IMPACT OF DAYLIGHT EXPOSURE ON HEALTH, WELL-BEING AND SLEEP OF OFFICE WORKERS BASED ON ACTIGRAPHY, SURVEYS, AND COMPUTER SIMULATION

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ABSTRACT

The purpose of this study is to examine how daylight exposure affects the health and well-being of office workers. Sleep actigraphy and health and well-being related survey data were the main dependent variables in this study. Research samples were composed of participants from the United States and South Korea, each set of workers divided into those having daylight at their workplaces and those without. Fifty participants in total wore for two weeks actiwatches equipped with light sensors to measure sleep quality and exposure to ambient light levels. Additional health and well-being measurements were taken using well established survey instruments such as the SF-36 for general and mental health, and the Pittsburg Sleep Quality Index (PSQI) for sleep. In order to estimate the levels of daylight participants were exposed to, computer simulation was used to generate the total annual daylight levels in each participant's office. Our results seem to indicate that working in daylit office spaces would lead to higher sleep quality and higher scores of the health and well-being scales compared to those who do not work under daylight conditions. Our findings indicate that it is important to provide and maintain significant daylight levels at the workplace. Consequently, in terms of architectural design, building orientation, building dimensions, and the size and height of windows should be taken into consideration to optimize or maximize daylight exposure.

KEYWORDS

light exposure, sleep quality, quality of life, architectural design, office environment

1. INTRODUCTION

People spend the majority of their lifetime indoors [1, 2], and most people spend the majority of the daylight hours at work, at school, or even at home. Daylight is the primary light source, and it is one of the most important factors that allow people to live and enjoy life. Daylight has a significant impact on our psychological and physiological well-being. This characteristic has attracted scientific research interest over the last few decades [3].

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People connect with daylight in psychological and physiological ways. The influence of daylight is difficult to fully assess and quantify, and its necessity is sometimes overlooked [4]. Research shows that daylight has a positive influence on human health, well-being, sleep quality, school and work attendance or absenteeism, performance, physical activity, and circadian cycles [5–10].

1.1 Daylighting and its impact on human health and well-being

Research has shown that the spectrum, intensity, duration, and timing of light exposure offer potent signals to our brain to regulate circadian physiology and behavior [11, 12]. Circadian Stimulus (CS) is a metric developed at the Lighting Research Center at Rensselaer Polytechnic Institute that takes into consideration the properties of light such as its intensity and spectral distribution that impact Circadian Rhythm (CR) [13, 14]. Thus, the human body requires adequate lighting to regulate its circadian phase [15–17]. This function can be synchronized and regulated through secretion hormones, such as cortisol, melatonin (the nighttime hormone), or serotonin (the daytime hormone) [18–21]. Insufficient light in the environment disrupts sleep quality [17, 22] and produces effects that contribute to sleep disorder [23], latency [24], and duration [25], leading to other potential health problems.

The intensity of light provided by the electric lighting system inside offices is usually no more than 400 lux [26]. These levels are below the minimum of 1000 lux deemed a minimum necessary to entrain our CR [9, 27]. Boubekri, M., et al. [28] study of daylighting in offices showed that office workers with windows and plenty of daylight throughout the day had higher light exposure, more total activity, and enjoyed longer sleep time than those without any daylight at their workstations. Other studies have found that melatonin hormone suppression tends to grow with increasing circadian light levels. Early morning high levels are also associated with increased circadian entrainment, increased sleep quality, and reduced sleep onset latency [29].

Blue-enriched light helps regulate the circadian phase, which is in turn associated with sleep-related problems. This type of wavelength, received particularly in the morning, is reported to have a significant effect on alertness and circadian phase regulation [17, 30].

The timing and duration of exposure to daylight (photoperiod) influences human seasonal and CR. This process can be referred to as the CR regulation or entrainment [31, 32]. The impact of light on CR regulation has been investigated for a variety of populations. Anderson, M., et al. [33] summarized the three daily time periods to categorize time-varied light exposures according to their expected non-visual effect. They determined the early morning time from 6:00 AM to 10:00 AM as the most impactful for circadian regulation and resetting.

1.2 Limitations of current studies and proposed approach

Although many questions regarding circadian rhythm entrainment have been answered, there remain many that are unanswered. At the outset, most previous studies were conducted using participants from one single geographical location. Few studies have analyzed participants from different geographical regions. Furthermore, most studies have focused on one or two health indicators at a time and without the simultaneous analysis of the health impact of lighting levels, timing, and duration, i.e. the characteristics of the overall data. Moreover, in these kinds of studies data are collected for a relatively short period of time (e.g., one or two weeks). The dynamic characteristics of daylight present somewhat of a challenge in determining the long-term exposure of a person to daylight at their workplace. It would be important to understand the full picture of exposure to daylight by the building occupant over a long period of time, such as an entire year, as the impact on a particular individual is not necessarily instantaneous. We are proposing that one way to assess what takes place in a room from a daylighting standpoint is through computer simulation.

Our study uses short-term sleep, and healthy data and daylight measurements as well as computer simulation to predict the year-long exposure to daylight by the office occupants at their own workstation. In particular, the detailed characteristics of light exposure and how each one of those characteristics affect human sleep and health are analyzed. Three of the approaches used by other researchers are combined in our study and form the foundation of our own methodology. The first one was proposed in a study by Boubekri et al. [3] in which they compared daylight and its impact of sleep on two different types of environment, namely with windows and without windows. The second one was used in Figueiro et al. [29], who examined the impact of timing of exposure to daylight. They analyzed the impact of early morning exposure versus other times and its relationship with sleep. The third approach was implemented by Andersen [33] who divided the timing and duration of daylight exposure; daily time period from 6:00 AM to 10:00 AM has non-visual effect on circadian resetting and needs sufficient daylight illuminance.

2. METHODS

2.1 Recruitment of Participants

A total of 50 participants were recruited, including 25 office workers in office spaces without windows or where the participants were very far away from window not benefiting from any exposure to daylight levels, and 25 comparable office workers in workplaces with windows. Participants were volunteers from the University of Illinois Champaign-Urbana campus and from offices in Seoul, Korea. The choice of these two locations was solely based on our access to these two locations. By selecting two areas, this study aims to confirm how effective the methodology and daylighting mechanism are. The total number of participants was 24 and 26 in Champaign and Seoul respectively. Besides, characteristics of offices are different, since all of the participants live in buildings in different environments. Therefore, the difference of these various building interior environments is having a hidden effect on human health and well-being. To minimize the effect of confounding variables on dependent variables, this study tried to compare two groups of office workers, one with windows and plenty of daylight and the other without any window or daylight.

The study was conducted under the guidelines of The Institutional Review Board (IRB) of the University of Illinois at Urbana-Champaign (UIUC) which approved the research study. All volunteers gave written informed consent as required by IRB of the UIUC.

2.2 Sleep and Health Measure Through Surveys

Three types of surveys were used to investigate general health, mental health, sleep, and daylight exposure. First, the health-related quality of life of the office workers was measured by the Short Form health survey (SF-36), a survey of 36 items relating to the physical and psychosocial aspects of health affected by human experience, beliefs, and perceptions of health. The SF-36 survey is a well-proven health status questionnaire that measures perceptions of an individual's ability to perform physical function; physical pain; and physical, social, and emotional role functions [34].

The Pittsburgh Sleep Quality Index (PSQI) [35] was administered to assess participants' self-reported sleep quality. The survey evaluates sleep quality and disturbance at 1-month intervals. The PSQI mainly consists of 19 self-assessment questions which generate seven component scores: self-reported sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. The higher the score, the lower the quality of sleep. A PSQI Global Score> 5 is considered to imply severe sleep disorders.

A daylight survey was utilized to evaluate the self-reported daylight exposure of the participants. It consists of a self-reported amount of exposure to daylight on a scale of 1–10 (1 being always exposed and 10 being never exposed) and duration of current light exposure level.

2.3 Sleep Measure Through Actigraphy

Participants wore an "Actiwatch Spectrum Plus" on their non-dominant wrist [28]. An actiwatch device is an ambulatory setting to detect and record motion during wake and sleep. Participants were instructed to continuously wear these actiwatches for 2 weeks without removing them (except for bathing) during the period of time they were answering the questionnaires. In order to ensure the accuracy of the sleep record, sleep time was recorded in triplicate. On the basis of the automatic measurement recorded by the watch itself, participants were asked to write a sleep log directly, and the left button of the clock was depressed to record the pre-sleep and post-sleep events. The surveys and actiwatches were administered during the summer and early fall seasons.

Sleep data were recorded for a range of 6 to 10 workdays and 2 to 4 free days by participants, with the average participant yielding 8.6 workdays and 3.2 free days of actigraphy data, meeting inclusion criteria for analysis, as determined by < 4 h off-wrist time per day. Analysis was conducted on Actiware software with 30-sec sampling epochs.

Actigraphy measures were calculated as the average of each participant's valid workdays (split into 7:30 to 10:00 for workday early mornings, 08:00 to 17:00 for work hours, and 17:00 to sleep start for workday evenings). Actigraphy variables analyzed include total activity counts (sum of all valid physical activity counts for all epochs in the active period from 7:30 to 10:00 for workday early mornings and 08:00 to 17:00 on workdays for work hours), sleep onset latency (time elapsed between the start time of a given rest interval and the following sleep start time on nights following workdays and free days), sleep efficiency (the percentage of scored total sleep time to interval duration minus total invalid time for the given rest period on nights following workdays), wake after sleep onset (total minutes between the start time and end time of a given sleep interval scored as wake on nights following workdays), sleep time (total minutes between the start time and end time of a given interval scored as sleep on nights following workdays), sleep fragmentation (sum of percent mobile and percent immobile bouts < 1 min duration to the number of immobile bouts for the given interval on nights following workdays), and average light exposure (sum of all valid illuminance data in lux on a logarithmic scale for all epochs from the start time to the end time of a given interval multiplied by the epoch length in minutes from 7:30 to 10:00 for workday early mornings, 08:00 to 17:00 on workdays for work hours, and 17:00 to sleep start for workday evenings).

2.4 Daylighting Assessment Through Computer simulation

Three metrics were used in our daylighting assessment, namely Daylight Factors (DF) [36], Spatial Daylight Autonomy (sDA) [37], and Mean hourly Illuminance (MHI) [38, 39]. DF represents the ratio between the internal illuminance level at a specific point to exterior horizontal illuminance, under a CIE overcast sky. For instance, if we have 1,000 lux (exterior, and

20 lux at a given location inside the room, that is a 2% DF. sDA is an upgraded version of DA [10] and it describes the percentage of area that is above 300 lux for 50% of the occupied hours. MHI measures the average illuminance level calculated at a given location, or as an average based on several prescribed locations inside a room. It represents the mean value of the total hourly illuminance levels in a room calculated at one or several preselected locations throughout a day, a month or a year [38].

Once the participants were recruited, DF and sDA at their offices were measured because we define a windowless workplace as one where workstations were far away from windows, having little or no exposure to daylight. In our study and like most daylighting standards, DF below 2% are considered too low to have any effect and are disregarded, especially knowing that DF metric is valid only under overcast sky conditions [40]. Also, sDA values greater than 50% were kept in the study for workers in workplaces with windows. In terms of sDA, values between 55% and 74% indicates a space in which daylighting is "nominally accepted" by occupants and 75% indicates a space in which daylighting is "preferred" by occupants [41]. In the next step, detailed daylight simulations inside the participants' office were performed, considering the dimensions of the building, material reflectance, and window transparency. Based on this, the daylight availability was measured using the daylighting metrics. sDA and MHI are calculated which allows us to determine the similarity or difference by comparing the given daylighting metric values from the simulations with two weeks of experimental data. Furthermore, parameters such as façade orientation, Window Wall Ratio (WWR) and Window Floor Ratio (WFR) are assessed in our simulation which allows us explain the relationships between building fenestration design, daylighting metrics and daylight availability outside the building [42].

2.5 Statistical Analyses

Two statistical techniques were used to analyze the differences between the two groups of office workrers with daylighting and those without. The first is a Chi-squared test (χ^2-test) which was used to determine if there are differences in demographic and behavioral characteristics. If there are no differences between the two groups according to demographic and behavioral characteristics in the χ^2-test, it can be used to effectively demonstrate the basic assumptions of this study, namely that the differences in daylight exposure impacts sleep, health, and well-being. Secondly, we used a t-test to find out how much the data of health and sleep-related surveys and actigraphy differ between the two groups. For this analysis, p-value is used as a key indicator whether there exists a significant statistical difference between the two groups. A low p-value ($p \leq 0.05$) means there is a statistical difference whereas a high p-value between 0.05 and 0.1 indicates a weak evidence of difference.

3. RESULTS

3.1 Demographic information and behavioral characteristics of the two groups of workers

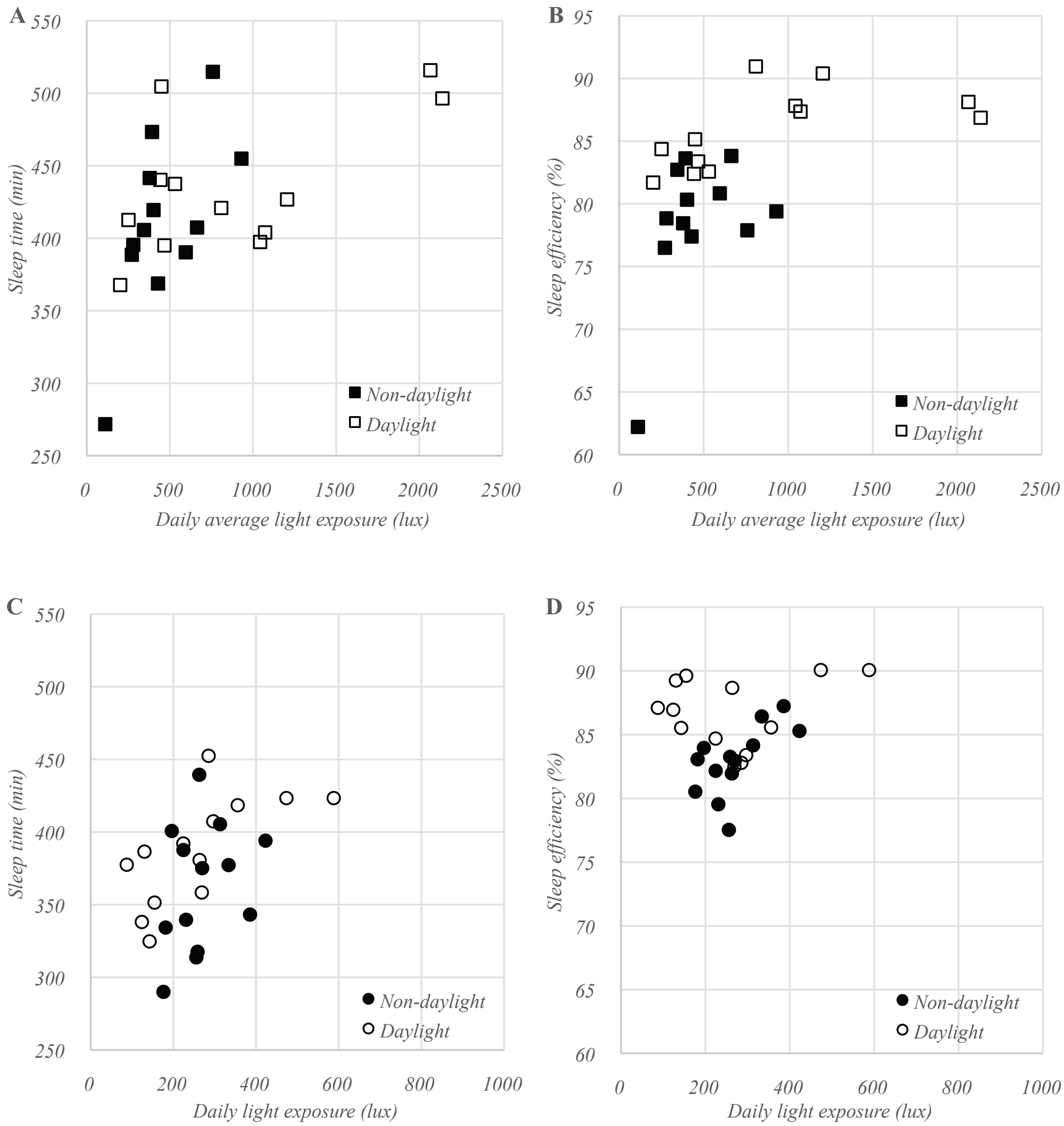
Tables S1 and S2 (see Appendix) illustrate the results of the demographic data analysis of the two groups from Champaign (Illinois) and Seoul (Korea). χ^2-test results indicate no significant differences between the two groups with regard to age, gender, work experience, hours of outdoor activities per day, eating behavior prior to going to bed, and duration of current light level exposure.

3.2 Actigraphy

3.2.1 Lighting levels and sleep

Figure 1 illustrates the association between the daily average daylight exposure and sleep time, and sleep efficiency of the two groups, the non-daylit offices are shown in black and the daylit offices are indicated in white. Figure 1 reveals a common trend, that is the higher the daily

FIGURE 1. Daily average light exposure and sleep, (A) Daily average light exposure and sleep time in Champaign, US; (B) Daily average light exposure and sleep efficiency in Champaign, US; (C) Daily average light exposure and sleep time in Seoul, Korea; (D) Daily average light exposure and sleep efficiency in Seoul, Korea.



average daylight exposure, the longer is the sleep time and better is the sleep efficiency. We also observe that daylight exposure, sleep time, and sleep efficiency were relatively higher among the workers in the daylit offices compared to those in non-daylit ones. The Illuminating Engineering Society of North America (IESNA) recommends that office spaces should be lit at 300 lux or higher [43]. Our observations indicate that there are some cases where these recommended average levels are not met. In fact, 76% of the office spaces in Seoul registered levels below 300 lux but only 20% of office spaces on the UIUC campus registered light levels at these recommended levels (Table 7).

In addition, the basic observation that can be made here is the relationship between sleep time and sleep efficiency. Sleep time and sleep efficiency tend to move in the same general direction among the Korean and the Illinois group as indicated in Figure 2.

3.2.2 Light timing and sleep

Based on the relationship between early morning lighting exposure and sleep presented by other researchers [29], we set out to explore the relationship between early morning exposure to light, related sleep time and sleep quality. Figures 3 A & B illustrate findings for the Champaign-Urbana site and the Seoul site respectively. In both cases, we found that sleep time and sleep efficiency increase proportionally with the exposure to light levels in the early morning. Differences in early morning hours in sleep efficiency and sleep time between the non-daylight scenario and the daylight one tend to be markedly distinct. Among them, sleep efficiency seems to be more closely correlated with the early morning lighting exposure than is the sleeping time. The difference between the early morning lighting level and the sleeping efficiency of the Champaign group is more distinct than it is the case of Seoul group. This may be further explained by the association between the daily daylight exposure and early morning daylight exposure. As shown in Figure 4, both sites show a significant correlation between the daily average exposure and early morning daylight exposure (R-squared value: 0.83 in Champaign and 0.71 in Seoul).

FIGURE 2. Sleep time and sleep efficiency, (A) Champaign; (B) Seoul.

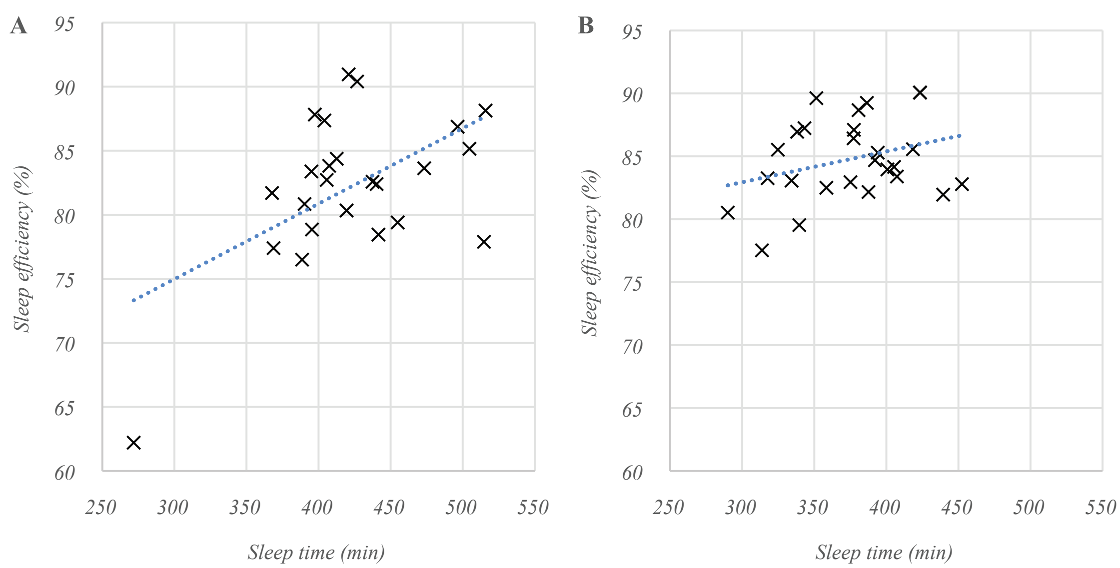
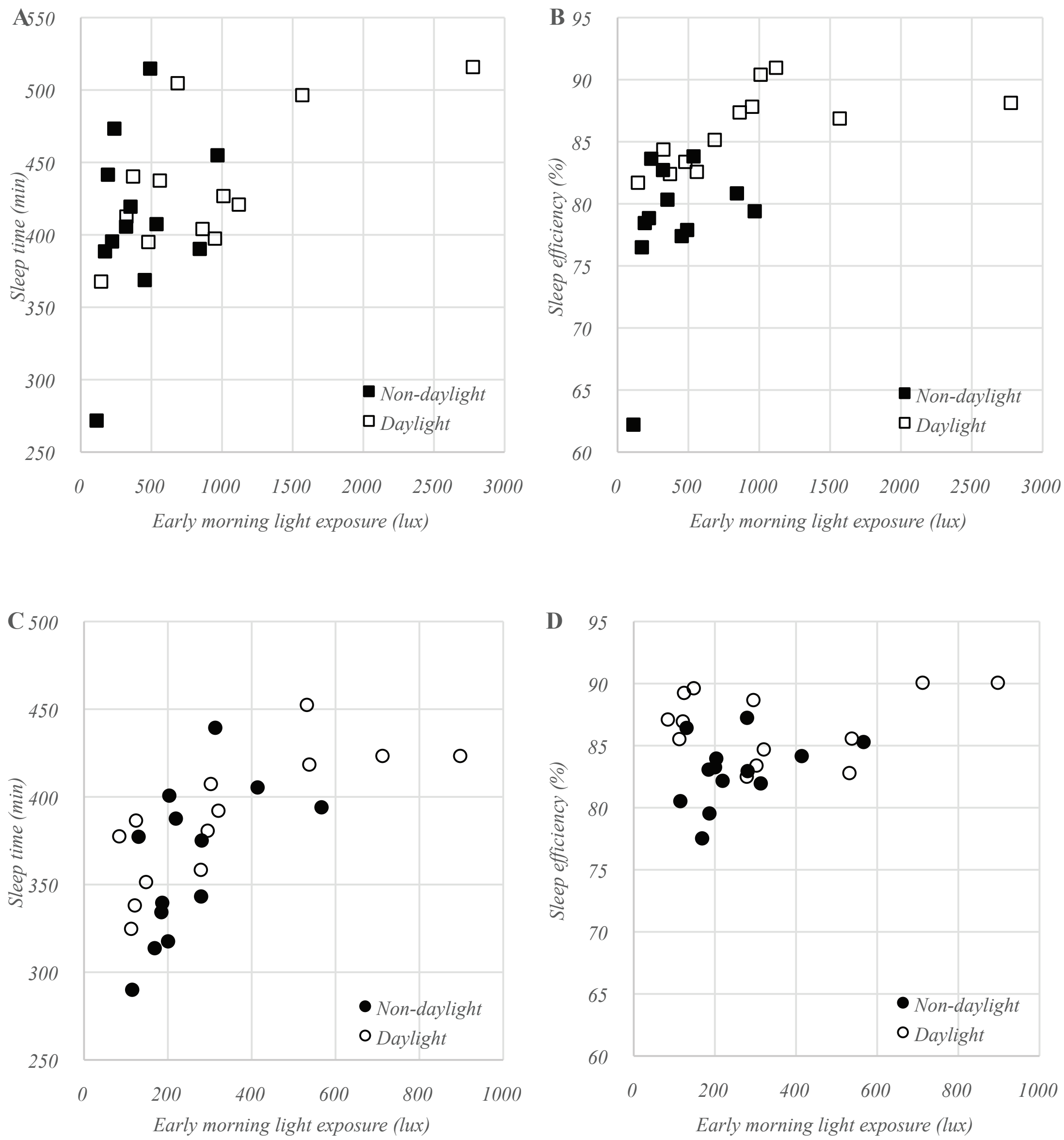


FIGURE 3. Early morning average light exposure and sleep, (A) Early morning average light exposure and sleep time in Champaign, US; (B) Early morning average light exposure and sleep efficiency in Champaign, US; (C) Early morning average light exposure and sleep time in Seoul, Korea; (D) Early morning average light exposure and sleep efficiency in Seoul, Korea.



3.3 Result of daylighting survey and computer simulation

3.3.1 Daylighting survey

The results of the self-reported exposure to daylight are shown in Table 1 for the Champaign-Urbana site and in Table 2 for the Seoul site. In the questionnaire, exposure to daylight is divided into 10 levels. Participants could choose from the survey levels ranging from "never exposed" (Level 1) to "always exposed" (Level 10). In both cases, the significant difference in daylight levels is quite noticeable between the daylit offices and non-daylit ones (Table 1; p = 0.07, Table

FIGURE 4. Average early morning light exposure and daily light exposure, (A) Champaign; (B) Seoul.

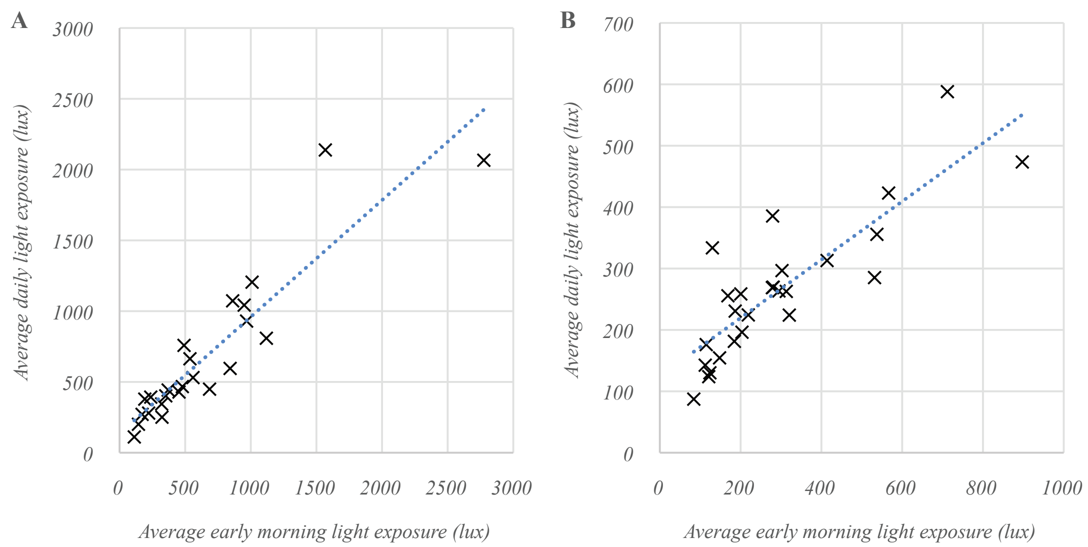


TABLE 1. Self-reported amount of exposure to daylight between the daylit and non-daylit offices (Champaign-Urbana, U.S., site).

Level of exposure to daylight		Work place without windows (N = 12)	Work place with windows (N = 12)	All (N = 24)	p value
1	Always Exposed	0	3	3	0.07†
2		0	3	3	
3		1	2	3	
4		1	1	2	
5	Sometimes Exposed	0	1	1	
6		1	1	2	
7		4	0	4	
8		3	1	4	
9		2	0	2	
10	Never Exposed	0	3	3	

† $p \leq 0.10$

2; p = 0.08). These results of reported daylight levels by the participants are compatible with those measured by the actiwatches worn by the participants.

3.3.2 Health and well-being survey

The outcomes of health SF36 survey are shown in Tables 3 and 4 for the US and Korean group respectively. The average value on this survey scales are higher in most cases in the case of office

TABLE 2. Self-reported amount of exposure to daylight between daylit and non-daylit offices (Seoul, Korea, site).

Level of exposure to daylight		Work place without windows	Work place with windows	All	p value
1	Always Exposed	0	3	3	0.08†
2		0	4	4	
3		1	2	3	
4		1	0	1	
5	Sometimes Exposed	0	0	0	
6		0	1	1	
7		1	1	2	
8		5	1	6	
9		4	1	5	
10	Never Exposed	1	0	1	

† $p \leq 0.10$

TABLE 3. Results of t-tests for Short Form-36 between the two groups, Champaign, US.

	Mean ± SD			p value
	Work place without windows	Work place with windows	Norms of USA general population	
PCS (physical component summary)	49.50 ± 5.23	52.42 ± 6.15	50.00 ± 10	0.22
MCS (mental component summary)	46.08 ± 3.94	48.41 ± 5.03	50.00 ± 10	0.21
Physical Function (PF)	86.50 ± 4.48	89.08 ± 3.50	82.29 ± 23.76	0.13
Role limitation due to physical problems (RP)	77.25 ± 10.97	84.91 ± 8.91	82.51 ± 25.52	0.07†
Bodily Pain (BP)	73.16 ± 7.97	76 ± 9.83	71.33 ± 23.66	0.45
General Health (GH)	70.66 ± 8.17	76.33 ± 9.07	70.85 ± 20.98	0.12
Vitality (VT)	53.00 ± 9.83	61.41 ± 10.65	58.31 ± 20.02	0.05*
Social Function (SF)	78.75 ± 6.35	81.58 ± 6.68	84.30 ± 22.92	0.29
Role limitation due to emotional problems (RE)	70.25 ± 8.82	76.16 ± 10.59	87.40 ± 21.44	0.15
Mental Health (MH)	69.41 ± 7.35	74.08 ± 6.28	74.99 ± 17.76	0.10†

† $p \leq 0.10$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

TABLE 4. Results of t-tests for Short Form-36 between the two groups, Seoul, Korea.

	Mean ± SD			p value
	Work place without windows	Work place with windows	Norms of USA general population	
PCS (physical component summary)	48.25 ± 4.80	51.58 ± 7.98	50.00 ± 10	0.23
MCS (mental component summary)	45.50 ± 4.23	47.83 ± 4.54	50.00 ± 10	0.20
Physical Function (PF)	84.83 ± 3.97	87.02 ± 2.44	82.29 ± 23.76	0.12
Role limitation due to physical problems (RP)	75.50 ± 10.70	83.50 ± 8.39	82.51 ± 25.52	0.05*
Bodily Pain (BP)	71.75 ± 6.63	76.33 ± 9.80	71.33 ± 23.66	0.30
General Health (GH)	68.66 ± 7.72	73.91 ± 6.92	70.85 ± 20.98	0.09†
Vitality (VT)	51.75 ± 8.66	58.91 ± 8.18	58.31 ± 20.02	0.05*
Social Function (SF)	76.91 ± 5.43	80.33 ± 5.12	84.30 ± 22.92	0.12
Role limitation due to emotional problems (RE)	69.33 ± 8.04	76.91 ± 14.70	87.40 ± 21.44	0.13
Mental Health (MH)	68.25 ± 6.44	72.25 ± 6.51	74.99 ± 17.76	0.14

† $p \le 0.10$, * $p \le 0.05$, ** $p \le 0.01$, *** $p \le 0.001$.

workers having daylight, albeit not in a very statistically significant manner. In other words, the general mental health and well-being of the workers operating in daylit offices register higher scores, signaling better health in general. Particularly in the United States, items that relate to the difference between the two groups are Role limitation due to Physical problems (RP) (p-value ≤ 0.07), Vitality (VT) (p-value ≤ 0.05), and Mental Health (MH) (p-value ≤ 0.10). VT score is lower for the group with no daylight (mean = 53) compared to the group with daylight (mean = 61.41). Furthermore, the differences for RP and MH are statistically significant. In particular, the average values of RP, VT and MH for office workers with daylight are quite similar to the US general population. Previous studies suggest VT, RP and MH are effective in measuring physical well-being, physical disability, and mental function and well-being respectively [44]. Our data indicate that the physical and mental well-being of people working in offices with windows with plenty of daylight are higher compared to those who do not have any daylight.

Among the Korean participants' items that registered differences between the two groups with and without daylight are the RP (p-value ≤ 0.05), VT (p-value ≤ 0.05), and General Health (GH) (p-value ≤ 0.10). In the case of RP and VT especially, the differences between the two groups are significant: 75.5 (without daylight) versus 83.5 (with daylight) for RP and 51.75 (without daylight) and 58.91 (with daylight) for VT. In Korea, just as in the US group, the average value of SF-36 for the group with daylight is comparable to the U.S. general population as well. In addition, RP and VT, both have a statistically significant difference found in both experimental sites. We conclude, therefore, that there is a good likelihood that people who work in daylit environments may experience higher levels of RP and VT.

Tables 5 and 6 illustrate the results of the PSQI questionnaire where one can see that the self-reported average sleep scores of the people inside the offices with daylight are higher than those without daylight. In particular, the Global PSQI Score shows that there is the statistical significance found between the two groups. Likewise, and in terms of sleep efficiency scores, we also found a significant difference between those with and without daylight. The Global PSQI Score for Champaign participants was 0.78 (without windows) versus 0.52 (with windows) and for Seoul participants, 0.87 (without windows) versus 0.62 (with windows). As shown in the results of the actiwatches, sleep efficiency shows a clearer significant difference than sleep time. The PSQI shows, however, a significant difference for sleep efficiency but not for sleep time.

3.4 Computer simulation

In order to consider what may be the annual exposure to daylight, we modeled 25 offices having daylight and computed the average lighting exposure per year using various well-established daylighting metrics, namely the sDA and MHI. As a reminder, actiwatches recorded light levels and sleep during a two-week period in our study. Using computer simulation, we are able to predict the exposure to daylight inside the offices for much longer periods including an entire year based on predicted climatic data of the specific experimental site. The daylighting simulation data, shown in Table 7, indicate that the average lighting level measured by the actiwatches are proportional to the sDA and AMHI values. One can also notice that the average values of lighting levels in the early morning are related to the building orientations that the offices are facing. For example, in offices with a north orientation, the sDA and the AMHI values are relatively low in most cases. The offices facing the west orientation also register low values of sDA and AMHI. In the case of the south and the east, the average daylight exposure value and the sDA and AMHI levels are much higher. In both test sites, the top two offices with the highest lighting levels in the early morning are facing East. In the case of WWR and WFR, it is difficult to find a meaningful correlation, but the offices with a relatively high WWR and WFR exhibit high daylight levels as registered by the actiwatches and computer simulation values.

4. DISCUSSION

4.1 Daylight vs. Non-daylight offices

Table 8 illustrates a t-test analysis of the actigraphy data of the two regional groups. In both cases, the sleep quality and quantity scores for daylit offices are higher compared to those without daylight. We also found a statistically significant difference between those with and without daylight, specifically in regard to the average early morning light exposure, average dailylight exposure, sleep onset latency, sleep efficiency, wake after sleep onset, and sleep fragmentation. In particular, Figures 5 and 6 show the maximum, minimum, and average values in detail. In the group on the UIUC campus, the difference in lighting levels between the two groups is clearly distinct. For the group on the UIUC campus, the difference in office light levels between those with and without daylight is clearly distinct. For example, the average lighting level in the early morning (between 8:00–10:00 AM) was 903.67 lux (daylight) and 480.24 lux (non-daylight) respectively, a difference of 423.43 lux which is very substantial. On the other hand, the average daily lighting level was also 889.64 lux (daylight) and 463.00 lux (non-daylight), a difference of 423.64 lux. Sleep efficiency is statistically different between the

TABLE 5. Results of t-tests for Pittsburgh Sleep Quality Index between the two groups, Champaign, US.

	Mean ± SD		
	Work places without windows	Work places with windows	p value
Component 1: Subjective sleep quality	1.04 ± 0.16	0.95 ± 0.23	0.27
Component 2: Sleep latency	0.98 ± 0.10	0.90 ± 0.16	0.13
Component 3: Sleep duration	1.26 ± 0.27	1.15 ± 0.46	0.48
Component 4: Sleep efficiency	0.78 ± 0.33	0.52 ± 0.35	0.06†
Component 5: Sleep disturbance	1.38 ± 0.97	0.93 ± 0.39	0.15
Component 6: Use of sleep medication	0.46 ± 0.33	0.28 ± 0.33	0.21
Component 7: Daytime dysfunction	1.12 ± 0.71	0.71 ± 0.37	0.08†
Global PSQI Score	7.05 ± 1.62	5.46 ± 0.94	0.05*

† $p \leq 0.10$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

TABLE 6. Results of t-tests for Pittsburgh Sleep Quality Index between the two groups, Seoul, Korea.

	Mean ± SD		
	Work places without windows	Work places with windows	p value
Component 1: Subjective sleep quality	1.24 ± 0.42	1.02 ± 0.36	0.18
Component 2: Sleep latency	1.26 ± 0.59	1.01 ± 0.49	0.27
Component 3: Sleep duration	1.31 ± 0.35	1.17 ± 0.43	0.40
Component 4: Sleep efficiency	0.87 ± 0.31	0.62 ± 0.34	0.07†
Component 5: Sleep disturbance	1.24 ± 0.56	0.94 ± 0.33	0.12
Component 6: Use of sleep medication	0.71 ± 0.36	0.47 ± 0.44	0.15
Component 7: Daytime dysfunction	0.93 ± 0.43	0.81 ± 0.36	0.48
Global PSQI Score	7.59 ± 1.30	6.07 ± 1.12	0.05*

† $p \leq 0.10$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

TABLE 7. Results of computer simulation for daylighting metrics.

	Location	Average daylight exposure (lux)	Early morning daylight exposure (lux)	WWR (%)	WFR (%)	Orientation	sDA (%)	MHI (lux)
01	Champaign	201.10	143.96	12	5	N	55.33	264.87
02		250.97	323.21	22	12	N	58.67	339.93
03		442.76	370.23	24	17	W	58.73	574.00
04		449.04	685.76	21	12	S	84.55	430.07
05		467.31	478.26	36	34	W	60.00	484.49
06		530.80	559.52	17	15	S	81.48	506.59
07		808.70	1118.58	29	19	S	94.27	535.65
08		1042.64	949.63	64	60	E	97.14	777.94
09		1072.83	861.92	31	25	S	97.22	918.44
10		1204.86	1009.68	36	29	E	100.00	1101.23
11		2066.21	2775.58	60	58	E	100.00	1565.22
12		2138.54	1567.82	64	54	E	100.00	981.16
13	Seoul	87.28	84.08	20	13	N	56.25	333.17
14		123.82	121.08	25	17	N	62.86	360.46
15		130.14	123.96	26	19	N	74.38	406.48
16		142.58	112.39	23	17	N	78.41	407.36
17		154.49	147.91	22	18	W	70.83	397.33
18		224.13	320.49	24	16	S	68.25	445.33
19		263.51	294.88	20	12	S	100.00	447.00
20		268.85	278.60	18	14	W	72.22	433.56
21		285.27	531.57	26	19	E	90.48	523.49
22		296.62	302.46	24	15	S	95.20	451.73
23		355.68	537.40	31	25	S	95.76	480.29
24		473.55	897.34	67	38	E	100.00	808.78
25		588.04	711.93	54	29	E	98.67	819.17

TABLE 8. Results of t-tests for actigraphy measures between the two groups.

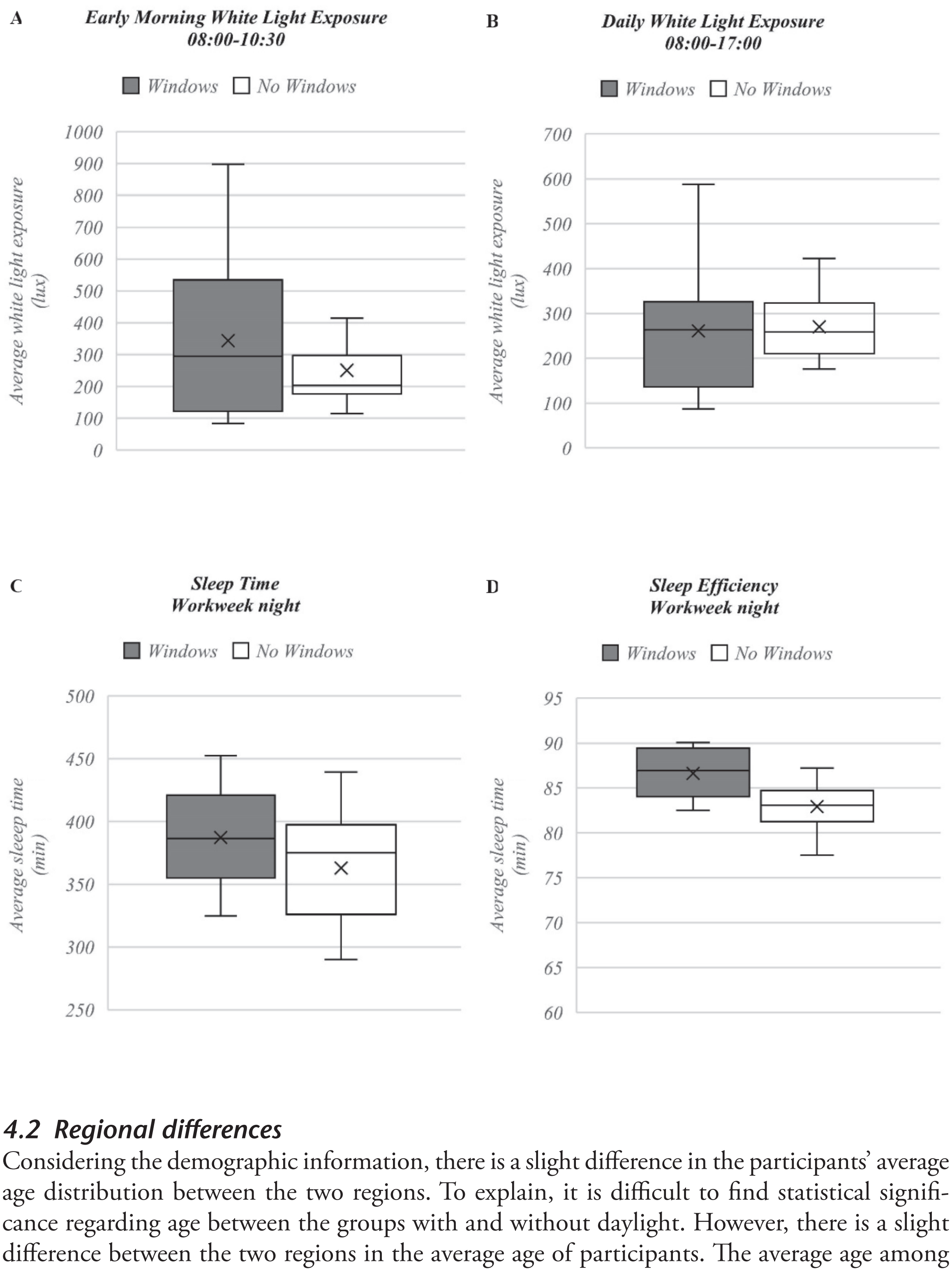
	Mean ± SD				p value	
	Work place without windows		Work place with windows			
	US	Korea	US	Korea	US	Korea
Early mornings (7:30–10:00)						
Total activity counts (arbitrary units)	251.22 ± 50.65	292.58 ± 52.01	260.14 ± 56.41	316.38 ± 112.35	0.68	0.49
Average light exposure (lux)	480.24 ± 268.33	250.83 ± 124.49	903.67 ± 710.43	343.39 ± 255.09	0.03*	0.25
Work hours (8:00–17:00)						
Total activity counts (arbitrary units)	225.08 ± 48.71	246.14 ± 78.03	240.34 ± 48.85	264.69 ± 65.50	0.45	0.51
Average light exposure (lux)	463.00 ± 231.23	270.05 ± 75.69	889.64 ± 652.95	277.43 ± 136.53	0.04*	0.86
Evenings						
Sleep onset latency	34.97 ± 14.65	26.04 ± 16.24	22.82 ± 9.93	13.01 ± 5.51	0.02*	0.01**
Sleep efficiency (%)	78.50 ± 5.66	82.93 ± 2.69	85.92 ± 3.13	86.63 ± 2.77	0.01**	0.01**
Wake after sleep onset	56.36 ± 15.24	36.98 ± 8.74	38.76 ± 11.54	30.03 ± 15.73	0.01**	0.17
Sleep time	410.99 ± 60.28	362.91 ± 43.35	434.93 ± 47.16	387.26 ± 37.45	0.29	0.13
Sleep fragmentation	22.59 ± 7.18	17.99 ± 3.92	16.87 ± 3.12	14.06 ± 4.85	0.08†	0.03*

† $p \le 0.10$, * $p \le 0.05$, ** $p \le 0.01$, *** $p \le 0.001$.

two groups (p-value 0.01 in Champaign and Seoul) compared to sleep time (p-value: 0.29 in Champaign and 0.13 in Seoul). Indicators of sleep efficiency, such as sleep onset latency and sleep fragmentation, also show clear significant difference between the daylight and non-daylight groups, and in both geographical locations.

The difference between these two groups can also be seen in the results of the survey (Tables 3, 4, 5, and 6). The results of the survey do not show a statistically significant difference among all actual sleep and health related indicators. However, the general tendency is that the indicators for sleep and health are better for those working in a daylight office environment. This is the case in both geographical regions.

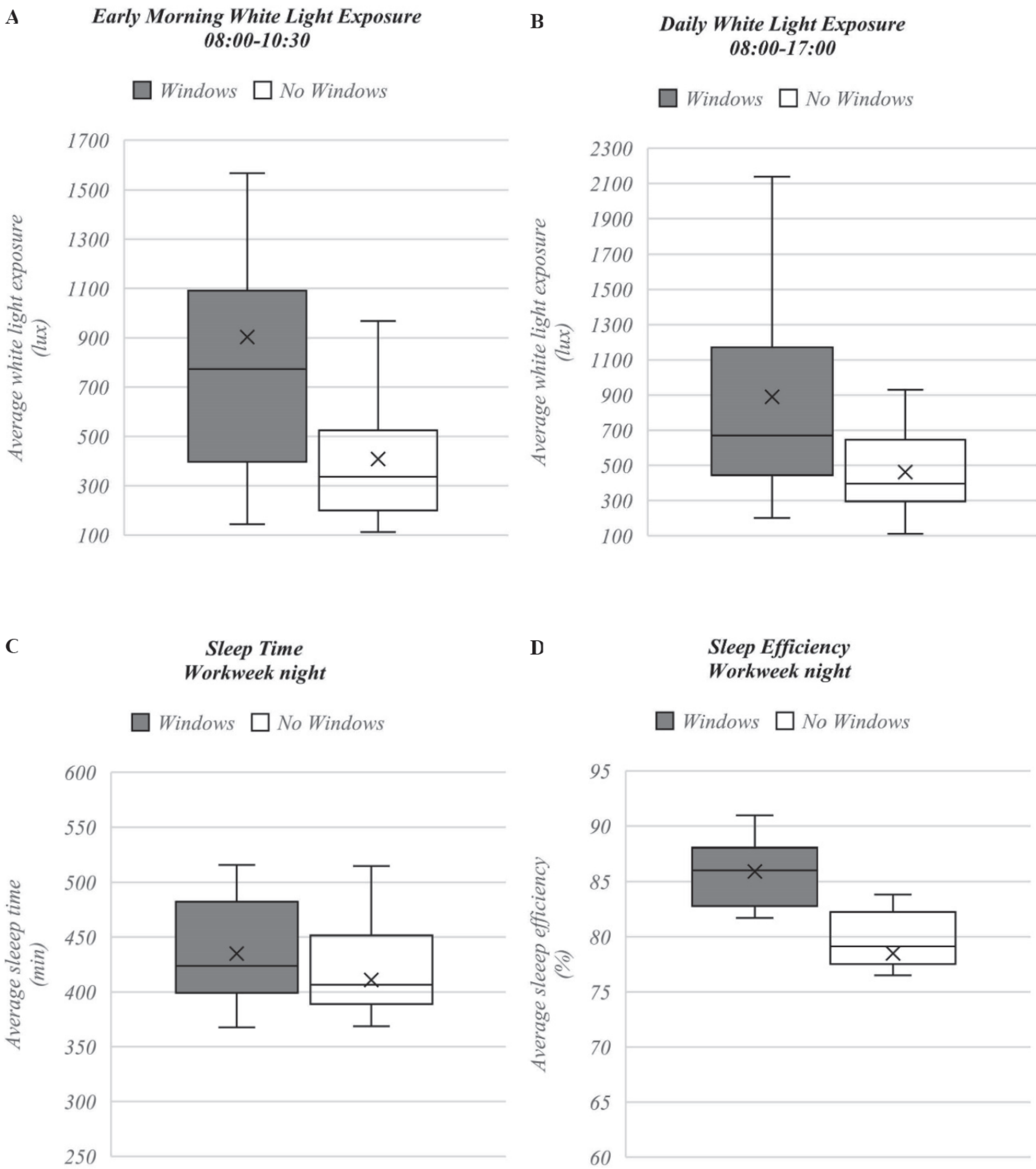
FIGURE 5. Maximum, minimum, and average values of actigraphy data, Champaign, US, (A) Early morning white light exposure; (B) Daily white light exposure; (C) Sleep time in workweek night; (D) Sleep efficiency in workweek night.



4.2 Regional differences

Considering the demographic information, there is a slight difference in the participants' average age distribution between the two regions. To explain, it is difficult to find statistical significance regarding age between the groups with and without daylight. However, there is a slight difference between the two regions in the average age of participants. The average age among the US site participants (mean: 48.32) was higher than that the average age among the Korean

FIGURE 6. Maximum, minimum, and average values of actigraphy data, Seoul, Korea, (A) Early morning white light exposure; (B) Daily white light exposure; (C) Sleep time in workweek night; (D) Sleep efficiency in workweek night.



participants (mean: 39.54). Except for age, no other statistical difference was found in the characteristics of the participants.

Also, there is no significant difference between the two regions when comparing the data collected from the surveys. However, here too we notice a slightly better sleep and health scores among the workers with daylight compared to their counterparts without daylight in both regions.

In terms of lighting exposure, the difference between the two regions is relatively large. Figure 7 shows the daily lighting average exposure level per year using computer simulation, the average daylight exposure, and the early morning light exposure level using actigraphy. Experimental data using actigraphy and yearly light exposure using computer simulation show that the lighting exposure level of the US participants is higher than that of the Korean participants. This difference may be due to climate data, differences in building design, as well as other factors.

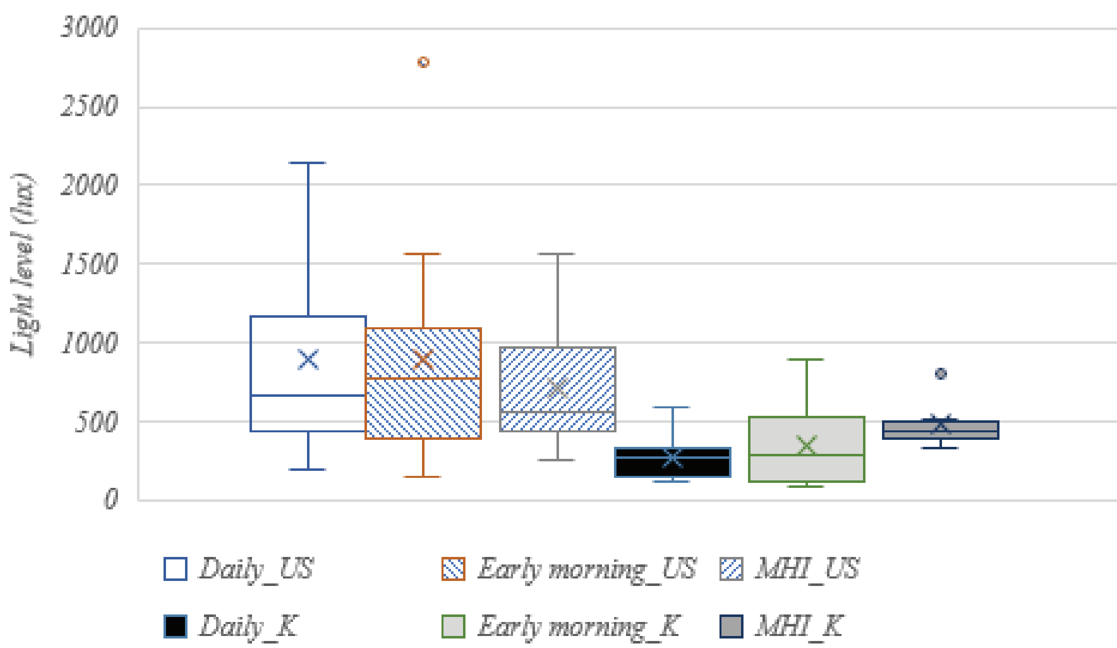
Finally, when comparing the sleep related data of the US and the Korean groups, it can be seen that the average sleep time among the group from Champaign is much higher (422.9 minutes) compared to the participants from Seoul (375.1 minutes). Sleep efficiency is much closer, however, showing 82.2 % for in the Champaign group and 84.8 % for the Korean group.

4.3 Surveys, experimental study, and computer simulation

Because surveys are a subjective evaluation of the conditions felt by the respondents, they do not necessarily accurately report states of sleep, health, and well-being. We could not determine in statistical terms significant differences between the two groups, we could see, however, a general trend whereby the health and sleep indicators are always higher for those with daylight compared to those without any daylight.

Computer simulations show that the two most important factors affecting daylighting performance are window orientation and the type of daylighting metric used in the assessment of such performance. As shown in Table 7, orientation significantly impacts the exposure of daylight in the early morning hours. Especially in the East and South, the early morning lighting level and the daily daylight level are relatively high. As far as the daylighting metrics, MHI has a tendency similar to that of the daily daylight level of actigraphy. This could be due to the

FIGURE 7. Comparison of lighting exposure level between two regions.



fact that the MHI calculates the illuminance level more directly than the sDA does. As can also be seen in Table 7, the MHI values derived from computer simulations are related to the actigraphy data, indicating a potential effect on sleep time and sleep efficiency. Further research is needed to see how building design parameters affect daylighting metrics and how controlling them affects people's health, well-being, and sleep.

5. CONCLUSIONS

The impact of daylight exposure on human health, sleep, and well-being was compared through actigraphy, surveys, and computer simulation. We compared two groups of office workers, one with windows and abundant daylight and the other without any windows or daylight. We also used two different geographical locations that were accessible to us, one on the UIUC campus (US) and the second in Seoul, Korea. Using the proposed methodology, this study confirmed its hypothesis that exposure to high levels of daylight positively affects sleep, health and well-being. Key findings are summarized below:

- There is no significant difference found between the two groups and the two regions as far as the demographic and behavioral characteristics.
- Actigraphy data confirmed the assertion that exposure to daylight will increase sleep time and sleep efficiency. In particular, early morning lighting exposure and sleep efficiency were found to be statistically significantly different between the two groups.
- We did not find statistical difference between the two groups of daylight in the data obtained through surveys. Overall, scores of health, sleep, and well-being were all higher in the group with daylight compared to the group without daylight, albeit it is not statistically significant.
- Computer simulations based on average annual daylight exposure show that the MHI value is similar to the daylight exposure average of the actigraphy. Orientation was associated with early morning lighting exposure.
- There is not much difference between the US and the Korean participants as far as demographic and survey data. However, when comparing the sleep related data, the US group registered 422.9 minutes of sleep time and 82.2% sleep efficiency per night compared to the Korean group which registered only 375.1 minutes of sleep time and 84.8% sleep efficiency

Exposure to a large amount of daylight in the working space increases the sleep time, sleep efficiency, and quality of life of sample office workers. We spend a lot of time inside buildings, and the exposure of daylight in the working space therefore affects the mental and physical health of office workers with a continuous and compounding effect. In order to optimize daylight exposure in the building, passive techniques such as rearrangement of furniture and adjustment of solar shade can be applied to existing buildings. Policy makers as well as building designers should use health criteria to establish building codes as well as design guidelines. New daylighting metrics should target specifically human health and well-being indicators such as sleep quality as used in this study.

SUPPLEMENTAL TABLE (APPENDIX)

TABLE S1. Demographic information and behavioral characteristics of the two groups (Champaign-Urbana, U.S.).

	Work place without windows (N = 12)	Work place with windows (N = 12)	All (N = 24)	p value
Demographic Characteristics				
Gender				
Males	4	5	30% (9)	0.67
Females	8	7	70% (15)	
Age (years)				
19–30	1	2	3	0.68
31–45	3	4	7	
46–59	8	6	14	
60+	0	0	0	
Race				
Black/African-American	1	1	2	0.82
American Indian/Alaskan Native	0	0	0	
White/Non-Hispanic	10	9	19	
Asian/Pacific Islander	0	0	0	
Latino/Hispanic	1	2	3	
Other	0	0	0	
Working experience (years)				
0–1	0	0	0	0.85
2–4	3	2	5	
5–7	3	4	7	
8–10	2	1	3	
> 11	4	5	9	
Behavioral Characteristics				
Outdoor activities (hours per day)				
0–1	8	7	15	0.67
2–4	4	5	9	
4–6	0	0	0	
Years at current light exposure level				
0–1	1	1	2	0.68
2–4	4	3	7	
5–7	3	4	7	
8–10	3	1	4	
> 11	1	3	4	
Eating behavior prior going to bed				
Eating directly prior going to bed	4	3	6	0.67
No eating prior going to bed	8	9	18	

TABLE S2. Demographic information and behavioral characteristics of the two groups (Seoul, Korea).

	Work place without windows (N = 13)	Work place with windows (N = 13)	All (N = 26)	p value
Demographic Characteristics				
Gender				
Males	4	5	10	0.67
Females	9	8	16	
Age (years)				
19–30	3	5	8	0.61
31–45	8	7	15	
46–59	2	1	3	
60+	0	0	0	
Race				
Black/African-American	0	0	0	—
American Indian/Alaskan Native	0	0	0	
White/Non-Hispanic	0	0	0	
Asian/Pacific Islander	13	13	26	
Latino/Hispanic	0	0	0	
Other	0	0	0	
Working experience (years)				
0–1	0	0	0	0.84
2–4	4	5	9	
5–7	8	7	15	
8–10	1	1	2	
> 11	0	0	0	
Behavioral Characteristics				
Outdoor activities (hours per day)				
0–1	11	10	21	0.67
2–4	2	3	5	
4–6	0	0	0	
Years at current light exposure level				
0–1	2	3	5	0.92
2–4	5	4	9	
5–7	5	5	10	
8–10	1	1	2	
> 11	0	0	0	
Eating behavior prior going to bed				
Eating directly prior going to bed	5	4	9	0.67
No eating prior going to bed	8	9	17	

ABBREVIATIONS

Chi-squared test (χ^2-test)
Circadian Rhythm (CR)
Circadian Stimulus (CS)
Daylight Factors (DF)
General Health (GH)
Mean hourly Illuminance (MHI)
Mental Health (MH)
Pittsburgh Sleep Quality Index (PSQI
Role limitation due to Physical problems (RP)
Seasonal Affective Disorder (SAD)
Short Form health survey (SF-36)
Spatial Daylight Autonomy (sDA)
Vitality (VT)
Window to Wall Ratio (WWR)

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