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Effects of Indoor Lighting on Occupants' Visual Comfort and Eye Health in a Green Building

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Key Words

Visual comfort and eye health · Green building · Post-occupancy evaluation · Indoor lighting environment · Questionnaire survey · Self-reported health symptoms

Abstract

This study investigated the effects of indoor lighting on occupants' visual comfort and eye health and to contribute to the management and maintenance of buildings. The illuminance of the working plane and windows at Samsung Corporation Headquarters were measured, and 2744 healthy occupants of Samsung Corporation were surveyed regarding the indoor lighting environment *via* the company's intranet for 1½ years. This building was certified with the highest ranking by Korea's Green Building Council. The cumulative data reflected the management and maintenance of the building, such as screen-type shading devices automatically controlled by seasons and time, improvement of visual display terminal glare by the veiling reflection on monitors, efficiency of artificial lighting arrays, and so on. The data were analysed for occupants' visual comfort and eye health. The result showed that daylighting could improve the occupants' psychological health and productivity. The screen-type shading device could intercept direct sunlight and reduce annoyance glare. However, the indoor lighting and visual environment of the building were poor. After examining the questionnaire feedback concerning improvements, the occupants' annoyance ratio was significantly reduced, and approximately 5% of the occupants' annoyance ratio was deemed to be caused by personal characteristics related to the lighting of the environment.

Introduction

As interest in health and the environment increases, maintaining a suitable environment in an office building is an important issue for people in the twenty-first century to simultaneously maintain health, while increasing productivity and efficiency of office workers. Most of the projects that office occupants undertake require mental labour rather than physical labour, which implies that the office environment should be closely related to health [1–9]. Furthermore, the deterioration of the interior environment

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could reduce the occupants' capability, which, in turn, would decrease productivity and increases stress, and there might be a cause of the sick building syndrome (SBS). Thus, maintaining a proper office environment is crucial [10–14].

Post-occupancy evaluation (POE) is a process that assesses the opinions of the occupants of a building after it has been operational for a certain period, and it is commonly used as a method to address the occupants' needs. In order to solve problems directly, examining the building and obtaining feedback to constitute an organised system for the occupants' use. Moreover, by evaluating how well the building has satisfied the needs of the occupants, POE could provide a method to identify improvements that would be needed to meet the requirements of the occupants in terms of design, efficiency, management and practical use of the building [15–20].

Recently, in Korea, green buildings that are capable of reducing energy while providing optimum living spaces have been constructed. The green building concept has an aim for continuous improvement and the building is constructed to achieve the balance in the relationship between humanity and nature such that energy and resources can be conserved to minimise the environmental pollution load, to create a healthy and decent building environment for the intended occupants [21].

In 2002, the Ministry of Land, Transport and Maritime Affairs of Korea began to enforce the Green Building Certification System, providing approval of the environmental credential of buildings, and due to the increasing interest in the Green Building Certification System and the incentives that the government offers, there has been steady growth in the demand of Green Building certified buildings in Korea.

Now, in Korea, most of the building envelopes of certified high-rise green office buildings are constructed with an all-glass curtain wall. These buildings maximise the openness of the space and allow daylight penetration into the inner part of the space such that a more pleasant indoor lighting and visual environment would be created. Lighting conditions must provide appropriate lighting for all of the different tasks that are completed in the space. In open-plan offices, there are many occupants of varying ages, preferences and abilities, doing a large variety of tasks; the target for lighting conditions should satisfy each of these needs [22,23].

In order to design a good lighting environment, the target lighting conditions must be considered from many dimensions, including light levels such as illuminance and luminance, control of glare, distribution, uniformity and light source colour. For open-plan office settings, where the most common tasks involve intensive computer use, the most important lighting dimensions are lighting levels and glare control [23–26]. Therefore, this study aimed to investigate the factors of the indoor lighting environment that could affect occupants' visual comfort and eye health, and to provide the information to effectively supplement the management and maintenance of buildings. For these purposes, this study measured the illuminance of the working plane and the luminance of the windows in the Samsung Corporation Headquarters, which was certified with the highest ranking by Korea's Green Building Council (KGBC). The cumulative data of the investigation over this period after the building was certified, included the feedback pertaining to the management and maintenance of the building, such as screen-type shading devices automatically controlled by seasons and time, improving visual display terminal (VDT) glare by the reduction process of veiling reflection on the monitor, efficiency of artificial lighting arrays, and so on. These data were used to assess the occupants' visual comfort and eye health in relation to the office environment of the building.

Green Building Certification System

The Ministry of Land, Transport and Maritime Affairs of Korea oversees the Green Building Certification System conducted by the KGBC. The system consolidated Green Building Pilot Certification by the Ministry of Environment and Excellent Residential Environment Pilot Certification by the Ministry of Construction and Transport in January 2002. The system evaluates the factors that affect a living environment, including energy saving and waste discharge, to assess the environmental performance of buildings, covering the entire process from the design and construction to the maintenance of a building.

The types of buildings that are subject to this certification system include office buildings, apartments, residential and commercial complexes, commercial facilities, accommodations, schools and so forth. The total score and distribution of points vary with types of buildings; according to the evaluation result, buildings are categorised into 1st Grade Green Buildings (above 85 points) and Certification Grade Green Buildings (65–84 points; Tables 1 and 2). The Ministry of Land, Transport and Maritime Affairs has designated four certification agencies to carry out the evaluations of green buildings.

Table 1. Assessment issues and points of Green Building Certification System

Issues	Office buildings	Apartments	High-rise residential buildings	Shopping centers	Hotels	Schools
Land/Site	7	22	7	5	8	7
Transport	5	8	5	3	5	4
Energy	23	15	14	24	18	17
Materials/resources	21	23	27	20	19	22
Water	14	13	14	14	15	14
Atmosphere	6	3	6	6	6	6
Management	10	7	9	10	11	7
Ecological environment	19	18	19	10	17	21
Indoor environmental quality (IEQ)	31	27	27	27	34	24
Total score	136	136	128	119	133	124

Note: IEQ, indoor environmental quality.

Table 2. Ratings of Green Building Certification System

Certification grade	Score	Emblem
1st grade green building	Above 85	
Certification grade green building	Above 65–Below 85	

Source: http://www.mltm.or.kr

Table 3. Certification of green buildings by building uses (as of 2009)

Categories of building uses	Preliminary certification			Certification			Total
	1st	Certified	Total	1st	Certified	Total	
Office buildings	27	105	132	15	36	51	183
Apartments	19	447	466	15	138	153	619
High-rise residential buildings	2	22	24	0	3	3	27
Shopping centres	2	10	12	1	4	5	17
Hotels	0	8	8	0	3	3	11
Schools	1	404	405	1	238	239	644
Total	51	996	1047	32	422	454	1501

Source: http://www.mltm.or.kr

As the interest in environment-friendly building increases and monetary incentives are promoted, the number of certified buildings has increased sharply since 2006. Most of these are apartments and office buildings. As of 2009, 454 buildings received certification and 1047 buildings received preliminary certification; and this number is expected to continue growing (Table 3 and Figure 1).

There are nine criteria for Green Building certification: land and site, transportation, energy, materials and resources, water, atmosphere, management, ecological environment and IEQ. The certification evaluation examines the 9 issues, 21 categories and 44 assessment items to

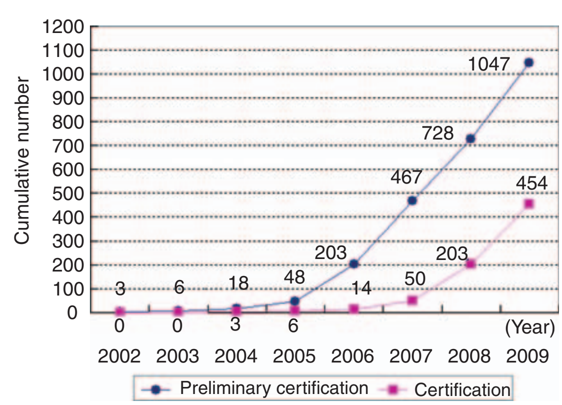


Fig. 1. Cumulative number of green buildings. Source: http://www.mltm.or.kr.

Table 4. Items for lighting and visual environment among green building certification criteria

Issues	Categories	Assessment items	Criteria	Assessment	Points
Land/Site	Effects of adjacent sites	Validity of the counter-measure for right-to-light	Maximum angle that measures designated points of the building from the borderline of adjacent sites	Supplementary	2
Energy	Energy saving	Lighting energy saving	Lighting density and methods	Base	6
IEQ	Comfortable indoor environment	Creating comfortable IEQ for occupants	Occupant's individual control of indoor environment	Supplementary	4

Table 5. General information of Samsung Corporation Headquarters

Building name	Samsung Corporation Headquarters
Location	Seoul Korea
Constructor	Samsung C&T Corporation
Design	KPF + Samoo architects
Building area	1859 m^2
Total floor area	81,117 m^2 (B7F – 34F)
Occupants	3000 persons
Certification	1st grade green building

determine the final grade. Among them, three assessment items address lighting environment and visual environment (Table 4). First, with respect to the land/site issue, five levels are identified according to the maximum angle, that is, the height of designated points in a building from the borderline with adjacent sites. This category earns two points. Next, regarding the energy issue, the efficiency of the lighting is measured to evaluate energy-saving performance. The assessment criteria distinguish three levels according to lighting density and methods. Moreover, the first level earns six points. Finally, with respect to IEQ, two levels are divided depending on whether the indoor environment can be adjusted. To earn the first level, the occupants of the building should be able to individually control two items among temperature, ventilation, wind flow and lighting in over 50% of the standard-floor office area. When this criterion is satisfied, the evaluation awards four points to the building [21].

Data Acquisition and Methods

Status of Building and Indoor Lighting Environment

(1) Characteristics of Building

For this research, recently built Samsung Corporation Headquarters in Seoul was chosen to assess the influence of indoor lighting environment on occupants' visual health and comfort in green building. The building has 7 basement floors and 34 ground floors, with floor area of 81,117 m^2. Some 3000 occupants use offices located on fifth and higher floors (Table 5). The building design aimed for a green office building in terms of IEQ, energy and green building, to ensure optimal energy efficiency and pleasant working environment, while trying to maintain aesthetic value of the building design. The building received 1st Grade Green Building certification, which was conducted by KGBC in January 2008.

Table 6. Points for Samsung Corporation Headquarters

Categories	Points for office building	Samsung Corporation Headquarters
Land/Site	7	4.27
Transport	5	5.00
Energy	23	18.16
Materials/Resources	21	10.00
Water	14	11.00
Atmosphere	6	4.50
Management	10	8.00
Ecological environment	19	0.00
IEQ	31	25.80
Total score	136	86.73

Table 6 demonstrates Green Building scores of the Samsung Corporation Headquarters. The building earned well-balanced points for different items, except for ecological environment. This has to do with geographical properties of the building and attributes of the certification system. Evaluation for ecological environment largely focuses on areas of greenery and formation of ecological system. Since Samsung Corporation Headquarters is located in central business district, it would be hard to secure enough space for landscaping. Instead, the building incorporated different types of landscaping, such as artificial structures, to provide resting area in the midst of bustling urban environment.

As for the three assessment items related to lighting and visual environment, the building received highest points (Land/Site: 2 points, Energy: 6 points and IEQ: 4 points).

(2) Indoor Lighting Environments

To maximise the open feeling and to allow sufficient natural light penetration, the building has a wide column span (12 m) for the perimeter of the standard-floor office area, in addition to having a high ceiling (2.8 m) and a slanted angle where the building envelope intersects the ceiling. The building envelope is constructed of all-glass curtain walls, using reflected type Low-E pair glass in consideration of its thermal attributes, permeability and reflectivity (Figure 2). These elements allow an ample amount of daylight into the building, providing pleasant lighting and visual environments.

A wide area of all-glass curtain walls might allow excessive daylight to enter the office space; therefore, this was controlled by installing automated roll shades on all four sides of the building, operated by individual systems on each floor. This enables the occupants, as well as central control tower, to adjust the amount of daylight that enters the office space (Figure 3).

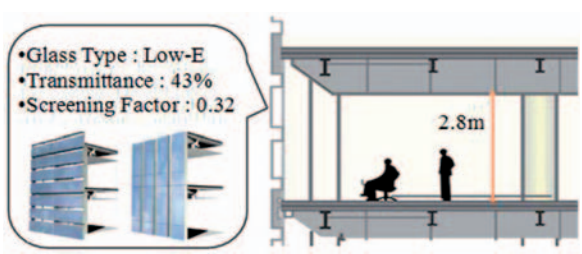


Fig. 2. Floor section and specifications of glass curtain wall.

Artificial lighting was designed to provide 650–800 lx of illuminance to meet Korean Standards criteria. On each floor, 86 lighting fixtures were installed to provide ambient lighting, in 2.4 m modules, using FPL-40 W fluorescent lamps that are half the length of an ordinary lamp and more energy efficient, and applying a special film of 95% permeability (Figure 4). At first, dimming was considered, but the idea was dismissed due to cost burden.

(3) Shades

As mentioned earlier, all-glass curtain walls allow daylight indoors for pleasant lighting and visual environments. However, the problem of glare must be addressed.

To adjust the amount of daylight, the building adopted an automatic roller shade system. Unlike previous systems, the system controls the amount of daylight according to sunlight conditions. With a manual roller shade, an occupant needs to adjust the shade and this tends to be neglected. However, the automatic system involves time control, based on a schedule control algorithm that reflects the sun shadow angle (Figure 5). As a result, the system can provide a more comfortable and reliable environment for occupants.

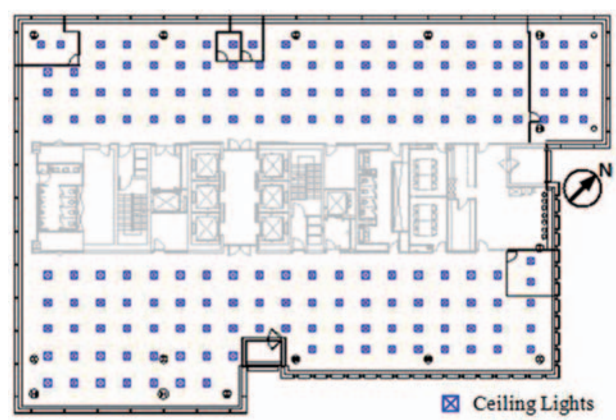


Fig. 4. Array of ambient lighting.

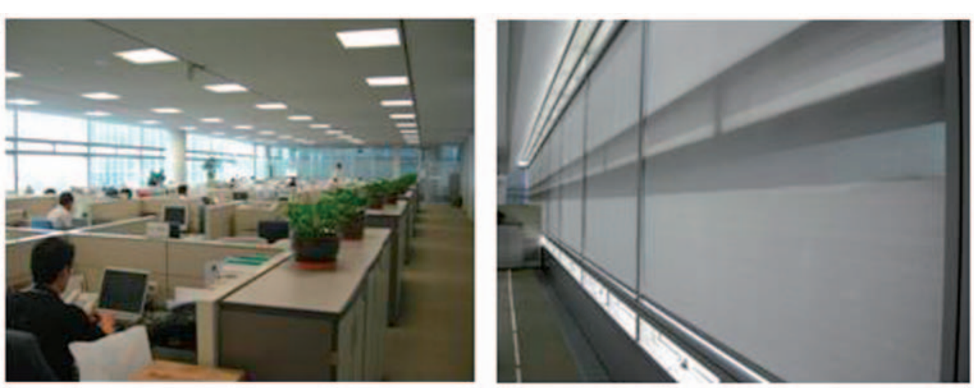


Fig. 3. Indoor lighting environment (left) and shades (right).

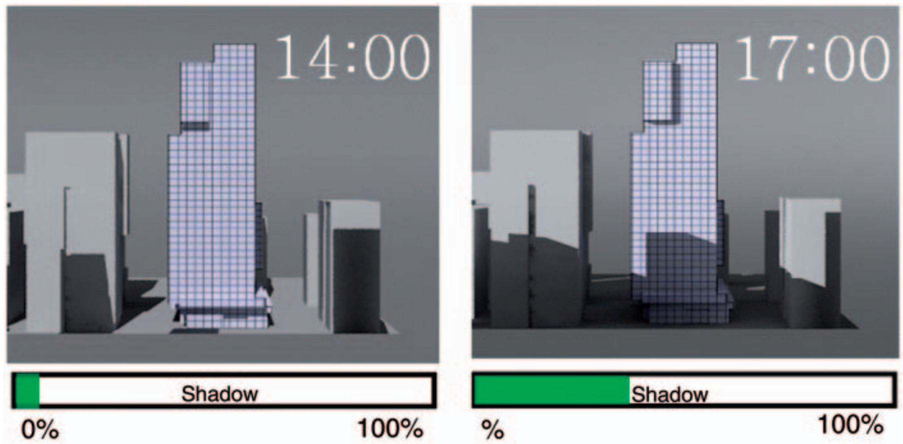


Fig. 5. Comparing with shadow distribution by CG software.

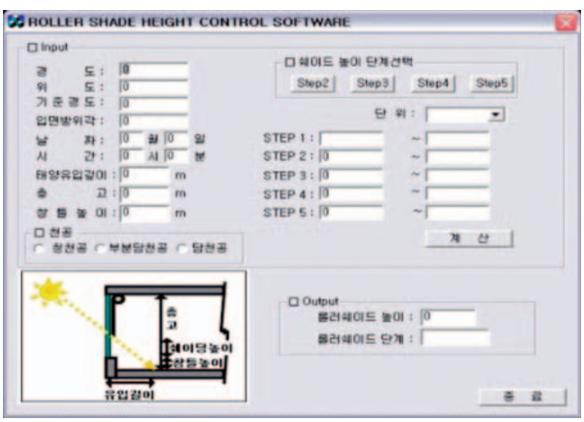


Fig. 6. Roller shade height control.

At the Samsung Corporation Headquarters, the height of the roller shade is controlled, based on shading control logic compiled in the *Roller shade height control software* that the company developed in 2006. The software demands input for the geographical properties of the building (longitude, latitude, standard longitude and azimuth angle), date and time, depth of sunlight penetration, floor height and window height. The occupants may select the height of the roller shade by directly inputting the height to ensure an optimal work environment (Figure 6).

The height of the roller shade is calculated using the sun shadow angle, which indicates solar altitude on the plane vertical to the building elevation. With excessive direct sunlight, the height of the roller shade can be adjusted to control the depth of direct sunlight penetration. The sun profile angle is used as an indicator to examine the influence of direct sunlight on the building interior, as shown by Equation (1). The program algorithm to control the roller shade height is shown by Equation (2).

$$\alpha_p = \arctan\left[\frac{sin\,\alpha_t}{cos\,\alpha_i}\right] \tag{1}$$

where α_p is the sun shadow angle, α_t is the solar altitude, and α_i is the incidence angle.

$$h = d \times tan\,\alpha_p - h_w \tag{2}$$

where h is the roller shade height, d is the depth of direct sunlight penetration, and h_w is the incidence angle.

Experimental Methods

Characteristics of the Test Space

In POE, ideally all occupied floors should be examined, but usually, the measurement is limited due to constraints of time, labour input and test equipment. Thus, it is of primary importance to select a standard floor that can represent the entire building. The Samsung Corporation Headquarters include 7 basement floors and 34 ground floors; the offices are located on the fifth floor and higher. The floor plan shows a central core, surrounded by working areas and this floor arrangement plan does not vary widely from floor to floor.

For this research, three test spaces (10F, 23F and 30F) were selected for consideration of the building scale, height and number of occupants. As Figure 7 shows, each floor was divided into four zones, depending on orientation, which is the most significant factor that could affect lighting and visual environments.

For interior finish, materials of high reflectance were largely used to maximise the open feeling and pleasantness. Table 7 illustrates the features of different working areas.

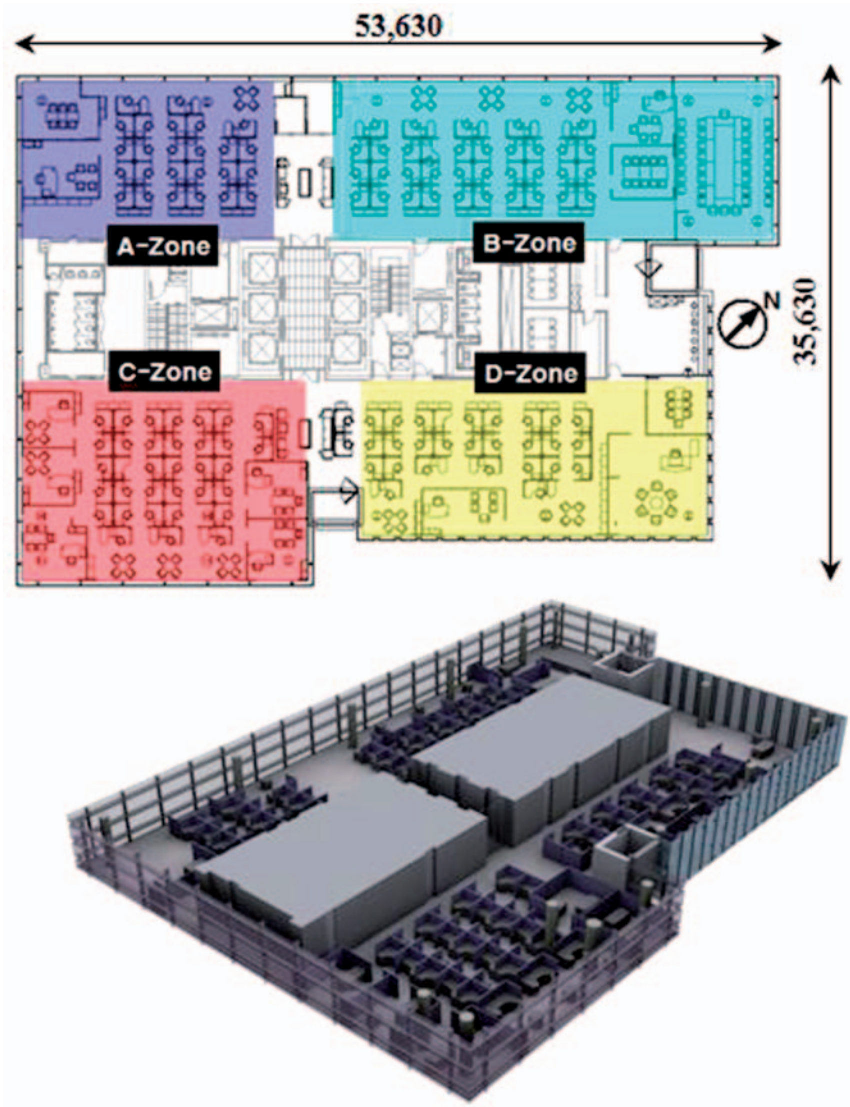


Fig. 7. Definition of zones (top) and three-dimensional perspective view of tested floor (bottom).

Table 7. Feature of tested floors

Contents \ Floor	10F	23F	30F
Occupants	72	111	115
Floor area		1859 m^2	
Ceiling height		2.8 m	
Wall		White paint (reflectance: 80%)	
Ceiling		White -absorbing (reflectance: 80%)	
Floor		Dark grey carpet (reflectance: 20%)	
Desk		Plastic system furniture	
Partition		Plastic and metal with textile fabric (H:1.2 m)	
Layout		Open-plan office	

Lighting Levels; Illuminance and Luminance Data Monitoring

To assess the effect of the indoor lighting environment on the occupants' visual comfort and eye health, the illuminance of the 75 cm-high working plane and luminance of the windows were measured five times in the three test spaces (10F, 23F and 30F) between February 2008 and April 2009 (Table 8). Data concerning sky conditions and cloud ratio were collected from the Korea Meteorological Administration [27]. To measure illuminance, a Digital Light Metre (Topcon-IM5; 1st Measuring, February 2008) and Lutron-YK2005LX (2nd–5th Measuring, April 2008–2009) were used. A two-dimensional Colour Analyzer (Minolta CA-2000) was used to measure the luminance of the window (Table 9).

During the first measurement (February 2008), the illuminance on the work plane at measuring points 125 (Topcon-IM5) and 12 (Lutron-YK2005LX) were measured for an independent sample *t*-test by SPSS. According to the results, the average values between the two groups did not show any statistically significant difference (Table 10). Based on this, Lutron-YK2005LX was used from the second measurement and, thereafter, the illuminance on the work plane was measured and analysed for a total of 12 measuring points on each floor, at 15-s intervals for 24 h (Figure 8).

Table 8. Measuring date and Sky condition

Measuring number	Date	Cloud ratio[a]
1st	18–29 February 2008	2.8
2nd	14–25 April 2008	2.5
3rd	17–28 July 2008	8.7
4th	17–21 November 2008	2.0
5th	22–25 April 2009	5.5

[a]Clear sky (0–2); partly clear sky (3–5); partly cloudy sky (6–8); and cloudy sky (9–10).

Survey Questionnaires

Questionnaires and Respondents

The most common psychological survey methods included an interview to measure a respondent's level of satisfaction; questionnaires consisted of multiple choice questions, scales or free surveys to acquire systematic answers, methods that depend on respondents' verbal responses such as psychological tests (for data collection in consensus method on work efficiency, personality, etc.), and other methods involving non-verbal responses such as figures (e.g. image map) and observation (e.g. factor survey and mapping) [28]. In this research, a subjective evaluation was carried out using a questionnaire, which is commonly used to effectively collect data at an affordable cost.

Lighting environment can influence an occupant's safety, level of fatigue, comfort, as well as work efficiency and accuracy. In an office, it is essential to provide a lighting environment that would ensure clear visibility of objects and psychological comfort. For this purpose, the prevention of glare, control of shadows, luminance and colour contrast must be considered in addition to a sufficient level of illuminance. Thus, the questionnaire should be designed to contain items regarding both

Table 9. Features of digital light meters

Models faculties	Topcon IM-5 (illuminance)	Lutron YK-2005LX (illuminance)	Minolta CA-2000A (luminance)
Sensor	Silicon photo diode	Silicon photo diode	CCD image sensor
Range	0.01–199,900 lx	0.1–100,000 lx	0.1–100,000 cd m^{-2}
Accuracy	±1 digit	±2 digits	3%
Sampling	Real time	2 s–9 h	Real time
Picture			

Table 10. Independent samples *t*-test between 125 points and 12 points

Zone	*t*-Test for equality of means						
	t	df	Significance (two-tailed)	Mean difference	Standard error difference	95% confidence interval of the difference	
						Lower	Upper
Perimeter zone	1.071	19	0.246	22.19	24.14	−10.18	61.40
Interior zone	0.890	19	0.331	19.48	21.20	−13.22	57.58
Corridor zone	0.723	19	0.410	15.02	17.95	−15.19	56.57

the quantity and quality of lighting in an office environment.

Referring to previous literature, the questionnaire was designed to include items to assess the lighting environment of Samsung Corporation Headquarters [28,29]. The first round of questionnaires was distributed to 20 occupants for preliminary survey. Based on the result, the questionnaire was modified to effectively assess visibility, glare, shade, level of satisfaction, fostering of the work environment and level of acceptance regarding the indoor lighting environment (Table 11).

The questionnaire was divided into sections for personal information and the respondent's level of satisfaction with the indoor lighting environment. The evaluation was based on seven stages of the semantic differential (SD) method.

Like test space measurement, the survey was conducted five times between February 2008 and May 2009. The occupants of Samsung Corporation Headquarters were asked to participate in the survey for 3 weeks after the measurement of the lighting environment was conducted. A survey website was launched for the respondents to complete *via* the intranet of Samsung Corporation. The collected data were analysed using SPSS 12.0.

Self-reported Health Symptoms

For this research, the office occupants' self-reported health symptoms were examined in addition to the survey on the lighting environment. The symptoms included headaches, eye fatigue, skin irritation and allergic reactions. The health-related indicators were identified from the SBS that is related to a lighting environment [30].

To measure the self-reported health symptoms, the respondents were asked to mark the frequency of watery eyes, dry eyes, eye ache and tired eyes. They were also asked to identify the time of the appearance and disappearance of the symptoms and their actions to deal with the symptoms. Table 12 describes the items of self-reported health symptoms.

The result could be used as basic data to improve the building operation system and to provide a healthier and more pleasant work environment. Feedback for the problems identified in the survey and self-health report was also provided, followed by the distribution of an additional survey to the occupants (June 2009).

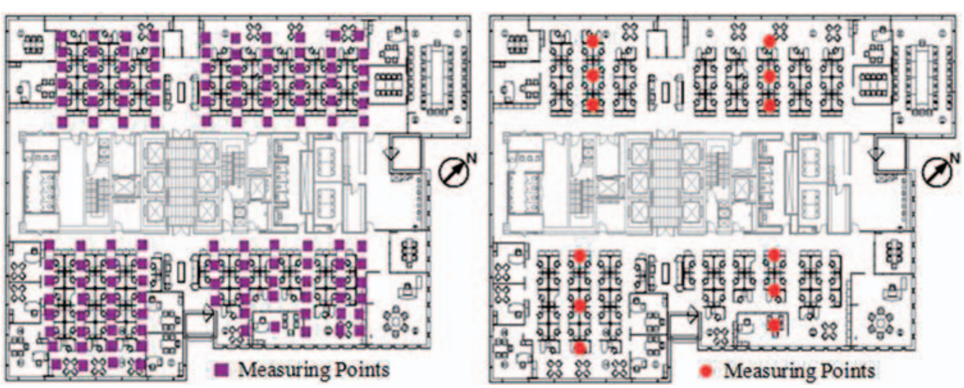


Fig. 8. Measuring points on 23F (February 2008–April 2009): (left) 1st measurement (right) 2nd-5th measurement.

Table 11. Question contents and rating scale of questionnaire survey

Number	Question contents	Answer	Rating scale
L1	Do you feel that your working plane is bright?	Strongly satisfied	3
L2	Overall, is the lighting condition of the office bright?	Slightly agree	2
L3	Do you feel visually comfortable in your office?	Moderately agree	1
L4	Do the electric and natural lights cause a glare that disrupts your work?	Neutral	0
L5	Is the lighting condition useful for your work?	Slightly disagree	−1
L6	Are you satisfied with the lighting condition?	Moderately disagree	−2
L7	Are you acceptable to the lighting condition?	Strongly disagree	−3
L8	What do you think will improve your visual and lighting satisfaction? (subjective question)		

Results

Physical Data Analysis

The standard list of the lighting environment of an office includes: visibility – working view is clear; safety and ability to work effectively; and visual comfort – being in a suitable mood for work and ability to work happily and comfortably. Thus, illuminance could physically satisfy these criteria, but qualitative elements such as brightness and darkness in the visual field, glare, direction of the light, shadow effect, light colour effect and influence of reflections should be included to assist illuminance [28].

Illuminance is an objective criterion that is not influenced by the occupant; however, it is not relevantly related to subjective brightness such as luminous intensity, direction of light, reflectance and luminance, which are also considered important criteria. Therefore, in this research, in order to measure the physical data, three floors, 10th, 23rd and 30th, were selected as test floors.

Illuminance Distribution and Uniformity Factor of Illuminance

In order to examine the effects of the indoor lighting environment on an occupant's visual comfort and eye health in a green building, the research analysed the illuminance in the work place; a height of 75 cm from the floor was measured, a total of five times, from February 2008 to April 2009. The measured illuminance was divided into four zones for analysis, as shown in Figure 7.

Table 13 shows the illuminance distribution that was measured in the test space. The illuminance distribution from the first measurement was 761–937 lx, the second 873–1001 lx, the third 620–1019 lx, the fourth 654–823 lx and the last 728–996 lx; and these measurements satisfied those suggested by the Korean Standards for the illuminance standard 300–400–600 lx (minimum–middle–maximum) [31]. Furthermore, these also met the illuminance goal range, which was the average illuminance of the office of 800 lx proposed in the lighting design of Samsung Corporation Headquarters.

By the zones, the measurement of illuminance distribution was considered high, but the illuminance of A- and B-zones, which are north-facing, was evenly distributed during the daytime. Similar to offices, the space where the ambient lighting was the main, uniformity factor of illuminance was an important aspect.

$$\begin{matrix}\textit{Uniformity}\\ \textit{Factor}\\ \textit{of Illuminance}\end{matrix} = \frac{\begin{matrix}\text{Minimum}\\ \text{Illuminance}\end{matrix}}{\begin{matrix}\text{Average}\\ \text{Illuminance}\end{matrix}} \qquad (3)$$

The result of examining the uniformity factor of illuminance is shown in Table 13, and this satisfied the recommendation given by the Illuminating Engineering Institute of Japan [32].

Figure 9 illustrates the illuminance distribution of the test spaces (10th, 23rd and 30th floors), at 10 in the morning and 2 in the afternoon. Generally, the pattern of the illuminance distribution was identical to the results in Table 13, but the illuminance on the 10th floor of C-zone and D-zone at 10 in the morning and the 30th floor of C- and D-zones at 10 in the morning and 2 in the afternoon were low. The 10th and 30th floors are architecturally designed such that during the investigation, the roller shades were completely blocking the daylight, hence low illuminance readings. Furthermore, during their working hours, the roller shades were completely rolled down, which was considered the necessary solution for this matter.

Table 12. Contents of self-reported health symptoms

Self-reported health symptoms	Contents
Frequency of symptoms	Watery eyes/dry eyes/eye ache/tired eyes
Appearance and disappearance times	Around 8:00; 8:00–12:00; 12:00–17:00; After 17:00
Action against symptoms	Taking a rest at one's desk, going out of office, using medicines, enduring the pain, etc.

Table 13. Results of illuminance distribution and uniformity ratio

Contents	IES recommendation	Measuring number				
		1st	2nd	3rd	4th	5th
Illuminance on work plane (lx)	300–400–600	761–937	873–1001	620–1019	654–823	728–996
Uniformity factor of illuminance	Above 0.5	0.52–0.68	0.65–0.70	0.62–0.89	0.74–0.91	0.55–0.80

Luminance Distribution of Windows

To measure the brightness that the occupants sensed with their eyes, the luminance distribution of windows in the four zones (A-, B-, C- and D-zones) were measured. Figure 10 shows the measurement of the luminance distribution of the windows in the test space on the 23rd floor.

When examining the luminance distribution of the windows in each zone closely, the A-zone's luminance distribution of the windows (Maximum–Average–Minimum) was 3983–185–5 cd m^{-2}; the B-zone's luminance distribution of windows was 5299–185–5 cd m^{-2}; the C-zone's luminance distribution of windows was 4700–442–6 cd m^{-2}; and the D-zone's luminance distribution of windows was 5477–571–9 cd m^{-2}. According to the recommendation for office buildings given by the Illumination Engineering Society (IES), windows or light sources and surrounding surfaces luminance contrast should be 20 : 1, and in the normal vision field, the luminance contrast should be 40 : 1 [23]. Therefore, the east, south and west facades' roller shades would need solar altitude and azimuth based on schedule control. On the other hand, the north-facing luminance of the A- and B-zones was evenly distributed during the daytime.

Subjective Analysis

Characteristics of Subjects

As described above, this experiment posed eight different questions pertaining to the level of satisfaction

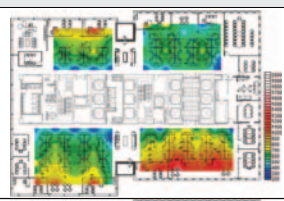
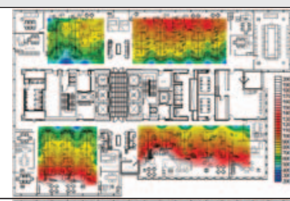
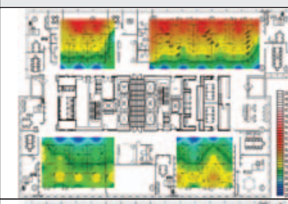
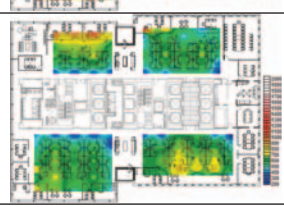
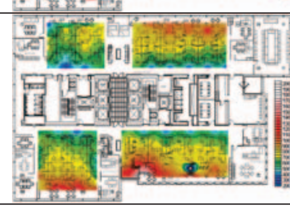
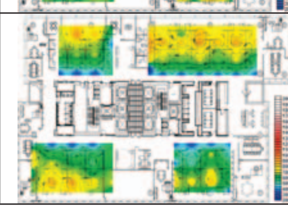
Time	10F	23F	30F
10:00			
14:00			

Fig. 9. Illuminance distribution at 10 : 00 and 14 : 00.

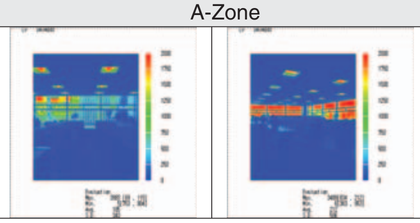
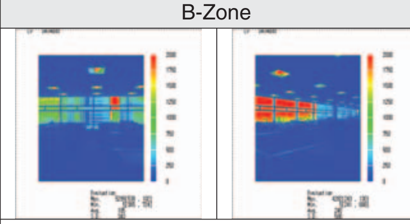
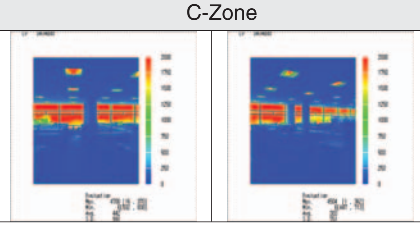
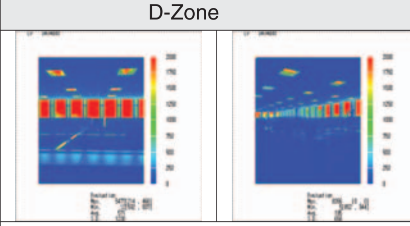
Contents	A-Zone	B-Zone
Luminance distribution		
Luminance (Max.-Avg.-Min.)	3983 cd/m^2–185 cd/m^2–5 cd/m^2	5299 cd/m^2–185 cd/m^2–5 cd/m^2
Contents	C-Zone	D-Zone
Luminance distribution		
Luminance (Max.-Avg.-Min.)	4700 cd/m^2–442 cd/m^2–6 cd/m^2	5477 cd/m^2–571 cd/m^2–9 cd/m^2

Fig. 10. Luminance distribution of windows on 23F by two-dimensional Colour Analyser (April 2009).

with the indoor lighting environment; moreover, the questionnaire survey was evaluated by a 7-Scale SD method. The survey was conducted five times during 1-week periods in February 2008 and May 2009 in conjunction with physical measurements; the occupants at the Samsung Corporation Headquarters were surveyed the day on which physical measurements were taken. The questionnaire was placed on the Internet and the occupants were requested to register on Samsung Corporation's intranet to participate in the survey.

The ratio of people who answered the survey shows that the total number of participants involved in the survey (all five times) was 2744, and the number of men was 2119 (77%), while the number of women was 625 (23%). This ratio precisely corresponded to the total ratio of occupants at Samsung Corporation Headquarters. Looking into the age range of this survey, the majority of the participants were 40 years of age, followed in order by 50 years, 30 years, 20 years and over 60 years. The age range ratio also corresponded to the ratio of the company at large.

For the first survey, which was conducted between 18 February 2008 and 7 March 2008, 699 respondents participated; out of the total number, there were 547 men (76%) and 168 women (24%). For the second survey, which was conducted between 14 April 2008 and 2 May 2008, 547 respondents participated; out of that number, there were 438 men (80%) and 109 women (20%). For the third survey, which was conducted between 17 July 2008 and 6 August 2008, 610 respondents participated; out of that number, 470 were men (77%) and 140 were women (23%). For the fourth survey, which was conducted between 17 November 2008 and 5 December 2008, 383 respondents participated; out of that number, 291 were men (76%) and 92 were women (24%). Finally, in the fifth and final survey, which was conducted between 22 April 2009 and 12 May 2009, 505 respondents participated; out of that number, 389 were men (77%) and 116 were women (23%).

Results of Questionnaire Survey

Figure 11 shows the questionnaire response of the employees at Samsung Corporation Headquarters about the lighting environment in the offices. The brightness values of the working plane category were as follows: first measurement, 0.62; second, 0.58; third, 0.61; fourth, 0.60; and fifth, 0.40. The brightness values of the offices were as follows: first measurement, 0.71; second, 0.71; third, 0.77; fourth, 0.72; and fifth, 0.54. The overall physical brightness had positive results in all time measurements; however, the fifth measurement showed a low result as compared to the other results. This result was expected, as Samsung Corporation launched an Energy Saving Campaign in March 2009, which required turning off half of the built-in artificial lights in the offices as a part of the national policy that drove the campaign. The fifth measurement of interior brightness indicated that with enough natural light coming in during the daytime, there was little difference in the illuminance distribution and uniformity ratio; however, natural light would create a darker office environment when the weather is cloudy and/or rainy.

Furthermore, the results of the visual comfort of the lighting condition were as follows: first measurement, 1.10; second, 1.06; third, 1.19; fourth, 1.02; and fifth, 0.89. The A-zone's occupants had the highest ranking in terms of

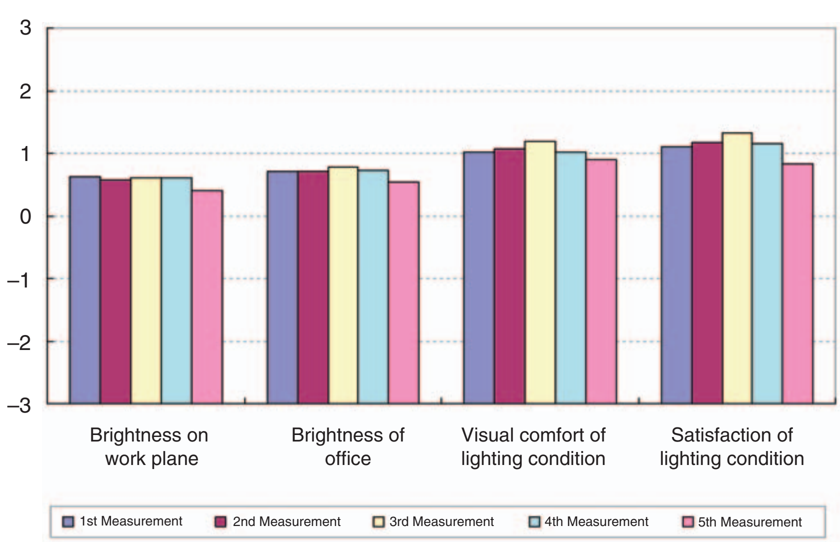


Fig. 11. Mean responses of questionnaire contents.

visual comfort, followed in respective order by B-, C- and D-zones. This result correlates well with the luminance distribution of the windows.

The results for satisfaction with the lighting conditions were as follows: first measurement, 1.10; second, 1.17; third, 1.32; fourth, 1.15; and fifth, 0.83. Satisfaction with the lighting conditions was measured at a constant value, unaffected by season, similar to the results for visual comfort in the lighting conditions. The A-zone's occupants had the highest ranking for visual comfort, followed in respective order by B-, C- and D-zones.

Visual Annoyance Ratio

On the basis of the responses regarding satisfaction with the lighting conditions as shown in Figure 12, the visual annoyance ratio could be measured. According to the 7-Scale SD method, slightly disagree, moderately disagree and strongly disagree, which are used to define the annoyance group, and thus enabled the calculation of the visual annoyance of each male and female. Figure 12 illustrates the fluctuation of the visual annoyance ratio.

Observing the fluctuation of the visual annoyance ratio, the third measurement of visual annoyance (Male: 10.9%, Female: 11.3% and Total: 11.1%), which was measured in the summer, was shown at a low rate, but as winter approached, the visual annoyance increased (Figure 12). This could be explained by the change in the angle and depth of the direct sunlight penetration. In Korea, the values of angle and depth of direct sunlight penetration are 28 degrees in winter and 72 degrees in summer. The desks were positioned on the basis of the solar incidence angle; and the angle and depth of direct sunlight penetration would be comparably higher during winter; thus the daylight entering through the windows would create a visual annoyance to the occupants.

Table 14 illustrates the causes of the visual annoyance. Through examining the causes of visual annoyance, glare received the highest rate at 31.9%, followed in respective order by darkness (19.4%), unqualified shade materials (15.3%) and logic error caused by shade (11.1%).

VDT glare and shade control logic which were the causes of visual annoyance were amended and applied to the operation (June 2009). To reduce VDT glare, the recommendation guide, Computer Workstation Evaluation Checklist (CWEC) from the State of Wisconsin, USA was used as a reference because there were no references and guidelines for them in Korea. Adjusting the viewing distance, height, angle and clarity of the display screen would reduce eye and neck strain. The requirements of CWEC are as follows:

- Display screen should be 18–30 inches away from the eyes.
- Top line of display (print) should slightly below eye level.
- Display should tilt slightly to reduce reflections and glare.
- Display screen should be clean and free of flickering.
- Brightness and contrast controls should be adjusted for viewing comfort.

Table 14. Cause of visual annoyance

Contents	Reponses ratio (%)
Glare	31.9
Darkness	19.4
Unqualified shade materials	15.3
Logic error caused by shade	11.1
Other	22.3

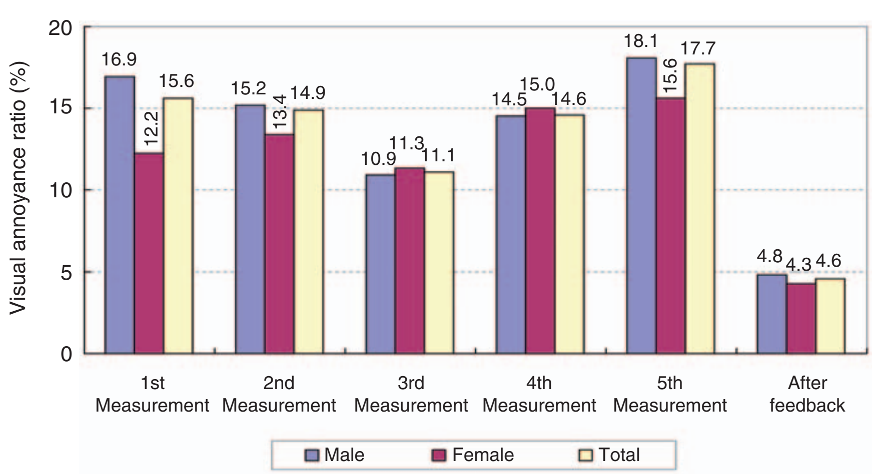


Fig. 12. Fluctuation of visual annoyance ratio.

To explain these contents, an illustration was created and it was displayed on the bulletin monitor in the elevator and broadcasted within the company. In addition, to improve the errors caused by shade control logic, the shading system was programmed to adjust to the season, time, angle and depth of direct sunlight penetration automatically. The system continued to run for a month and, after the month was completed, additional survey was carried out. As illustrated in Figure 12, comparing the visual annoyance ratio after feedback (Male: 4.8%, Female: 4.3% and Total: 4.6%); the fifth measurement of visual annoyance ratio (Male: 18.1%, Female: 15.6% and Total: 17.7%) decreased greatly. As a result, approximately 5% of the occupants' annoyance ratio was caused by the personal characteristics of the lighting environment.

Result of Self-reported Health Symptoms

Tables 15–17 show the results of the self-reported health symptoms. Self-reported symptoms were measured during the fifth measurement; after examining the feedback concerning several problems related to building management and maintenance, questionnaire surveys were conducted on the occupants once again (June 2009). Comparing the results of the fifth measurement and the questionnaire survey feedback, the differences were minimal. To find a solution, it was necessary to interview several of the surveyed respondents. The symptoms were found not to be due to the lighting environment; rather, they were found to be the effects of indoor air quality (IAQ). Therefore, in this experiment, the causes of the self-reported health symptoms in relation to the lighting environment could not be determined.

Table 17. Taking action against symptoms

Measuring number	Action	Frequency	%
5th	Taking a rest at the desk	51	21.3
	Going outside	128	53.6
	Using medicines	6	2.5
	Enduring the pain	19	7.9
	Other	35	14.6
After feedback	Taking a rest at the desk	43	22.2
	Going outside	133	68.6
	Using medicines	4	2.1
	Enduring the pain	9	4.6
	Other	5	2.6

Table 15. Results of self-reported health symptoms

Symptom	Measuring number	Yes (%)	Frequency		
			1–3/Month	1–2/Week	3–5/Week
Watery eyes	5th	226(44.8)	175(77.4)	39(17.2)	12(5.4)
	After feedback	174(41.7)	132(75.7)	31(17.8)	11(6.5)
Dry eyes	5th	102(20.2)	76(74.5)	19(18.6)	7(6.9)
	After feedback	88(21.1)	68(77.1)	13(14.7)	7(8.2)
Eye ache	5th	133(26.3)	110(82.8)	14(10.5)	9(6.6)
	After feedback	96(22.9)	79(82.5)	11(11.5)	6(6.0)
Tired eyes	5th	239(47.4)	194(81.0)	41(17.1)	4(1.8)
	After feedback	194(46.5)	156(80.3)	37(19.0)	1(0.7)

Table 16. Appearance and disappearance times of symptoms

Measuring number	Time (24-h clock)	Appearance		Disappearance	
		Frequency	%	Frequency	%
5th	Around 8	6	2.5	0	0.0
	8–12	64	26.8	17	7.1
	12–17	107	44.8	83	34.7
	After 17	62	25.9	139	58.2
After feedback	Around 8	2	1.0	0	0.0
	8–12	49	25.3	18	9.3
	12–17	93	47.9	65	33.5
	After 17	50	25.8	111	57.2

Working time of Samsung is officially from 8:00 to 17:00.

Conclusion

This study aimed to determine the factors of the indoor lighting environment that had an effect on occupants' visual comfort and eye health, and to inform the effective management and maintenance of the office building. The findings of the research are as follows:

1. After dividing the test space into four different zones (A, B, C and D) according to azimuth, the work spaces satisfied the standards of luminance established by Korea Standard office and the Recommendation of Illumination Engineering of Japan. A-zone and B-zone are north-facing offices; therefore, their illuminance was evenly distributed during the daytime. On the other hand, the occupants in the south-facing offices were working with their roller shades pulled all the way down most of the time; thus, a solution to this situation might be necessary.
2. The mean of the luminance distribution was 185–571 cd m^{-2}. The luminance of the north-facing A-zone and B-zone was evenly distributed during the daytime; whereas, the east, south and west facades would need a roller shade schedule control based on solar altitude and azimuth.
3. To examine satisfaction with the indoor lighting environment, a survey was conducted five times, and the results were as follows: All the question contents had positive values; however, the fifth measurement had low values because half of the artificial lights were turned off to conform with the national policy of the Energy Saving Campaign. There was little difference between the fifth measurement's illuminance distribution and uniformity ratio because there was sufficient daylight penetration; however, darkness due to cloudy and rainy days could have an effect on the results.
4. There was significant correlation between the occupants' visual comfort and satisfaction with the lighting conditions and luminance distribution of the windows. The visual annoyance ratio was the lowest in value during the summer, because of the depth of direct sunlight penetration into the offices; however, as the seasons progressed from summer to winter, the visual annoyance ratio increased. The causes of visual annoyance were glare, darkness, unqualified shade materials, logic error of shade, etc.
5. After making the betterment on practical use of building; the causes of visual annoyance, glare and shade control logic, the visual annoyance ratio decreased tremendously. As a result, approximately 5% of the occupants' annoyance ratio was deemed to be caused by personal characteristics of the lighting environment.
6. The feedback from the questionnaire showed little differences after making changes to the operation of the building in relation to the self-reported health symptoms (related to the lighting environment). After the interview of the respondents, the reported symptoms were mainly affected by IAQ rather than the lighting environment. Therefore, these causes of the self-reported health symptoms were not determined in the research.

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