the employees willing to implement electricity-saving measures. However, 72% of the respondents expressed some degree of inconvenience caused by the measures. Accordingly, self-estimated productivity in the summer of 2011 was 6.6% lower than the previous year.

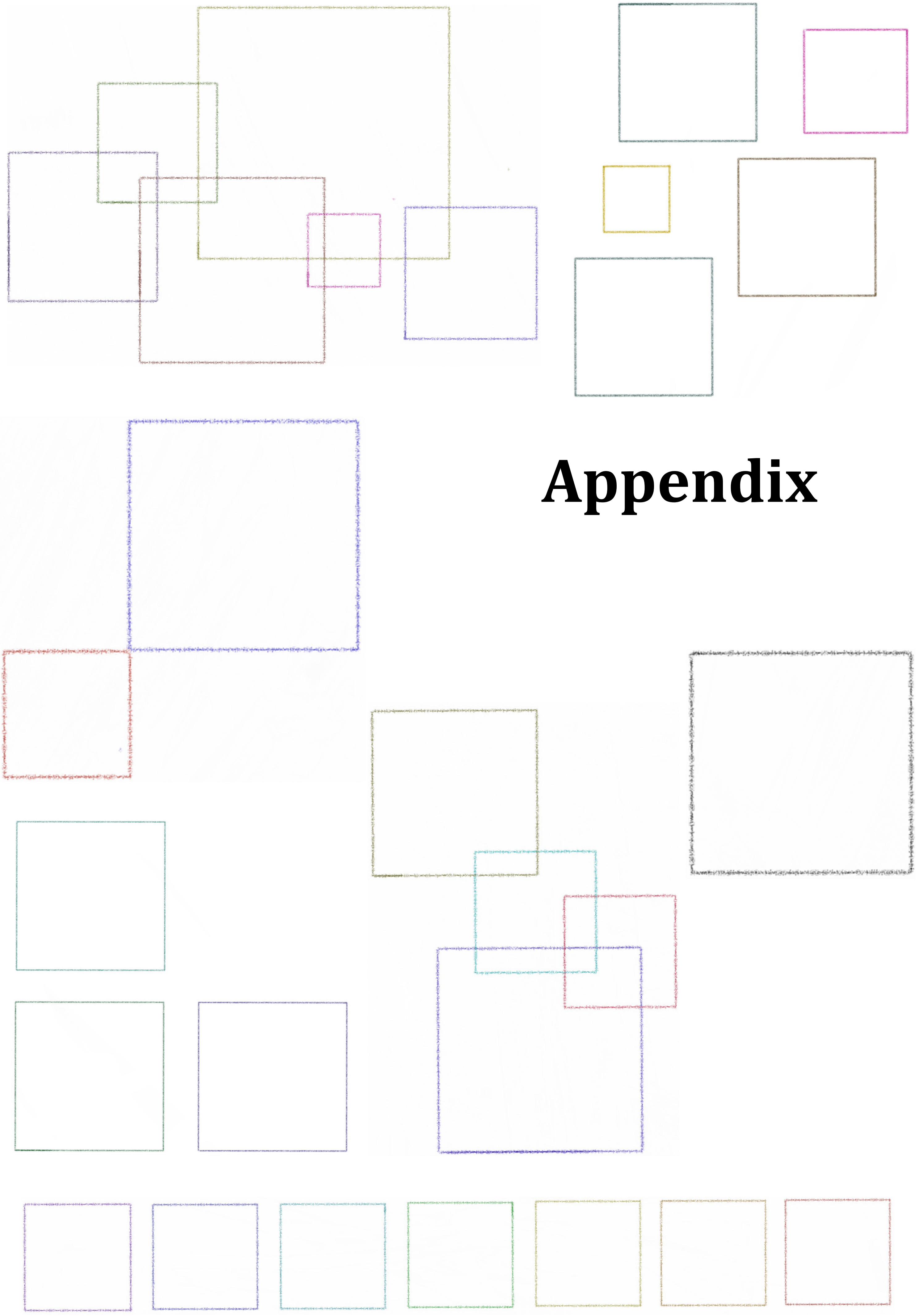
In Chapter 3, a web-based questionnaire that was conducted for 1200 employees in Tokyo, Nagoya, and Osaka to investigate whether different earthquake and electricity-saving experiences affected their awareness, electricity-saving measures, and comfort is discussed. Similar electricity-saving measures were implemented in three areas; especially, the measure of “increasing the set temperature point” was practiced by more than 60% of the respondents. However, this was also considered the most annoying measure. Lowering the illumination caused lower dissatisfaction than turning up the set point of the air conditioning as mentioned in Chapter 2. However, employees’ awareness towards saving electricity was different; employees in Tokyo who had directly experienced the earthquake were more positive towards saving electricity. Moreover, the more positive about saving electricity the workers were, the less thermal dissatisfaction rate they reported in all the three areas, although the indoor environments of the offices were assumed to be almost the same. The satisfaction of the employees towards the office environment was affected to a larger degree by their feelings than the indoor environment or their gender and age. It was observed that the post-earthquake experiences of the mandatory electricity saving had changed the awareness of the workers more in Tokyo than in the other regions.

Chapter 4 reveals the extent to which employees' behaviors had changed regarding energy consumption and productivity since the impact of the earthquake disaster. The authors conducted continuous field and questionnaire surveys in seven electricity-saving office buildings in the summers of 2011–2013. Additionally, the past research data of our laboratory were collated, and in total, 60 cases with 3692 questionnaires were analyzed. The internal heat load decreased after the earthquake in several ways; the average desk level illuminance decreased substantially to 391 lux from the typical 750 lux setting and energy-efficient office automation (OA) equipment was introduced and implemented. Additionally, excessive indoor air temperatures were avoided, thereby increasing the number of offices with 27°C indoor temperature by about 15%. The CO_2 concentration did not change; the average was about 710 ppm. The awareness of the workers regarding saving electricity hardly diminished after peaking in 2011; about 90% of the workers felt positive about saving electricity. Measures that are not very stressful, such as wearing light clothing and turning off lighting during lunch, were continuously practiced. This resulted in the 2011 pre-earthquake self-estimated productivity change rate of -6.6% to rise to about 0% in the post-earthquake years. Electricity saving was implemented in a proper manner such that it did not negatively affect the comfort of the workers. This behavior change was established in offices after the earthquake. In addition, it was shown that the satisfaction of the workers depended on the indoor air quality and thermal environment more than the other environmental factors such as lighting, sound, space, and usability of ICT (Information and Communication Technology) facilities. However, the post-earthquake satisfactions in the areas of indoor air quality and thermal environment were still poor; hence, effective improvement measures were needed.

Chapter 5 presents the problems caused by the post-earthquake behavioral change in the workers that resulted in an internal heat load decrease as explained in Chapter 4. The internal heat load and the operation of a multi-split type air-conditioning system of an indoor-air conditioner (VRV: Variable Refrigerant Volume) and a DOAS (Dedicated Outdoor Air System) which consists of two parallel systems: a dedicated system for delivering outdoor air ventilation and a parallel system to handle the indoor loads, were investigated in an office drawing a low heat load. Two indoor air temperature settings, 26°C and 27°C, were chosen to investigate the changes in the operation of the DOAS. Field and questionnaire surveys and an energy consumption analysis were also performed. The results showed that the primary energy consumption of the OA equipment was approximately 95 MJ/m^2 per year and 235 MJ/m^2 per year for the lighting. The average desk lighting illuminance was 520 lux. These values are relatively small compared to the officially published average energy consumption value of 369 MJ/m^2 for OA and 363 MJ/m^2 for lighting. The total cooling capacity settings of the VRV and the DOAS were 158 W/m^2, which is relatively small considering the common cooling capacity of 200 W/m^2. However, the average load factor for both the VRV and the DOAS under normal operation was small; below 30%. The actual indoor air temperature was controlled as desired. The relaxation of the air-conditioning setting temperature and the improvement in the control of the air conditioning operation reduced the energy consumption. However, it was confirmed that the operational balance of the VRV and the DOAS collapsed due to stoppage or excessive operation of the DOAS. Furthermore, it was found that the humidity setting of the system was the main cause for the change in operation. The operational method of the DOAS had a large influence on the total electric energy consumption in offices practicing internal load reduction. Thus, introducing the air-conditioning systems having appropriate capacity and a comprehensive energy saving operation method, rather than a partial optimization of each device, would be beneficial in terms of total energy saving.

Chapter 6 attempts to identify the under-researched problems of perceived air quality stated in Chapter 2. Since the focus on human bioeffluents and their contribution to indoor air quality has increased again recently, an experiment to investigate the difference between the effects of exhaled and dermally-emitted bioeffluents on perceived air quality (PAQ) was conducted as the first attempt by chemical analysis and sensory evaluation of humans bioeffluents. Conditions in which exhaled and dermally emitted bioeffluents could be sampled separately or together (whole-body emission) were created. Lightly-dressed subjects sat in a ventilated climate chamber, located at the International Centre for Indoor Environment and Energy, Technical University of Denmark, with very low surface emissions. They exhaled the air through a mask to another, identical (twin) chamber or without a mask to the chamber in which they were sitting; the outdoor air supply rate was the same in both chambers. The carbon dioxide concentration in the chambers with exhaled air was 2,000 ppm. Chamber temperatures were 23^{o}C or 28^{o}C and ozone was present or absent in the supply airflow. When dermally-emitted bioeffluents were present, the PAQ was less acceptable and the odour intensity was higher than when only exhaled bioeffluents were present. The presence or absence of exhaled bioeffluents in the unoccupied chamber made no significant difference to the PAQ. At 28^{o}C and with ozone present, the odor intensity increased and the PAQ was less acceptable in the chambers with whole-body bioeffluents. The concentrations of nonanal, decanal, geranylacetone and 6-MHO were higher when dermally-emitted bioeffluents were present and they increased further when ozone was present; the concentration of squalene then decreased and increased again at 28^{o}C. Dermally-emitted bioeffluents seem to play a major role in the sensory nuisance experienced when occupied volumes are inadequately ventilated.

Chapter 7 summarizes the conclusions of each chapter. From the results of this thesis, it can be seen that the post-earthquake mandatory electricity-saving experiences as a stressor softened the workers' perception about the environment and changed their behavior, thus promoting energy-efficient offices. Consequently, the result shows that energy saving measures corresponding to the reduced internal heat load are required in the offices. Additionally, new findings about the pollutants emitted by humans were obtained in the context of developing effective methods for air quality control. This quantitative knowledge can be used to save energy in offices and prevent global warming in the future.



Appendix

Appendix A_ Summary of measurement points (chapter 2)

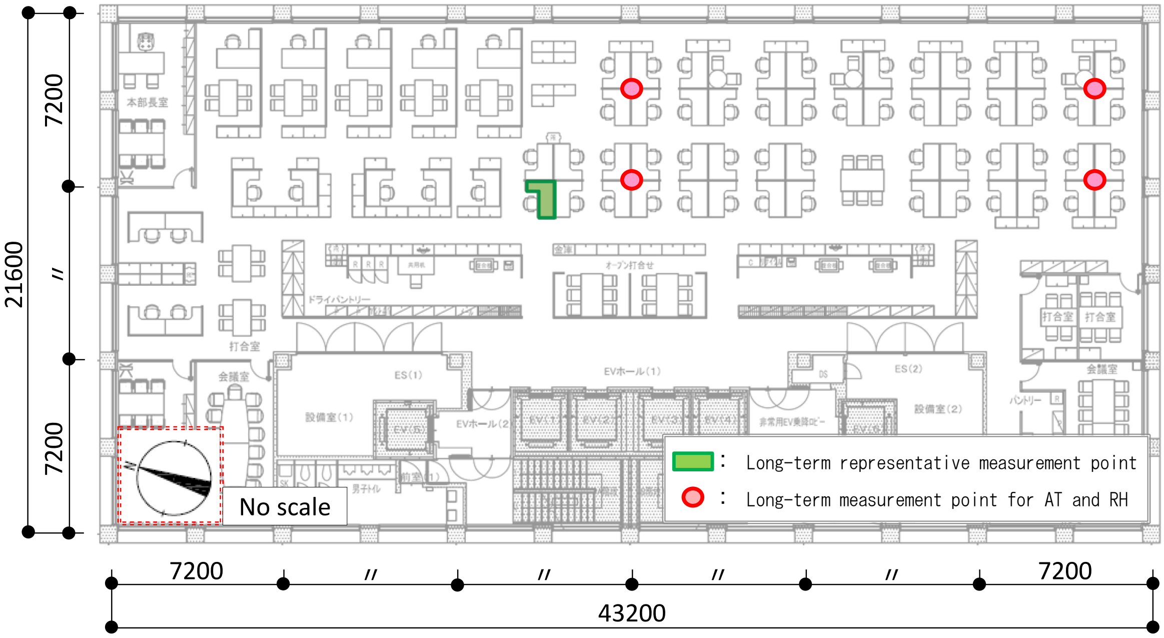


Figure A-1. Office plan and measurement points of A8F.

Figure A-2. Office plan and measurement points of A10F.

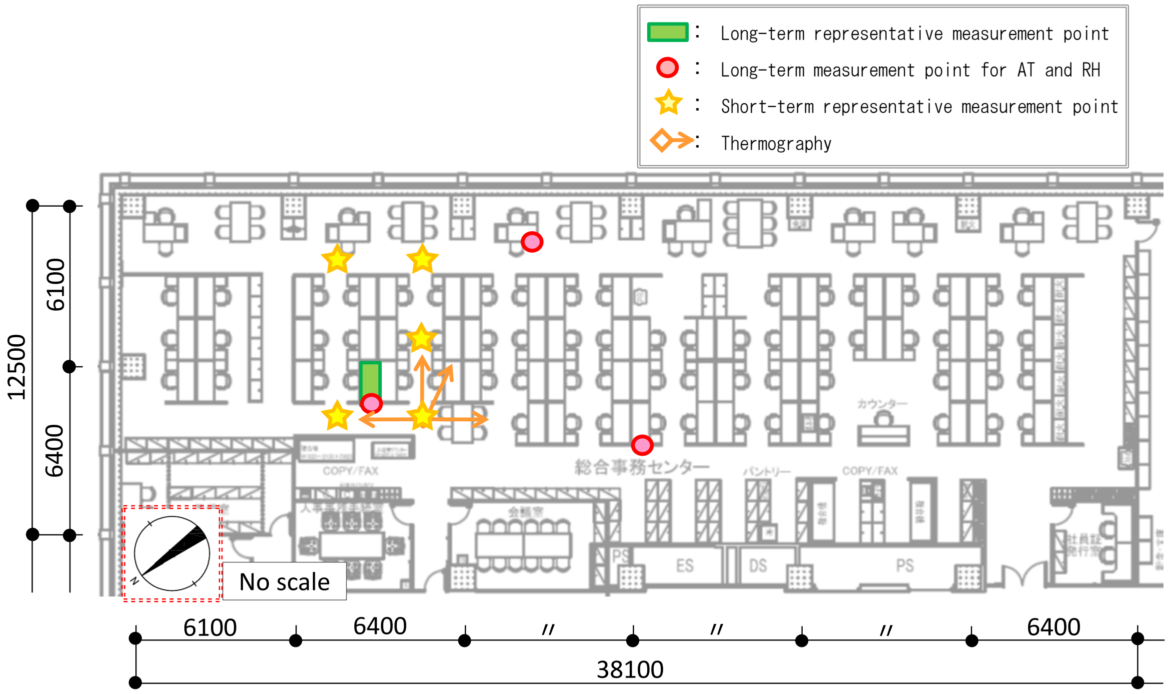


Figure A-3. Office plan and measurement points of B2F.

Figure A-4. Office plan and measurement points of B9F.

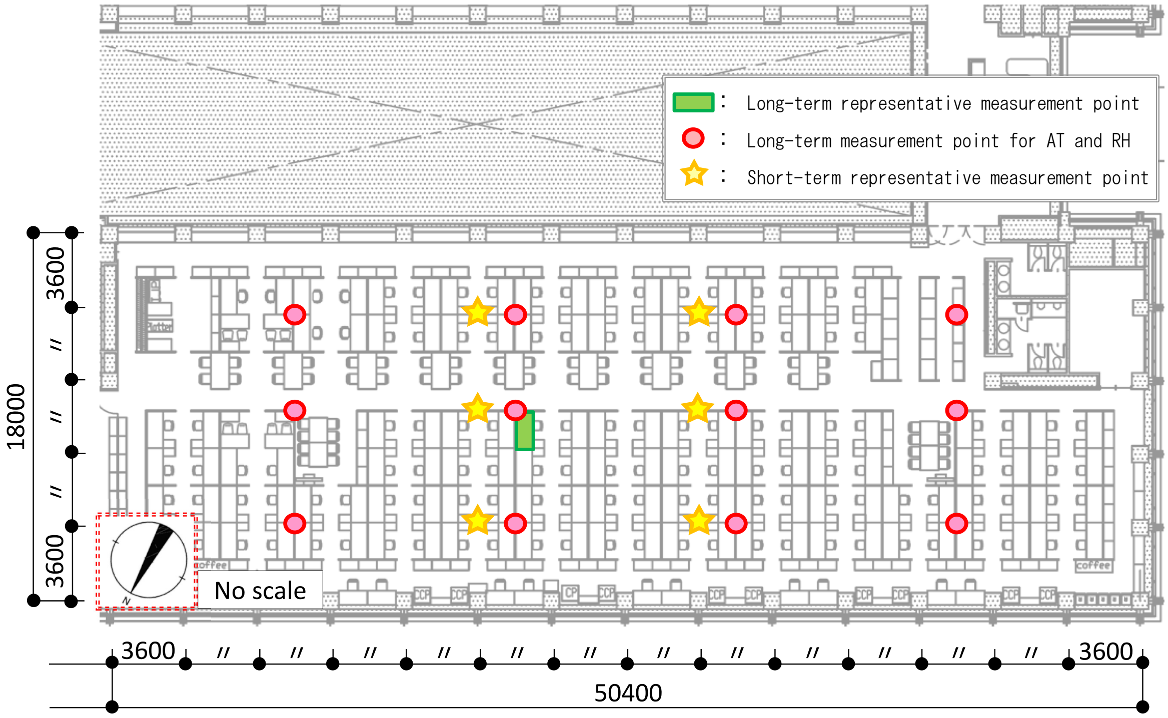


Figure A-5. Office plan and measurement points of C4F.

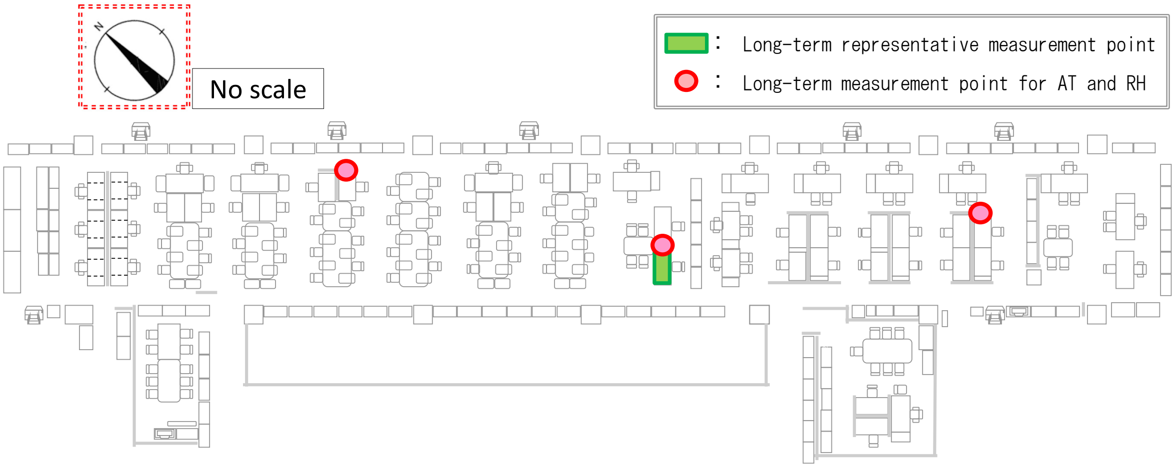


Figure A-6. Office plan and measurement points of D3F.

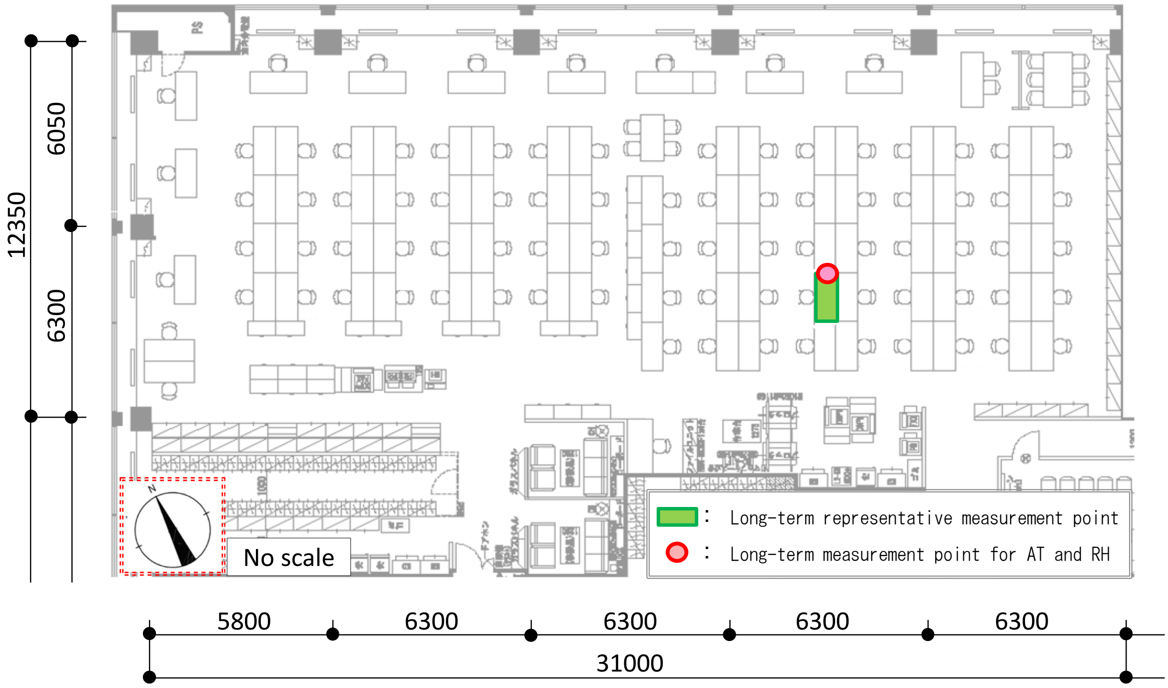


Figure A-7. Office plan and measurement points of E7F.

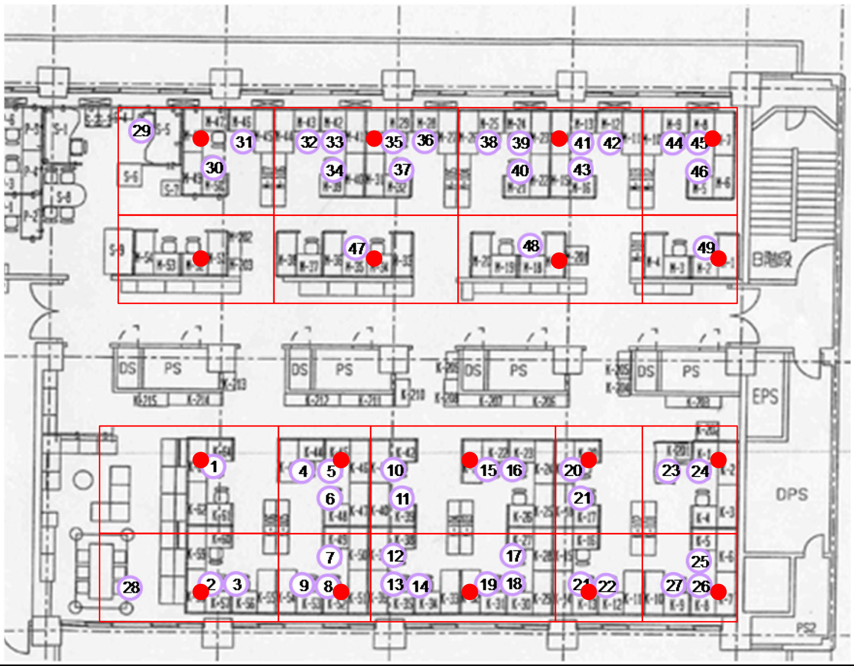
Appendix B_ Summary of measurement points (chapter 4)

● : measure point of AT and RH
☐ :allocated zones of AT and RH

Building A (Survey number 1)

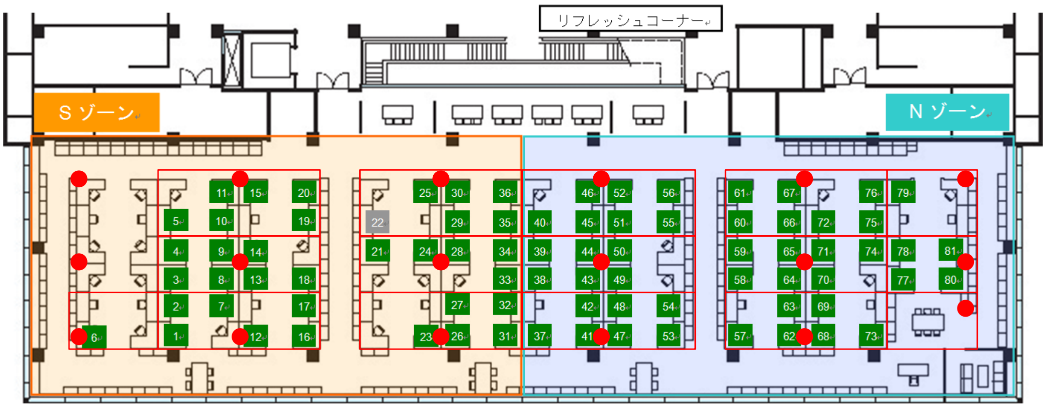
Building B (Survey number 2)

Building C (Survey number 3)

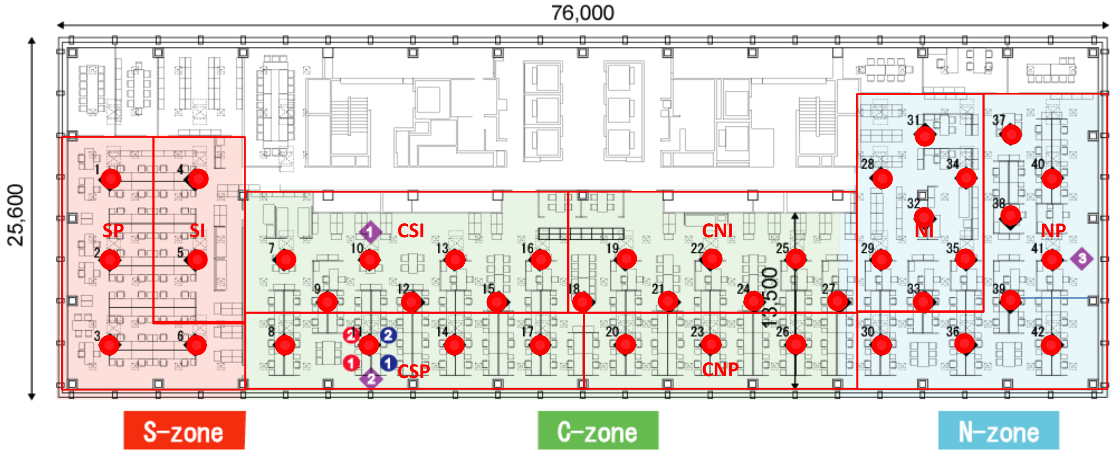


Building D (Survey number 4,7) no data

Building E (Survey number 5,6)



Building F (Survey number 8)

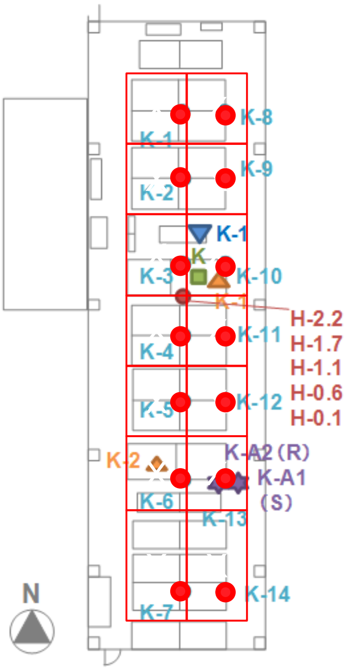


Building G (Survey number 9) no data

Building H (Survey number 10) no data

Building I (Survey number 11)

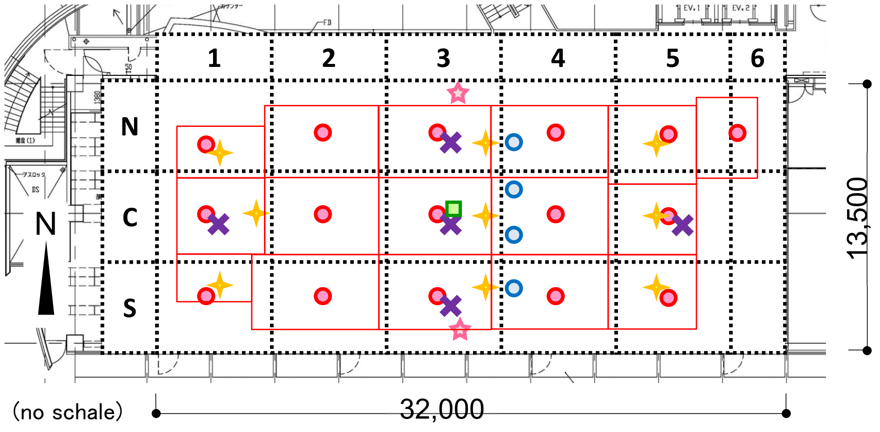
Building J (Survey number 12)



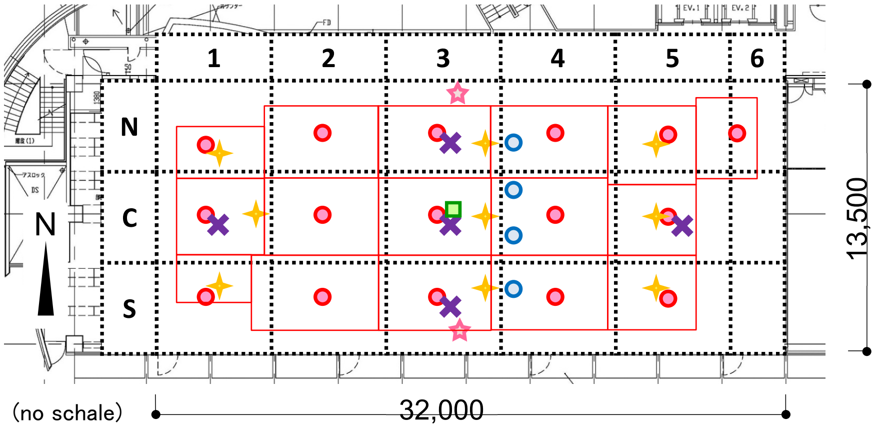
Building J (Survey number 13)

Building L (Survey number 14)

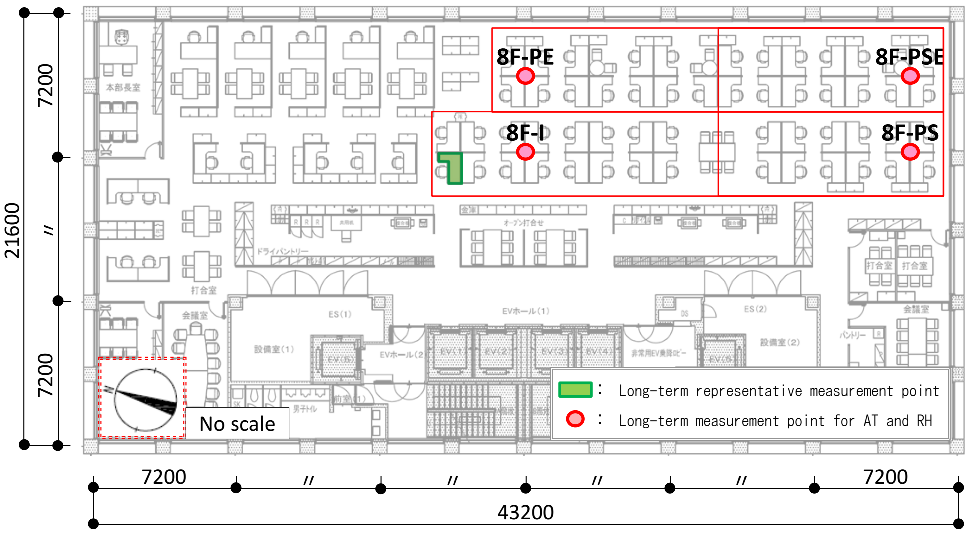
Building M (Survey number 15)



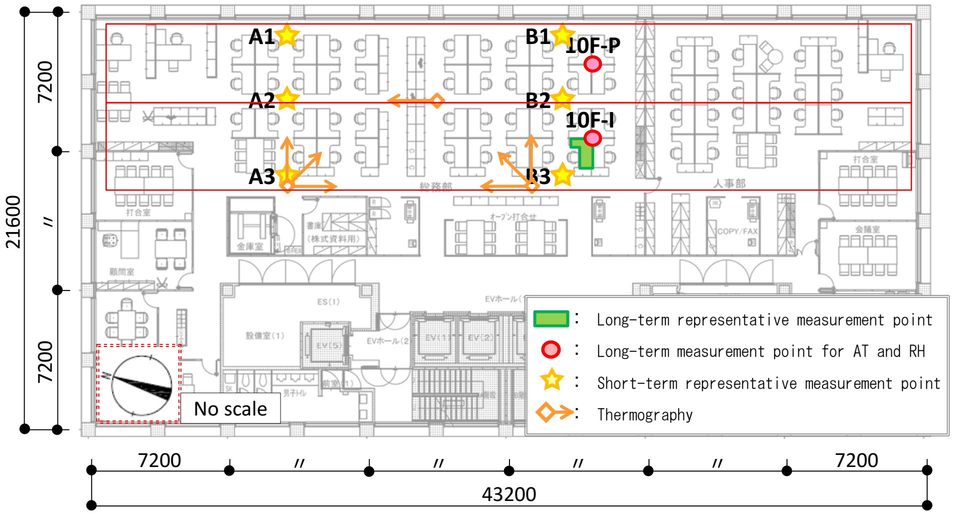
Building M (Survey number 40,52)



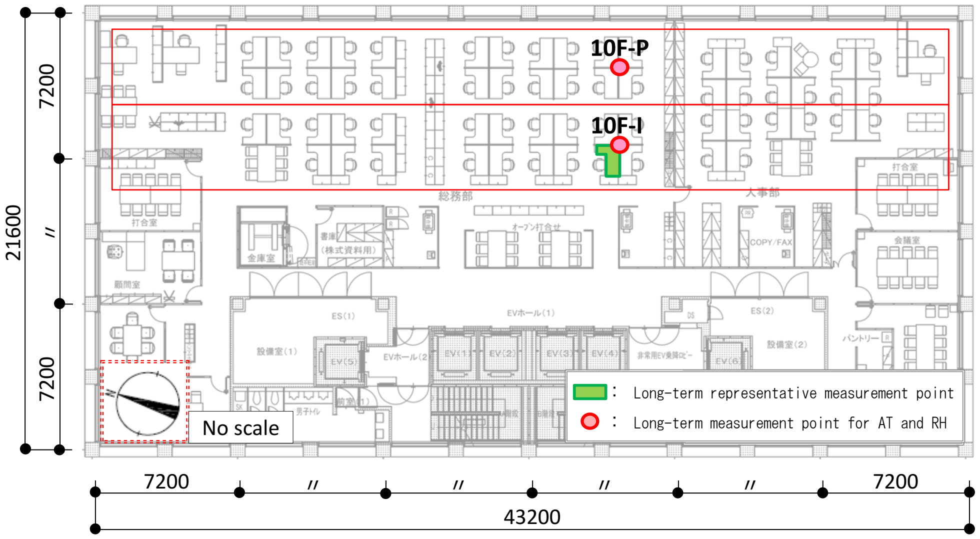
Building N (Survey number 16-19)



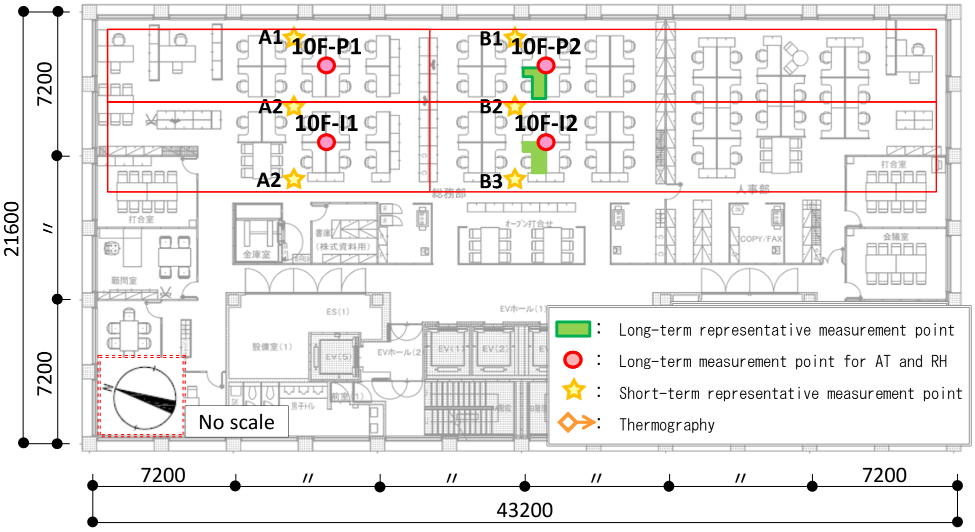
Building O (Survey number 20-23)



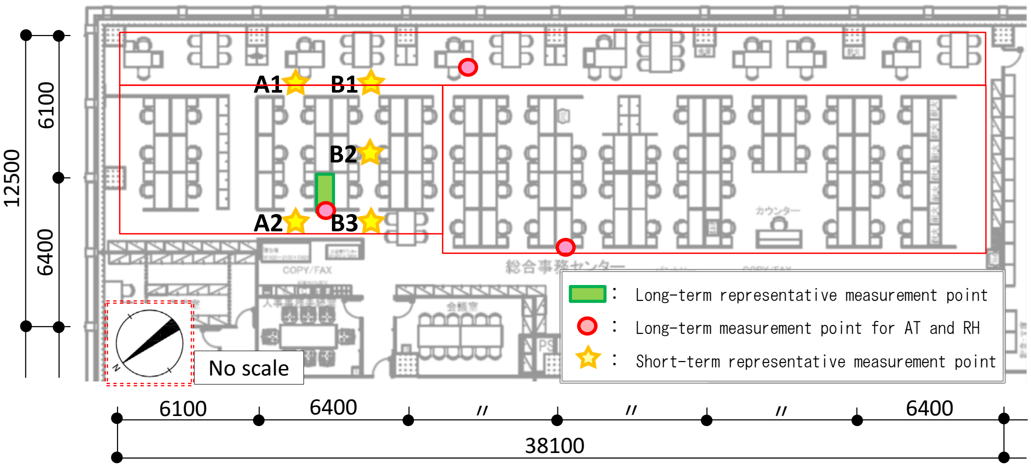
Building O (Survey number 45)



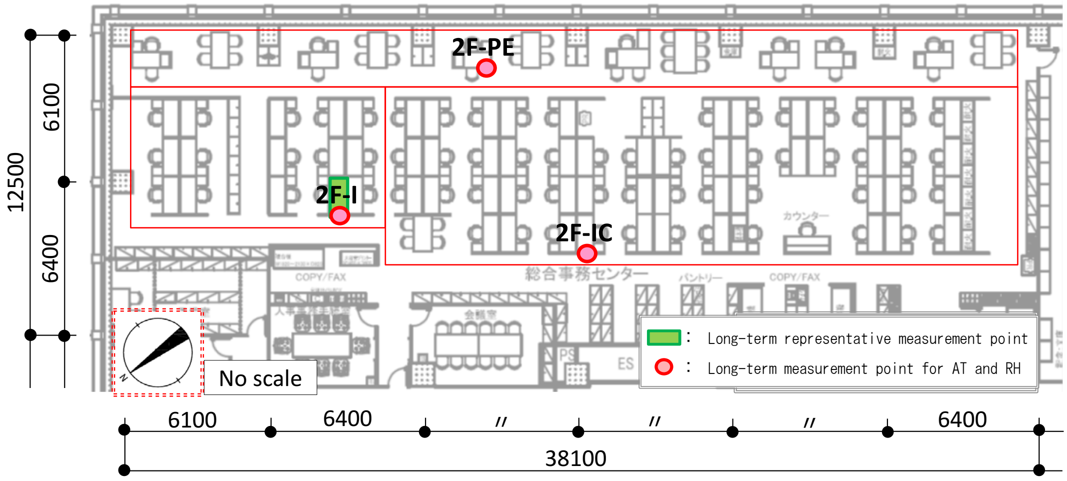
Building O (Survey number 53)



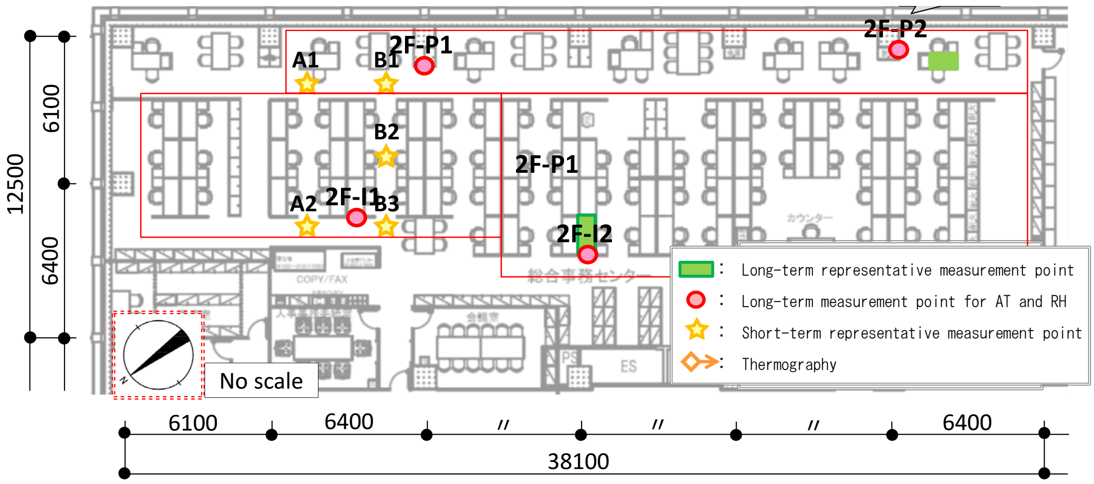
Building P (Survey number 24-27)



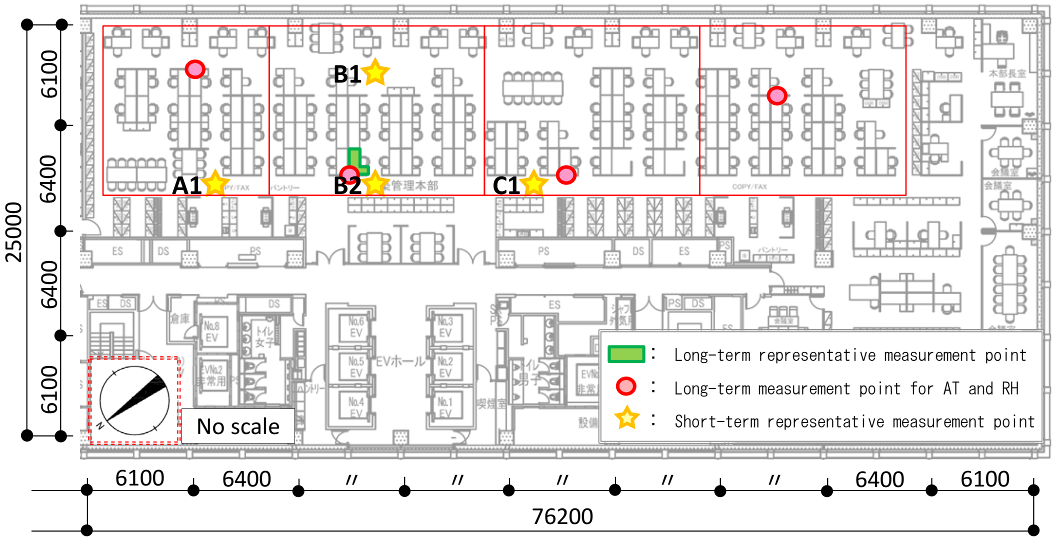
Building P (Survey number 46)



Building P (Survey number 54)

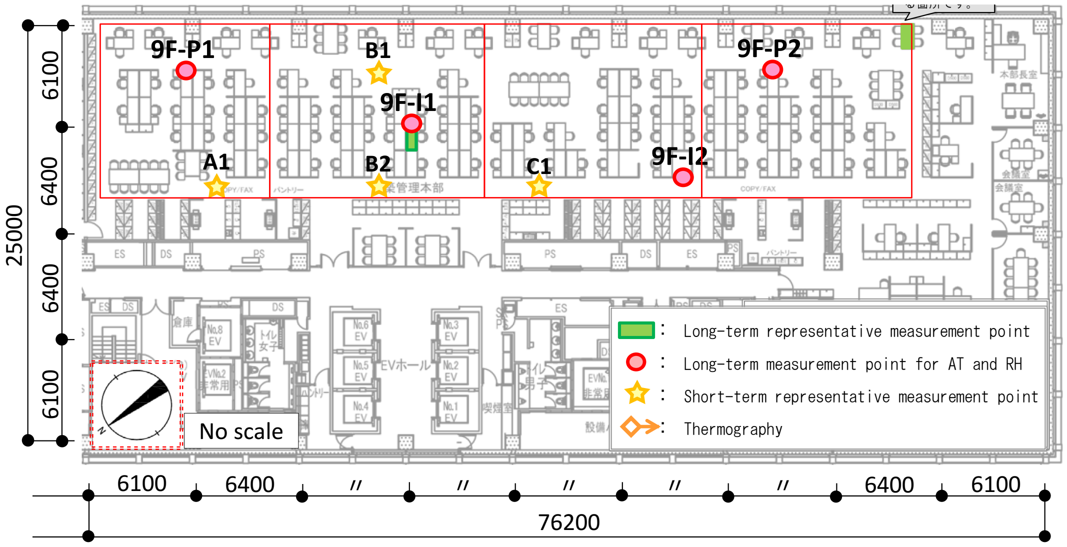


Building Q (Survey number 28-31)

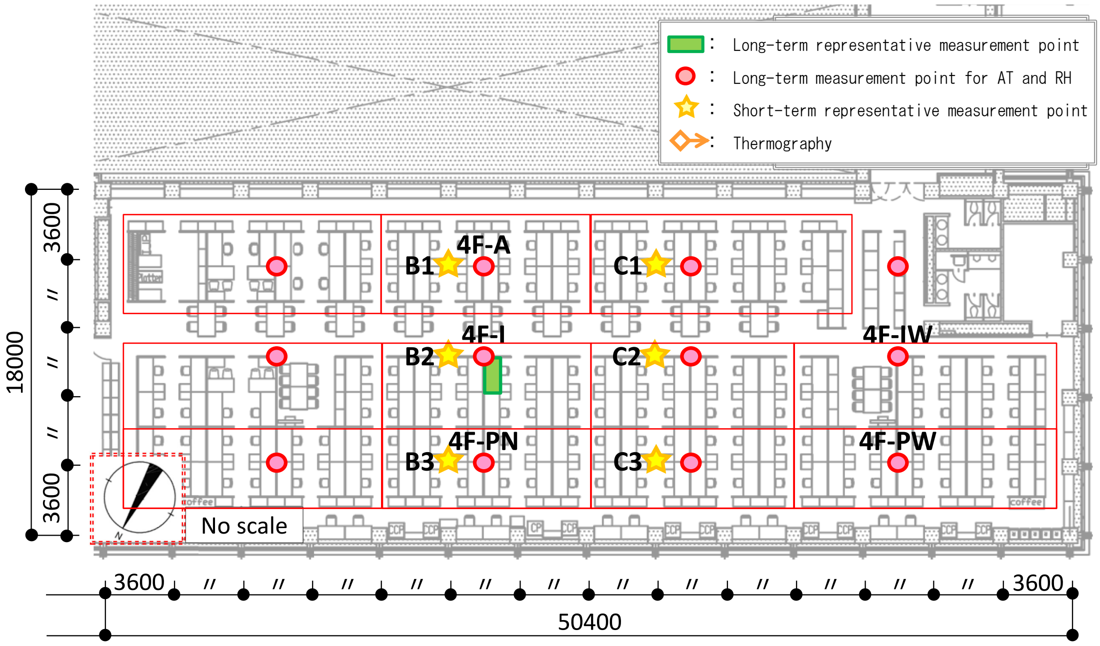


Building Q (Survey number 47)

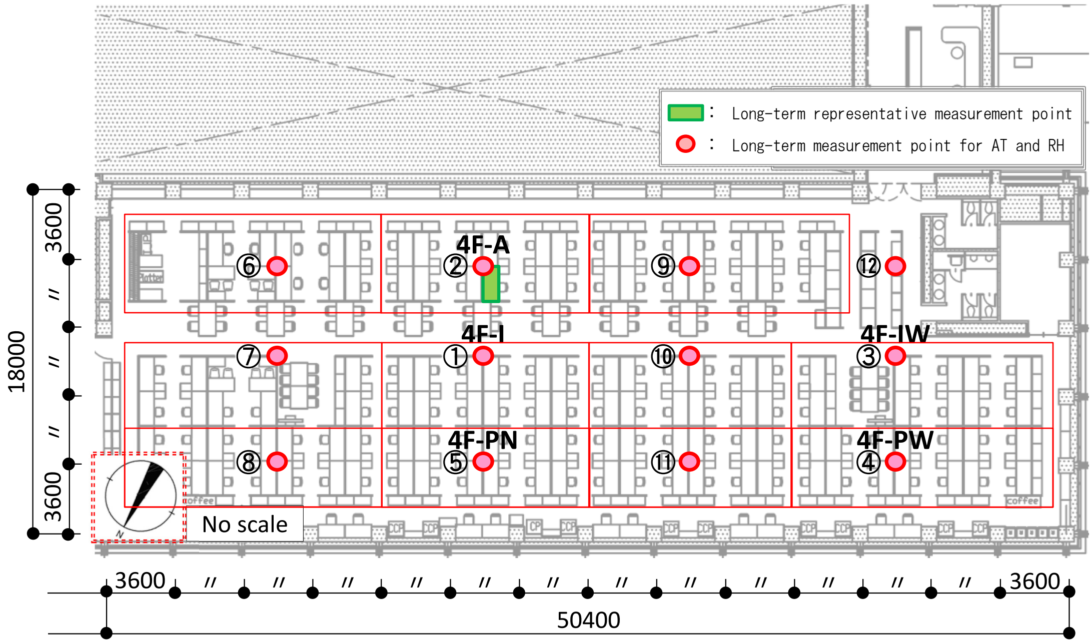
Building Q (Survey number 55)



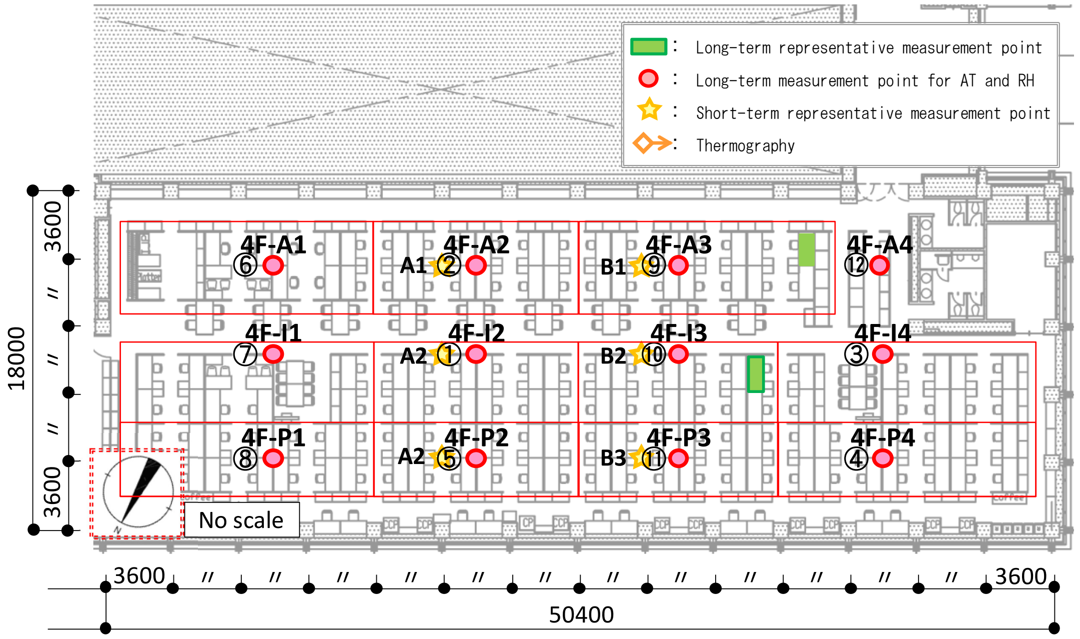
Building R (Survey number 32-36)



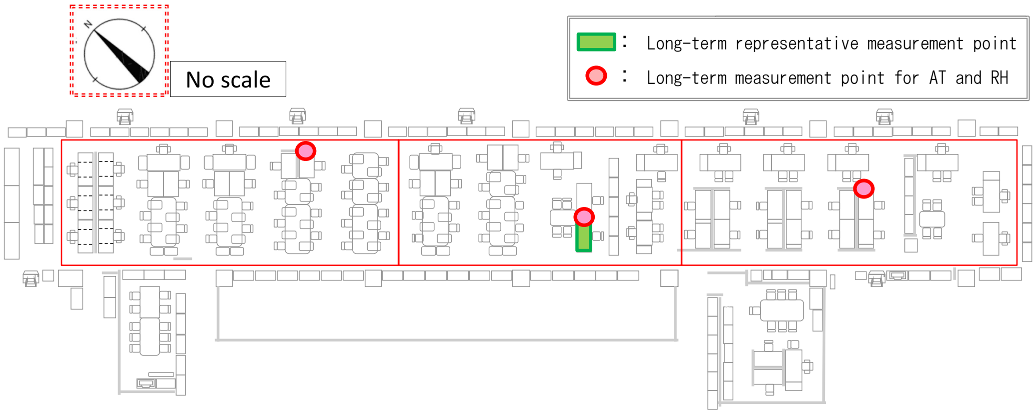
Building R (Survey number 48)



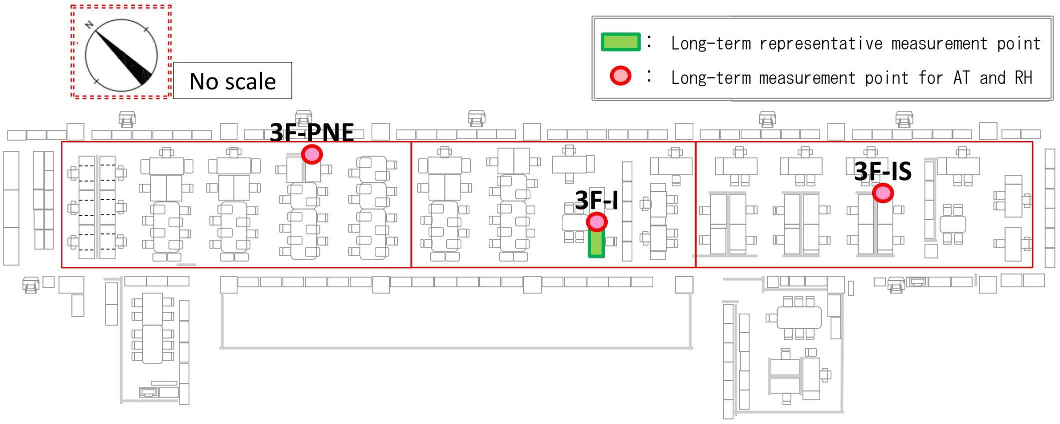
Building R (Survey number 56)



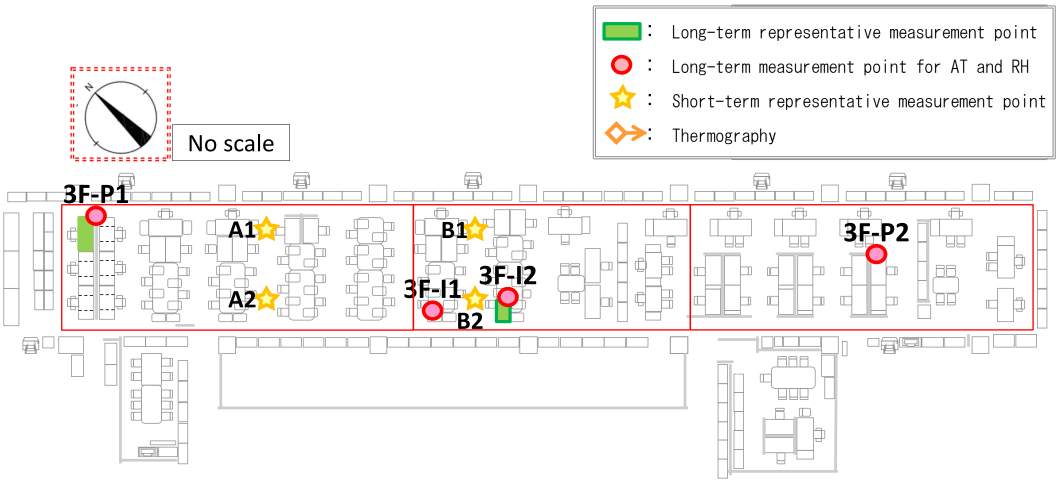
Building S (Survey number 36)



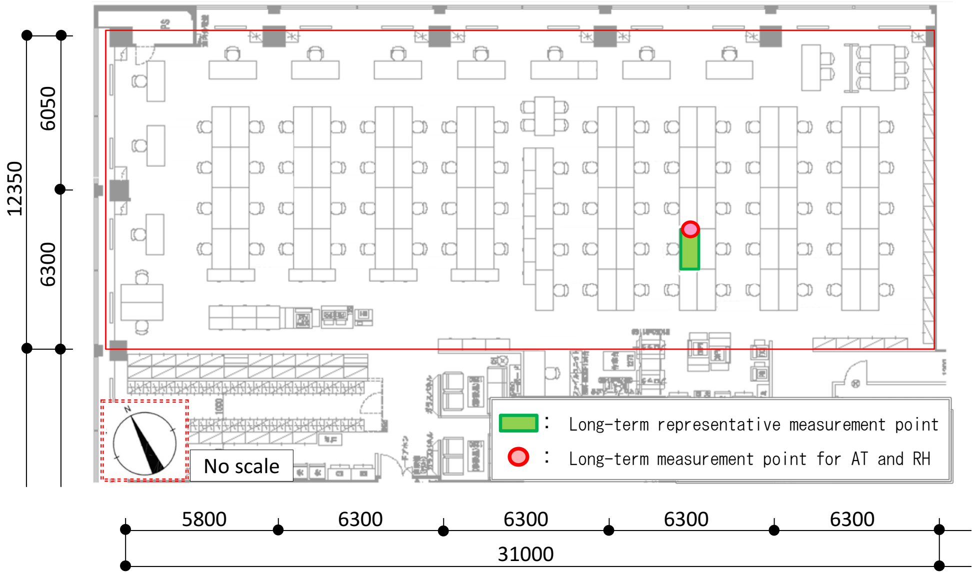
Building S (Survey number 49)



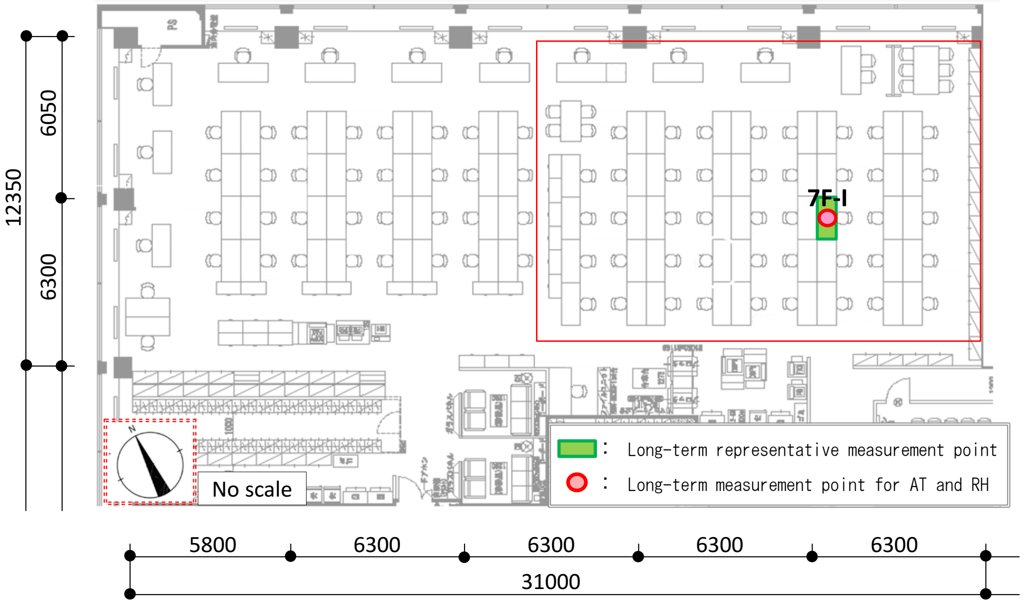
Building B (Survey number 57)



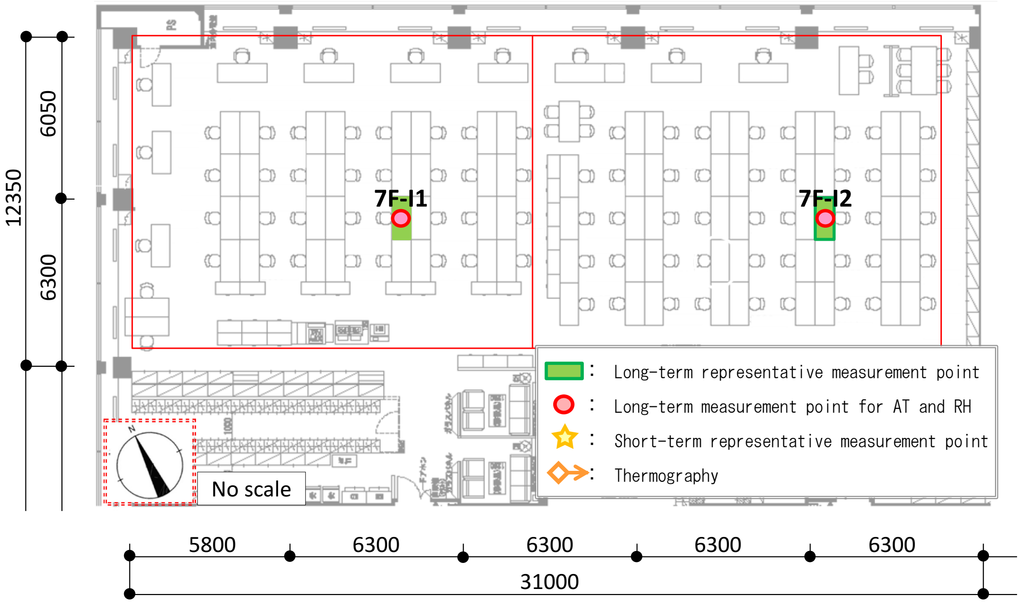
Building T (Survey number 37)



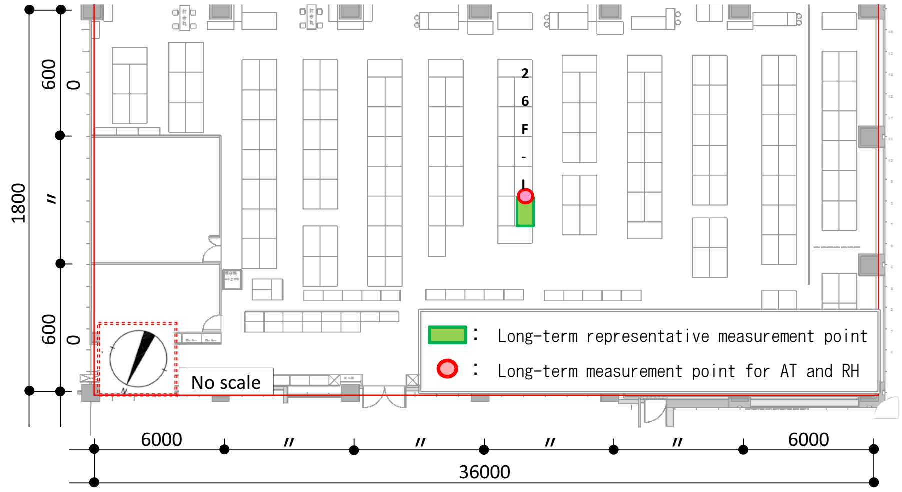
Building T (Survey number 50)



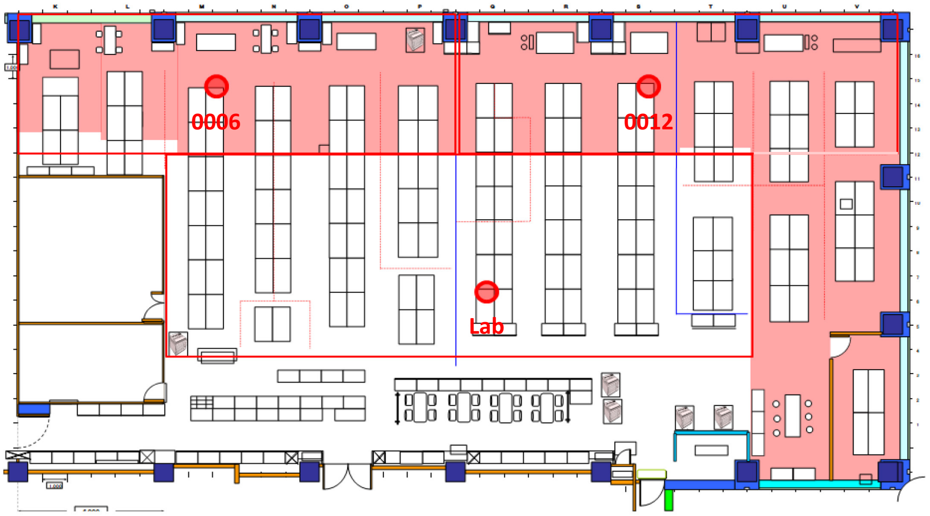
Building T (Survey number 59)



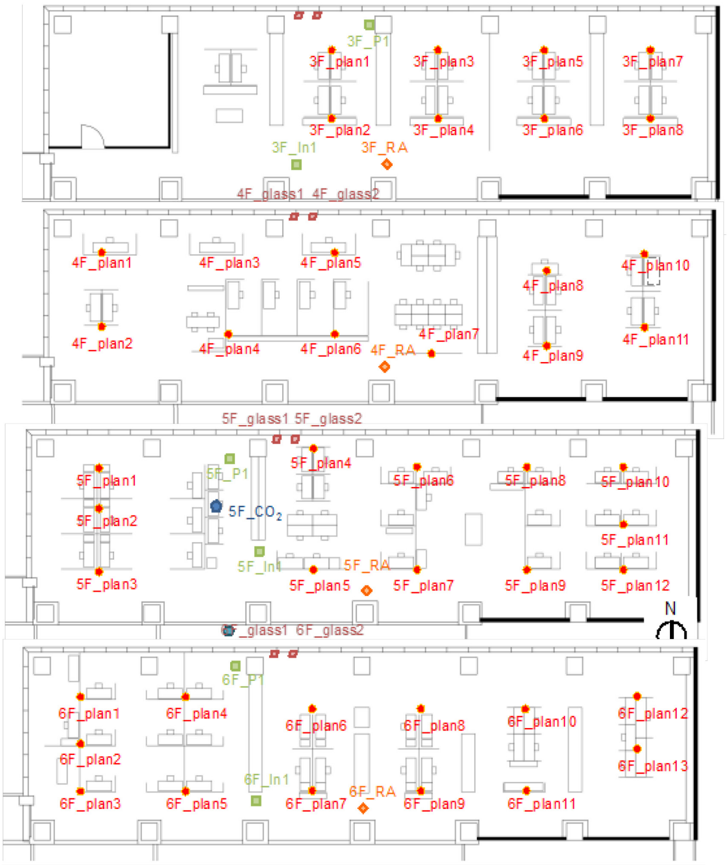
Building U (Survey number 38-39)



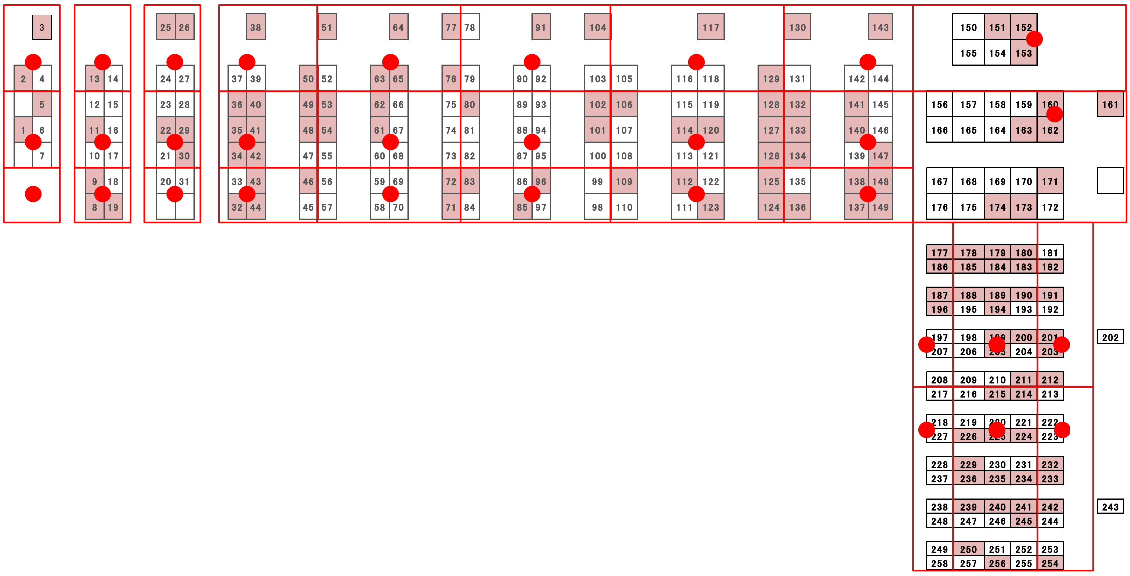
Building U (Survey number 51)



Building V (Survey number 41)

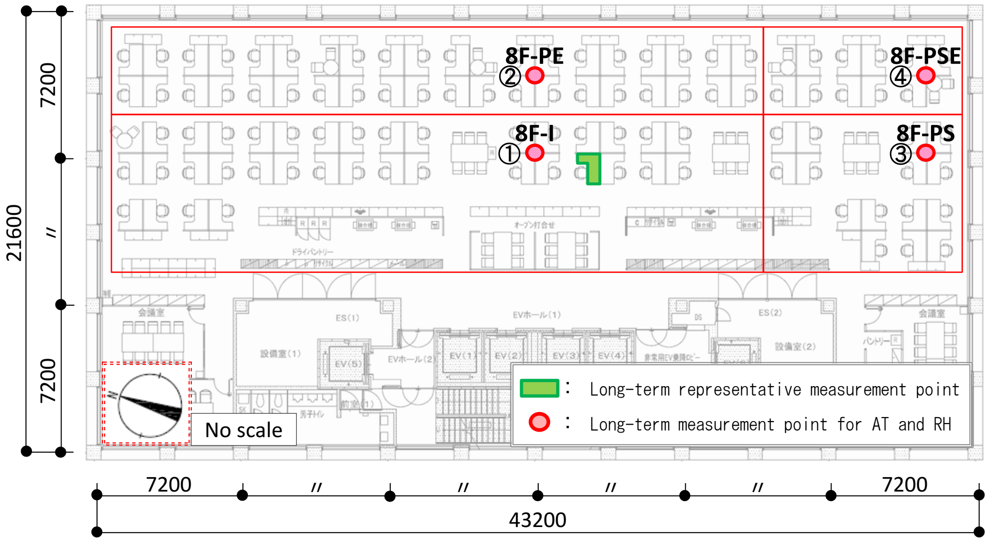


Building W (Survey number 42)

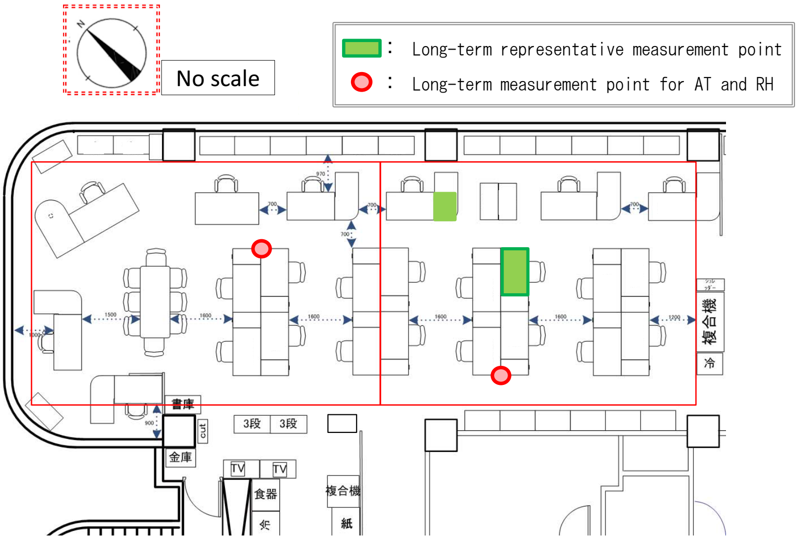


Building X (Survey number 42) no data

Building Y (Survey number 44)

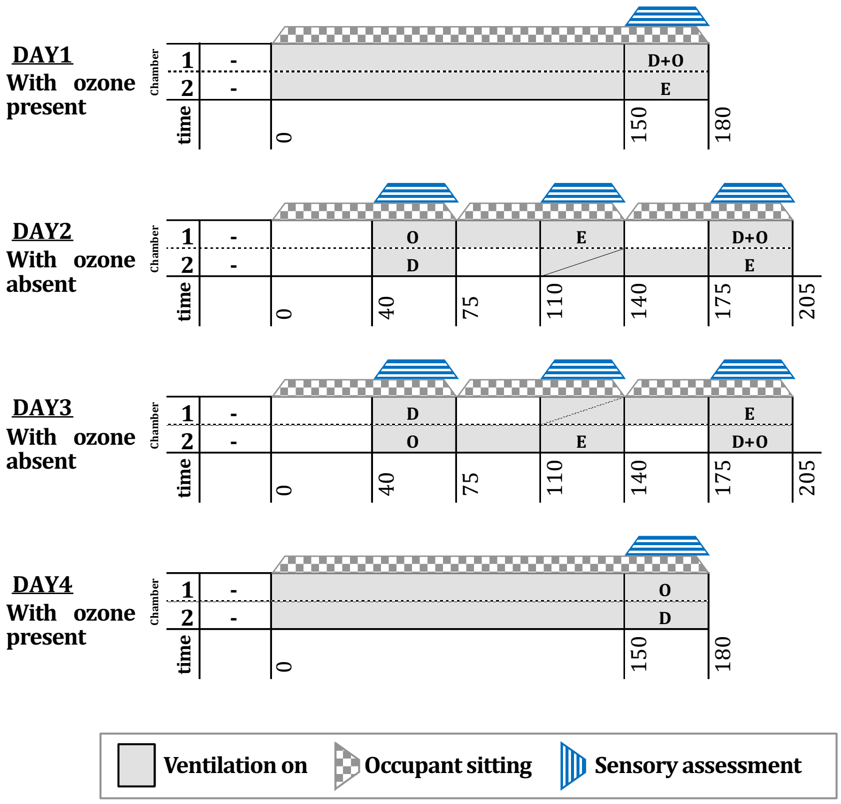


Building Z (Survey number 58)



Appendix C_ Supplemental materials (chapter 6)

S1. Detailed description of procedures with bioeffluent inside the chambers. *E=without bioeffluents (empty), O=exhaled, D=dermally-emitted, D+O=whole-body (dermally-emitted+exhaled)



S2. Measurement parameters and accuracy.

Measurement item	Model number	Interval (sec)	Point number per chamber	accuracy
AT, RH and CO_2	CO_2 Recorder (TR-76Ui)	10	1	±0.3 ^{o}C, ±2.5%RH, 0-9999 ppm ±(50 ppm + 5% of the readings)
ozone	2b Monitor, Model 205	-	1	Greater of 1.0 ppb or 2% of reading

S3. Experimental parameters for chemical analysis.

Parameter	Velue/Description
GC/MS system	Shimadzu QP-2010 Ultra
Thermal desorption unit	Markes TD-100
Cold trap	Air Toxics Analyzer Trap
Capillary column	Restek RXI®-624 Sil MS 60 m x 0.25 mm x 1.4 µm
Linear velocity	38 cm/s
Scan range [m/z]	30 – 550

S4. Mean measurement (Standard Deviation) data and questionnaire data for each condition of main experiment.

				Measurement data									Questionnaire data									
Day	Condition		session	Air Temperature (°C)		Humidity (rh%)		CO_2 (ppm)		Ozone Concentration (ppb)			Number of valid respondent / total respondent		Odour Intensity				Acceptability			
	Ch. 1	Ch. 2	-	Ch. 1	Ch. 2	Ch. 1	Ch. 2	Ch. 1	Ch. 2	Ch. 1	Ch. 2	Outside	Ch. 1	Ch. 2	Ch. 1 (A / B)		Ch. 2 (A / B)		Ch. 1 (A / B)		Ch. 2 (A / B)	
Day 1 June 21	dermally-emitted+ exhaled	empty	-	22.7 (0.1)	22.8 (0.2)	43 (3)	39 (2)	2249 (31)	558 (2)	2.2	7.4	16.0	23	23	1.84 (1.10)	-	1.24 (0.91)	-	0.10 (0.36)	-	0.27 (0.30)	-
Day 2 June 22	exhaled	dermally-emitted	1	22.8 (0.1)	24.8 (0.1)	54 (5)	36 (0)	1763 (69)	887 (22)	0	3.1	21.6	20	20	1.07 (0.76)	1.28 (0.81)	1.62 (0.57)	1.45 (0.74)	0.34 (0.28)	0.05 (0.28)	0.11 (0.30)	-0.04 (0.35)
	empty		2	22.9 (0.1)	24.4 (0.1)	49 (3)	36 (0)	552 (27)	1857 (22)	-	-	23.9	22	22	0.95 (0.73)	1.26 (0.75)	1.58 (0.86)	1.55 (0.93)	0.42 (0.22)	0.21 (0.28)	0.19 (0.32)	-0.07 (0.32)
	dermally-emitted+ exhaled	empty	3	24.0 (0.1)	22.1 (0.2)	53 (1)	38 (2)	1960 (15)	522 (7)	-	-	28.0	21	21	1.47 (0.69)	1.51 (0.82)	1.22 (0.82)	1.16 (0.90)	0.14 (0.29)	0.03 (0.34)	0.31 (0.29)	0.11 (0.33)
Day 3 June 23	dermally-emitted	exhaled	1	27.6 (0.4)	27.7 (0.2)	38 (4)	32 (2)	641 (49)	1787 (179)	-	-	28.9	21	21	1.81 (0.94)	1.84 (0.95)	1.25 (0.69)	1.37 (0.78)	0.01 (0.24)	0.03 (0.32)	0.19 (0.23)	0.12 (0.25)
		empty	2	27.9 (0.2)	28.1 (0.2)	45 (3)	29 (1)	1885 (175)	482 (52)	-	-	31.6	21	21	2.08 (1.04)	2.36 (0.92)	1.09 (0.61)	1.48 (0.87)	-0.09 (0.29)	-0.17 (0.37)	0.26 (0.29)	0.15 (0.28)
	empty	dermally-emitted+ exhaled	3	28.3 (0.1)	27.9 (0.2)	31 (1)	30 (0)	480 (14)	1880 (27)	2.8	4.8	32.2	21	21	1.28 (0.72)	0.96 (0.76)	1.79 (1.03)	2.12 (1.04)	0.17 (0.36)	0.34 (0.31)	0.08 (0.36)	-0.08 (0.33)
Day 4 June 24	exhaled	dermally-emitted	-	24.0 (0.5)	24.4 (0.1)	34 (1)	33 (0)	1862 (8)	533 (2)	16.6	13.7	24.4	17	17	1.13 (0.84)	0.83 (0.78)	1.31 (0.69)	1.78 (0.93)	0.26 (0.31)	0.43 (0.27)	0.12 (0.20)	0.04 (0.29)

S5. The result of chemical analysis of GC-MS.

Substance 1)	CAS No.	RT [min]	Odor thresholds [µg/m^3]		Concentration [µg/m^3] in toluene equivalent										
			Nagata	Devos	exhaled bioeffluent		dermally-emitted bioeffluents		dermally-emitted+exhaled bioeffluents			no bioeffluents			BLANK
					23°C with ozone absence	23°C with ozone presence	23°C with ozone absence	23°C with ozone presence	23°C with ozone absence	23°C with ozone presence	28°C with ozone absence	23°C with ozone absence_1	23°C with ozone absence_2	28°C with ozone absence	-
VVOC															
Propane	74-98-6	3.1	2953125	4897788.19	5	2	4	1	2	1	2	2	2	2	-- 5)
Isobutane	75-28-5	3.5		23988.33	12	7	12	8	3	7	1	4	4	-- 4)	-- 5)
Butane	106-97-8	3.8	3112500	489778.82	12	6	11	7	2	5	-- 4)	4	2	-- 4)	-- 5)
Acetaldehyde	75-07-0	4.1	2.95	338.84	1	2	2	2	2	2	1	2	1	1	-- 4)
Methanol	67-56-1	4.4	47142.86	186208.71	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 5)
2-Methylbutane	78-78-4	5.2	4184.38		21	21	18	25	7	18	2	10	7	2	-- 5)
Pentane	109-66-0	5.8	4512.5	95499.26	7	15	7	17	3	7	4	5	3	3	-- 5)
Ethanol	64-17-5	6.1	1070.18	54954.09	15	12	16	15	8	31	6	7	5	3	-- 4)
Isoprene	78-79-5	6.4	145.93		5	11	2	4	16	16	19	1	1	-- 4)	-- 5)
Acetone	67-64-1	7	108937.5	34673.69	5	7	5	11	6	11	8	3	3	-- 4)	-- 4)
Acetonitrile	1975/5/8	7.7	23852.68	165958.69	-- 4)	6	25	4	2	4	5	5	4	7	-- 4)
2.3-Dimethylbutane	79-29-8	8.2	1616.25		2	2	2	4	1	3	-- 5)	1	-- 4)	-- 4)	-- 5)
2-Methylpentane	107-83-5	8.3	26937.5		6	11	9	18	5	12	1	4	3	-- 4)	-- 5)
3-Methylpentane	96-14-0	8.9	34249.11		3	8	4	9	3	6	-- 4)	2	2	-- 4)	-- 5)
VOC															
n-Hexane	110-54-3	9.6	5772.32		1	3	2	4	1	3	-- 4)	-- 4)	2	-- 4)	-- 5)
Methylcyclopentane	96-37-7	11.2	6390.18		2	7	4	9	3	5	-- 4)	4	4	-- 4)	-- 5)
Cyclohexane	110-82-7	12.8	9397.32	77624.71	1	4	2	5	2	3	-- 4)	3	2	-- 4)	-- 5)
3-Methylhexane	589-34-4	13.2	3757.5		-- 4)	5	2	5	2	3	-- 4)	2	2	-- 5)	-- 5)
Heptane	142-82-5	14.3	2997.05	40738.03	1	3	1	3	1	2	-- 4)	1	2	-- 4)	-- 5)
Acetic acid 2)	64-19-7	14.5	16.1	363.08	15	8	11	6	12	10	10	19	9	11	2
Formic acid	64-18-6	15.2		54954.09	2	-- 5)	-- 5)	-- 5)	-- 4)	-- 5)	-- 5)	2	-- 5)	2	-- 5)
Toluene	108-88-3	18.5	1358.3	5888.44	13	20	13	24	12	19	4	14	15	3	1
1,2-Ethanediol	107-21-1	19.5			7	5	2	2	2	4	-- 4)	11	-- 4)	3	-- 5)
Propylene Glycol	57-55-6	20.4			13	10	6	4	3	10	3	22	2	7	-- 5)
Hexanal 2)	66-25-1	20.5	1.25	57.54	-- 5)	-- 5)	-- 5)	5	-- 5)	-- 5)	3	2	1	-- 5)	-- 4)
Acetic acid, butyl ester	123-86-4	20.6	83	933.25	4	-- 5)	5	1	-- 5)	-- 5)	-- 5)	-- 4)	-- 5)	-- 5)	-- 5)
Ethylbenzene	100-41-4	22.6	805.98	12.88	3	3	3	4	2	4	-- 4)	2	2	-- 4)	-- 5)
p-Xylene	106-42-3	22.9	274.98	2137.96	10	9	10	13	6	11	1	8	8	-- 4)	-- 5)
o-Xylene	95-47-6	24	1801.61	3801.89	3	4	3	5	2	4	-- 4)	3	3	-- 4)	-- 5)
C3 Alkyl aromatic hydrocarbon	-- 3)	26.6			3	2	3	2	2	3	-- 4)	2	2	-- 4)	-- 5)
C3 Alkyl aromatic hydrocarbon	-- 3)	26.7			1	-- 4)	2	1	-- 4)	1	-- 4)	1	1	-- 4)	-- 5)
1,3,5-Trimethylbenzene	108-67-8	26.9	912.23		1	1	2	1	1	2	-- 4)	1	1	-- 4)	-- 5)
2,2,4,6,6-Pentamethyl-heptane	13475-82-6	27			2	4	2	4	1	2	1	2	1	-- 4)	-- 5)
Benzaldehyde	100-52-7	27.9		186.21	2	3	2	4	2	2	1	2	1	-- 4)	-- 4)
1,2,4-Trimethylbenzene	95-63-6	27.9	643.93		4	2	5	2	2	3	-- 4)	3	3	-- 4)	-- 5)
6-Methyl-5-hepten-2-one 2)	110-93-0	28		251.19	-- 5)	2	4	11	4	6	3	1	3	-- 4)	-- 5)
Octanal	124-13-0	28.6	0.06	7.24	1	2	2	3	2	2	1	1	1	1	-- 4)
Limonene	138-86-3	28.8	231.05	2454.71	-- 4)	-- 4)	-- 4)	-- 4)	2	-- 4)	-- 4)	5	1	-- 4)	-- 5)
Benzyl alcohol	100-51-6	31			2	2	-- 5)	3	3	2	2	3	2	1	-- 5)
Nonanal 2)	124-19-6	32.1	2.16	13.49	3	5	6	11	6	7	5	4	5	3	-- 4)
Decanal 2)	112-31-2	35.4	2.79	5.89	2	4	8	15	7	7	7	2	5	3	-- 4)
Tetradecane	629-59-4	39.7			1	-- 4)	2	2	2	2	-- 4)	-- 4)	-- 4)	-- 4)	-- 5)
2-Butyl-1-Octanol	3913/2/8	40.8			-- 4)	-- 4)	2	2	1	3	2	-- 5)	-- 4)	-- 4)	-- 5)
6,10-Dimethyl-5,9-undecadien-2-one	689-67-8	42			-- 4)	-- 4)	6	3	4	3	5	-- 4)	1	1	-- 5)
1-Dodecanol	112-53-8	42.3		100	-- 4)	-- 4)	3	3	2	2	3	-- 4)	1	2	-- 4)
Hexadecane	544-76-3	43.7			5	4	6	8	5	6	6	5	4	5	-- 4)
SVOC															
2,2,4-Trimethyl-1,3-pentane dioldiisobutyrate	6846-50-0	44.6			-- 4)	-- 4)	4	3	2	3	3	2	2	3	-- 5)
Heptadecane	629-78-7	45.3			2	2	3	4	3	3	4	3	3	4	-- 4)
Octadecane	593-45-3	46.7			3	2	4	4	3	4	5	6	20	-- 4)	-- 4)
Squalene 2)	111-02-4	48.4		363.08	13	3	20	3	5	3	6	-- 5)	-- 4)	-- 4)	3
Unknown hexanedioc acid ester (m/z=129,147,57,112)	-- 3)	48.9			2	-- 5)	1	-- 5)	2	-- 5)	-- 5)	2	2	3	-- 5)

S6. The result of chemical analysis of HPLC-DAD

Substance 1)	CAS No.	RT [min]	Odor thresholds [μg/m³]		Concentration [μg/m³]										
			Nagata	Devos	exhaled bioeffluent		dermally-emitted bioeffluents		dermally-emitted+exhaled bioeffluents			no bioeffluents			BLANK
					23°C with ozone absence	23°C with ozone presence	23°C with ozone absence	23°C with ozone presence	23°C with ozone absence	23°C with ozone presence	23°C with ozone presence	23°C with ozone absence_1	23°C with ozone absence_2	28°C with ozone absence	-
Acetaldehyde	75-07-0	11.5	2.95	338.84	-- 3)	3	-- 3)	4	-- 5)	2	-- 4)	-- 3)	-- 4)	-- 4)	-- 4)
Acetone	67-64-1	16.4	108937.5	34673.69	25	32	2	5	33	57	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)
Acrolein	107-02-8	16.7	9.02	407.38	2	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)
Propionaldehyde	123-38-6	18.5	2.59		1	-- 3)	-- 4)	-- 4)	-- 4)	-- 3)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)
Octanal 2)	124-13-0	35.6	0.06	7.24	-- 4)	-- 4)	1	1	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)	-- 4)

1) Identification by mass spectra library. quantitation as toluene equivalent (excluded Methanol, Ethanol, Isoprene, Acetone, Hexanal, Acetic acid, 6-Methyl-5-hepten-2-one,Nonanal, Decanal and Squalene)

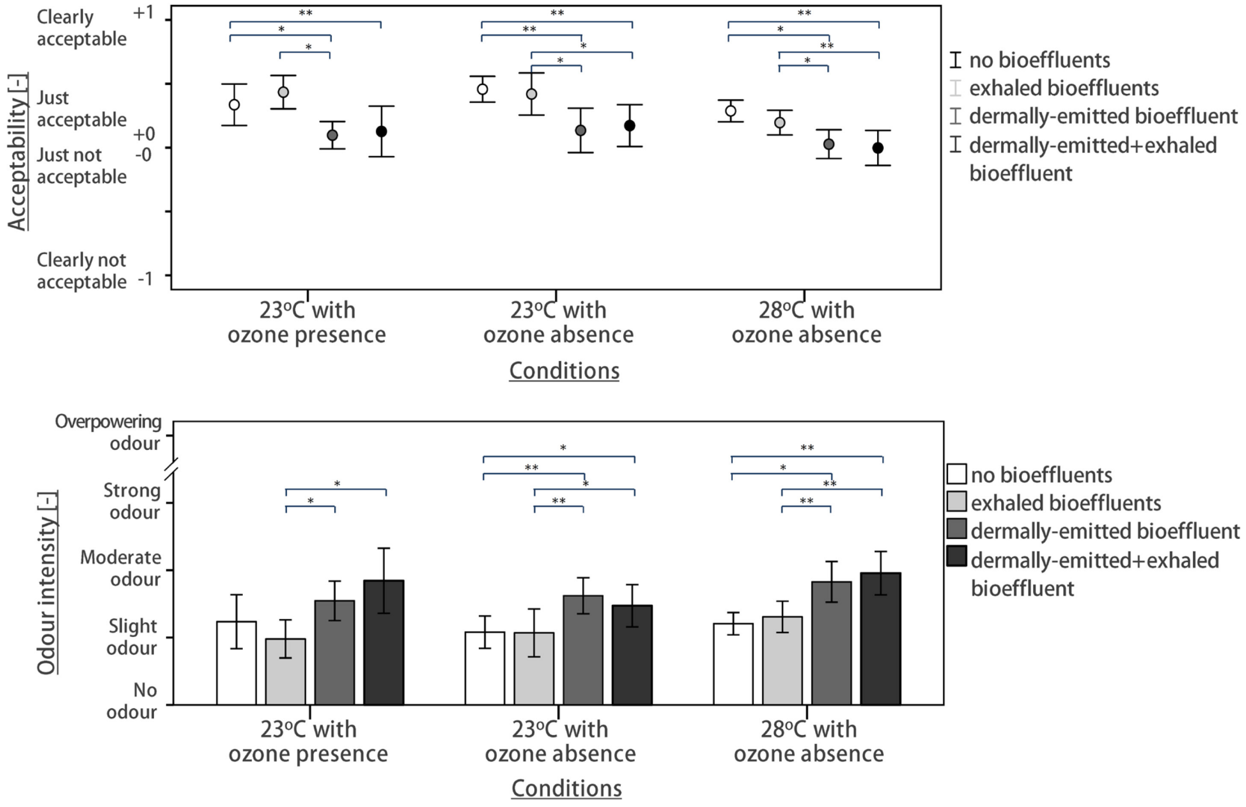
2) Identification and quantitation by gas chromatographie/mass spectrometry, using substance specific reference compounds

3) CAS No. not available

4) Below limit of quantitation (1μg／m^3 toluene)

5) Substance not detected

S7. Acceptability of air quality (top) and odor intensity (bottom) in the chambers at different conditions. Bars show 95% confidence intervals. The air presented for sensory assessments had the same temperature as the air in the chamber. Asterisks show the level of statistical significance: *: 0.01<p<0.05, **: p<0.01



List of publications

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Journal Paper

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