Lighting preferences in office spaces concerning the indoor thermal environment

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Abstract The accurate prediction of the visual comfort zone in an indoor environment is difficult as it depends on many parameters. This is especially the case for large compact urban areas in which the density and shadow from neighboring buildings can limit the accessible daylighting in indoor spaces. This paper investigates the satisfaction range for illuminance regarding indoor air temperature in office buildings and the significant parameters affecting this range in six office buildings in Tehran, Iran. Lighting comfort has been evaluated by a subjective survey (509 total responses) and field measurement. The questionnaires were filled out in 146 and 109 rooms in summer and winter, respectively. The results show that the illuminance should not be less than 550 lx, while illuminance between 600 and 650 lx provides the highest satisfaction level. The satisfaction with lighting level is affected by individual parameters such as age, type of activity, and environmental parameters such as window orientation, external obstructions, and season. A relationship was observed between lighting level satisfaction and thermal condition acceptance, and the overall comfort depends more on thermal conditions than the lighting level.

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1. Introduction

Providing comfortable indoor spaces is a constant challenge for architects, especially in office spaces where employees spend many hours of the day. In these spaces, lighting is one of the most important environmental parameters as most of the activities are based on receiving visual information from
the surroundings. Also, satisfaction with lighting conditions is one of the main elements that significantly affects the environment’s overall comfort levels (Veitch et al., 2007). However, other studies have reported that lighting conditions are the least important factors in buildings when other indoor environmental factors are considered. Among lighting sources, daylighting is an essential and useful strategy to provide visual comfort. It is directly associated with energy-saving by reducing energy consumption caused by artificial lighting (Sharma et al., 2018). But to support visual and non-visual requirements in indoor environments, it is essential to consider adequate integration of natural and artificial sources of light (Krüger et al., 2018).

To assess the lighting in living/working spaces and define conformity conditions based on the design standards, metrics are used as a physical measure (Tregenza and Mardaljevic, 2018). Generally, there are static and dynamic metrics to evaluate various aspects of daylight (Reinhart and Weissman, 2012). Static metrics such as illuminance-based daylighting metrics and Daylight Factor (DF), luminance distribution, view of the sky is typically evaluated based on illuminance (Andersen et al., 2008) and have been used in building regulations for a long time (Aries, 2005). In most standards and codes, the minimum recommended illuminance level on work planes for regular office work is 500 lx. For instance, the Canadian Labor Code, IESNA, NS-EN 12464–1:2011, suggested a minimum of 500 lx on the desk in office spaces (Reinhart and Fitz, 2006; Grynning et al., 2014). There are lower values recommended in some codes, for example, 300 lx in the National Building Code (NBC) of India (National Building Code (NBC) of India, 2005). In National building Code No. 13 of Iran, a minimum illuminance level in office spaces is suggested not to be less than 500 lx (National Building Regulations, 2009). In BS8206-2, the average daylight factor is at least 2%. (Yun et al., 2012; British Standards Institution, 2008). Green building rating system such as LEED in 2007 expresses the daylight attributes in terms of daylight factor distribution (LEED-NC 2.1) or glazing factor distribution (LEED-NC 2.2) and view to the outside (Galaslu and Reinhart, 2008). However, in most of these standards, the minimum lighting level in indoor spaces is more according to the economic considerations than the technical criteria to provide comfort conditions (DiLaura et al., 2011; Mardaljevic and Christoffersen, 2016).

Most studies on visual comfort and users’ lighting preferences indicate people prefer much higher light levels than what is typically recommended by standards and regulations (Boubekri, 2008). Many studies have been conducted to find an acceptable lighting level in offices to create a comfortable office environment. Previous studies show the desired lighting level is different when the environment lighting source is daylight or artificial lighting. It was observed that the illuminance preference of occupants under only artificial light varies significantly from 100 to 800 lx (Newsham and Veitch, 2001; Boyce et al., 2006; Veitch and Newsham, 2000). Laurent et al. (Laurentin et al., 2000) found that people prefer 300 lx when the lighting source is only daylight. Galasiu and Veitch (2006) expressed when daylight was available in office spaces; users chose a low artificial light level. For instance, people added 150–400 lx artificial light to the daylight on their desks; however, when daylight illuminance was below 100 lx, many said no more than 280 lx is required.

Building occupants have different preferences of lighting conditions depending on a large number of parameters, which could be categorized to personal variables such as the type of work, duration and time of work, the users’ age (Arimilos and Heracleous, 2017); physical environment variables such as floor level, window orientation, external obscuration (Xue et al., 2016) and physical quantity of light such as the amount of light and its distribution in space (Carlucci et al., 2015). In addition to visual parameters, three other main factors of air quality, thermal parameters, and acoustic contribute equally (Frontczak et al., 2012). So, it is necessary to evaluate the overall comfort to determine potential interactions of at least two of these factors (Laurentin et al., 2000). Buratti et al. (2018) introduced an evaluation index for each of the thermal, visual, and acoustic comforts in Italy and evaluated overall satisfaction with these factors’ simultaneous effect. According to the heat-color hypothesis, visual and heat perception affect each other (Reijgs and Stringer, 1988). The most important physical parameters for thermal and visual comfort are temperature and illuminance (Sicurella et al., 2012).

Despite the large number of studies considering visual and thermal comfort conditions, there is still a need to further investigate the relationship between the indoor environment’s thermal perception and lighting preferences. Hence, in this study, the correlation between lighting and thermal satisfaction will be investigated. Additionally, the acceptable lighting level in office spaces and those personal parameters and physical environmental variables affecting lighting comfort zone in this study are identified.

2. Methodology

Identifying factors influencing the subjective evaluation of natural light in office environments is possible through two methods: test room and field study. In test rooms, ambient conditions can be controlled, high-quality measurement technology can be used, and the measured values are very accurate. The test room environment is not the “real” working environment because participants only spend a few minutes or hours in the room. In the test room studies, only a few volunteers can be interviewed simultaneously, limiting the sample size. Compared to studies in test rooms, field studies show greater validity of the results since they consider real influencing parameters on occupant’s satisfaction. Psychosocial factors related to the working environment and the presence of other people who work in the same room are engaged in studies in the real workplace environment (Moosmann, 2015). To this end, this paper presents a field study integrated with physical lighting quantities to define the level of occupants’ satisfaction with the lighting in the workplace, which is done after the long-term interaction between user and building. Most of the participants have spent at least three months in their working room. So, they have been adapted to the environment. As the shading directly affects visual and thermal perception (Nowak et al., 2016), the survey shading devices were switched off during the survey.

The research methodology contains three main steps;
(1) identifying variables that affect lighting satisfaction level;
(2) data collection, which consists of three parts:
   • Selecting case studies and participants;
   • Subjective survey; users’ evaluations of physical variables and other measured environmental variables are investigated; and
   • Measurement of the lighting intensity
(3) through statistical analysis and the field survey results, the desired lighting level and related variables are identified based on the correlation between variables and occupants’ responses.

2.1. Buildings and occupants

2.1.1. Buildings

The underlying study is part of a field study conducted in 146 rooms in summer and 109 rooms in winter of six office buildings in Tehran. These six offices are selected to consider different spaces in old and new buildings, one-story and high-rise buildings, open plan, and cellular offices with varying window orientation. In these six buildings, the rooms were selected according to one, two- or multi-person offices. Rooms selection concerning the plan was a uniform distribution in taking the spaces (floors, window orientation, optionally atrium/outside window or old/new).

The available features for each building are as follows:

2.1.1.1. Building A. An institutional building with 30-rooms located in the northwest of Tehran, which has only one-story in the Power Research Center site. Windows are oriented to the north, south, east, and west. Several rooms had two windows oriented north and east, and other rooms had south and east windows. There were seven rooms without any windows. The curtains shade the windows from the inside. The ratio of the external window area to the room area (WFR) is 17% on average, and the ratio of the window area to the exterior wall (WWR) is 23%. Participants filled out 42 questionnaires in 27 different rooms in summer and 24 questionnaires in 21 rooms in winter.

2.1.1.2. Building B. Administrative building of the University of Art located in the central part of Tehran; a historical two-story building. Windows are oriented to the north, south, east, and west. Most of the windows face south and north, and only a few windows face east or west. Curtains shade windows from the inside. WFR is 22% on average, and WWR is 30%. Most rooms in this building are 4.6 m × 3.6 m × 2.8 m, and the window dimensions are 1.5 m × 1.5 m with a window sill height of 1 m above the finished floor level. In this building, 26 questionnaires in 18 rooms in summer and 42 questionnaires in 27 rooms in winter were filled out by participants.

2.1.1.3. Building C. The municipality building, small size and a newly built four-story building in downtown Tehran. Windows are oriented to the north, south, east, and west. Curtains shade them from the inside. WFR is 22% on average, and WWR is 30%. Most rooms in this building are 6 m × 3.8 m × 2.75 m, and the window dimensions are 3 m × 1.2 m. The window sill height is 1 m. Twenty questionnaires were completed by participants in 9 different rooms in summer and 14 questionnaires in 10 rooms in winter.

2.1.1.4. Building D. Student Affairs Organization Building in the central part of Tehran; a 50 years old and six-story-high building. Windows are oriented to the north, south, east, and west. Curtains shade windows from the inside. WFR is 16% on average, and WWR is 29%. Most rooms in this building are 3.2 m × 4.8 m × 2.65 m, and the window dimensions are 1.2 m × 1.2 m. The window sill height. Thirty-two questionnaires were filled out by participants in 25 rooms in summer and 29 questionnaires in 21 spaces in winter.

2.1.1.5. Building E. Kayson INC., located in the northern part of Tehran; a six-story open-plan office building. Windows are oriented to the north and south, and there are some rooms without windows. Seventy-one participants filled out the questionnaire in the spaces with openings to the atrium. Curtains shade windows from the inside. WFR is 26% on average, and WWR is 56%. Most rooms in this building are 9 m × 7 m × 3 m, and the window dimensions are 6.5 m × 2.8 m. In this building, 65 questionnaires were completed by participants in 17 spaces in summer and 46 questionnaires in 9 rooms in winter.

2.1.1.6. Building F. The Ministry of Science, Research and Technology in the northwest of Tehran; a 13-floor Building. Windows are oriented to the north, south, east, and west, and 15 participants filled out the questionnaire in the rooms with openings to the atrium. Curtains shade windows from the inside. WFR is 17% on average, and WWR is 35%. Most rooms in this building are 3 m × 4.6 m × 2.65 m, and the window dimensions are 1.5 m × 1.3 m. The window sill height is 1 m. In this building, 95 questionnaires were filled out by participants in 50 rooms in summer and 74 questionnaires in 21 rooms in winter (Figs. 1 and 2).

Additionally, the glass of exterior windows is typical clear glass; with a thickness of 0.003 m, visible transmittance of 0.898, solar reflection of 0.075 and without a Low-e coating. In all buildings, internal curtains were used as a shading system, but they were open during the measurement to provide similar conditions during the survey.

2.1.2. General characteristics of occupants

The survey involved 509 questionnaires (280 in summer and 229 in winter), 55.9% female and 44.1% male with a mean age of 38 years (22-68). Most of the participants (38.5%) are between 30 and 39 years old. Table 1 shows the age and gender range of the occupants in percentage. The participants have been in the rooms for an average of 3.4 years (min. 1 month and max. 20 years). 35.2% reported that they spend more than 8 h in the office during the day, 51.7% between 6 and 8 h, 11.5% between 4 and 6 h, and 1.6% less than 4 h. The 136 questionnaires were completed before 11:30, 244 were completed between 11:30 and 13:10, and 129 after 13:30.

47.7% of activities are just paper-based, 6.7% only with a computer, and 45.6% both of them. 24.6% reported that they suffered from severe headaches, and 36.6% used glasses for reading. 18% had a private room, 25.8% were in a double occupancy room, 34.8% in a space with three or four persons, and 21.4% in open-plan spaces.
2.2. Data collection

The required data consist of two sections: first, the physical data were collected by field measurement. As there is a significant correlation between illuminance levels and visual comfort (Ricciardi and Buratti, 2018), the illuminance level has been measured. The other measured parameters were temperature and relative humidity. Physical data were collected when users filled out the questionnaire. The second section was data collected through a questionnaire which consists of two parts: the first part was completed by the researchers, which included the physical parameter of the space, outdoor obscurations, and the characteristics of the light sources, and users filled out the second part consists of individuals’ parameters and their assessment of the environmental conditions.

2.2.1. Field measurement

To consider the seasons’ influence, the measurements and surveys were carried out during summer from July 3rd to July 23rd, 2017, from 9:00 a.m. to 5:00 p.m. During winter, data collection was conducted from January 30th to February 25th, 2018, from 9:00 a.m. to 4:00 p.m. The average annual sunshine hours in Tehran are over 2903 h/year based on Mehrabad meteorological station data. 38% of the year, the sky is totally clear (cloud cover is less than 10%), 18% of the year, there is overcast sky (with more than 90% cloud cover), and in other times the sky is 10%–90% cloudy (U.S. Department of Energy, 2018).

<table>
<thead>
<tr>
<th>Table 1 Age and gender of the participants.</th>
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Fig. 1 Studied buildings.

Fig. 2 Some of the indoor spaces were selected for the field measurement.
The sky condition during the survey in winter and summer was similar and totally clear. The following physical variables were measured in the environment simultaneously:

- Horizontal illuminance at the desk level (if two or three people were in different parts of the room, the measurement of the intensity of light at the desk level would determine how the lighting was distributed in the room; otherwise, the intensity of the light at the user’s desk and two other points in the room at the same level) were measured. Light intensity was measured once with artificial lighting and once without it;
- Room air temperature and radiant temperature by using black globe temperature sensor;
- Relative humidity.

For the measurement of illumination, the LX-1128SD device was used which has three ranges of measurements: from 0 to 1999 lx, 1800–19,990 lx, and 18,000–99,900 lx. For this study, since the maximum illuminance was 1298 lx, the first range was nominated for the measurement. The air temperature and radiant air temperature were measured by the WBGT-2010SD Heat index (the measurement range for air temperature is from 0 to 50°C, and for radiant temperature, 0–80°C) and the relative humidity by the HT-3007SD with 5%–95% measurement range.

Measured data were collected in 146 rooms in summer and 109 spaces in winter. In each room, lux meters were located at the user’s desk level and in a few other places (two or three units per room) to measure the room’s lighting distribution, 1.5–2 m from the window or the wall. Thus, data related to the lighting level at the user’s desk height and light distribution in the room were collected simultaneously. Measurements were completed while occupants were filling out the questionnaires. Each value was recorded in 15 min and at intervals of 10 s.

The lighting measurement was done both with and without artificial light. The questionnaire contained questions that ask the satisfaction of occupants in these two different conditions. In this study, as we seek visual comfort regarding the impact of the thermal condition, the illuminance level with daylight was applied in the data analysis.

2.2.2. Questionnaire survey
Determining comfort illuminance in office spaces is possible through the subjective survey (Yun et al., 2012). Horizontal and vertical illuminances have already been assessed by personal evaluation in various studies (Day et al., 2012; Dahlan et al., 2009; Wienold and Christoffersen, 2006; Maki and Shukuya, 2012; Iwata et al., 1994; Kim and Kim, 2007; Linhart and Scartezzini, 2010; Axarli and Meresi, 2008). A longitudinal approach using the questionnaire has been conducted to clarify the relationship between occupants, buildings, and perceived physical environmental conditions in the current study. The occupants’ subjective responses were compared with the physical measurements to evaluate the buildings’ lighting conditions. The questionnaire aimed to investigate the staff’s sensation and satisfaction levels in terms of the indoor environment. Occupants have different lighting preferences according to their sensitivity and character (Chraibi et al., 2016), which are considered for evaluating the lighting environment. Therefore, the questionnaire contains two parts: first general information about gender, age, type of work, and second, satisfaction and sensation on physical and environmental parameters (Table A1 and A2). The second part is classified as below:

- Perceived lighting level
- Occupants’ satisfaction with lighting
- Occupants’ tendency to change the amount of light
- Occupants’ rating of lighting distribution
- Light source preferences
- Preferred kind of space

A five-point Likert scale is used to quantify the occupants’ satisfaction levels with environmental conditions. The Likert scale is one of the most common ranking scales applied in lighting researches (Moore et al., 2002). The paper questionnaires were in Persian, and a summary of the English translation is presented in Appendix A. The numbers assigned for the Likert scale in the Appendix for very little, little, average, much, too much have assumed as 1,2,3,4,5, respectively. As shown in Appendix A, other data collected from the environment are related to building and room characteristics such as building type, floor level, and window orientation. According to the answers given by occupants, on their preferences to decrease or increase lighting level, 15.1% of occupants prefer very little increase and 30.3% prefer very slight decrease of lighting level; 24.2% little increase and 28.9% little decreases of lighting level; 24.4% and 21.6% selected average level of change; 29.7% much increase and 4.1% much decreases of lighting level; and 6.7% very much increase and 4.1% much reductions of lighting level.

2.3. Data analysis

The collected data through measurement and survey contain different kinds of information on a different scale (nominal, ordinal, and interval scale). For instance, the physical measures such as illuminance are interpreted as an interval scale, the response scales of the questionnaire were a 5-point scale (“very little” to “very much”) is taken as an ordinal scale. In contrast, other response scales in questionnaires, such as gender are nominal. Due to the diversity in the data scale, different tests have been used to analyze statistical data (Cramer and Howitt, 2004). Statistical analysis was performed using the IBM SPSS Statistics version 25.0 (SPSS Inc. Chicago, IL, USA).

Data analysis consists of three steps. First, the relationship between temperature and visual perception and overall satisfaction of the environment is studied. The second step is to define the lighting comfort level. This step involves two sections. The first is to determine whether there is a significant correlation between the illuminance level and the occupants’ satisfaction level with the illumination. The second is to define the lighting comfort zone. In this section, illuminance levels measured at the field are assorted into eight different levels to determine the acceptable range of illumination. To achieve a more precise comfort range, illuminance was classified into 14 groups. In the third step, a statistical analysis is conducted to determine the relationship between occupants’ subjective satisfaction with daylight and the
factors affecting the desired lighting level, which is defined in the previous step. An ANOVA test was used to assess the impact of individual parameters such as age, gender, etc., on a nominal scale (Chellappa et al., 2017, 2017). Spearman rho-correlations are appropriate for defining correlation among environmental parameters in ordinal scale and subjective responses (Zhang et al., 2019; Krüger et al., 2018; Andargie and Azar, 2019).

The Spearman rank correlation coefficient was applied for quantitative variables. The Spearman rank correlation coefficient is a non-parametric measure that assesses statistical dependence between two variables using a monotonic function to describe the relationship between them (Field, 2017; Xue et al., 2014). Paired t-test for visual and thermal satisfaction in winter and summer and linear regression to assess different factors that have an impact on the visual perception responses are applied. The last part is to investigate staff satisfaction with the lighting and thermal conditions. For this step, it is appropriate to use descriptive analysis for the mean value and standard deviation of occupants’ comfort perception and the environmental factors (Zhang et al., 2019). It is worth mentioning that the comparison of satisfaction level of lighting was separately made according to the window orientation, type of building, season, and space adjacencies.

3. Results of the occupant’s survey

3.1. Step 1

The measured illumination at the desk level is presented in Fig. 3a. The highest illumination was 1298 lx in summer and 1150 lx in winter. The minimum illumination was 77 lx in summer and 35 lx in winter, and the mean illumination levels were 472.64 lx in summer and 470.21 lx in winter. In Fig. 3b, the measured indoor air temperature based on time of day and season is presented. The highest air temperatures were 33 °C and 29 °C, and the lowest was 17 °C and 21 °C in summer and winter, respectively. The mean indoor air temperature in summer and winter was 25.3 °C. Fig. 3c shows the indoor relative humidity, which is 17.9%–55.1% in summer with a mean of 34.7% and 17.2%–26.5% in winter with a mean of 25.8%. To determine if there is any relationship between the perception of the thermal and visual conditions and the space’s overall perception, Spearman correlation has been applied, and results are shown in Table 2. The 136 participants have filled out the questionnaire in the morning, 244 participants at midday, and 129 participants in the afternoon.

As shown in Fig. 3a, the total illumination of combined natural and artificial light in winter increase during the hours of the day. The illumination in the morning in summer is more than that in winter. Still, in the morning and afternoon, the illumination in winter is higher than in the summer (these values are measured in rooms with different window orientations and do not necessarily reflect the pattern of illumination during the day). The measured indoor air temperature, in the midday and during the afternoon in summer, is higher. Still, in the morning, the air temperature in winter is higher than in the summer due to heating and cooling equipment. The relative humidity is generally higher in summer than in winter.

Spearman correlation has been used to compare the occupants’ sensation of thermal and visual conditions with the environment’s overall satisfaction. According to Table 2, there is a meaningful correlation between occupants’ responses to thermal and visual requirements and overall satisfaction in office spaces.

3.2. Step 2

To find the acceptable range of illumination, it is essential to investigate a significant correlation between occupants’ subjective satisfaction toward the lighting condition and the illumination level. For this purpose, the Spearman correlation has been applied (Bluysen et al., 2018). As shown in Table 3, a statistically significant relationship exists (p-value<0.05) between lighting and thermal satisfaction and illumination level. Besides, linear regression is carried out to identify the determination coefficient ($R^2$) (Jakubiec et al., 2021). The correlation between illumination level and lighting satisfaction ($R^2 = 0.258$) is moderate, while for illumination level and thermal satisfaction correlation ($R^2 = 0.015$), indicating a very low correlation (Ferguson, 2009). So, illumination level has a very low impact on thermal satisfaction (Fig. 4).

As the illumination level significantly affects occupants’ satisfaction, it could be examined whether there is an optimal range for lighting comfort in office spaces. To investigate the acceptable range for the lighting level, the measured illumination is categorized into individual levels. So, the collected values, which were on an interval scale, have been converted into the ordinal scale. For this purpose, the measured lighting level was classified into eight ranges. The values of less than 300 lx are in the first category, higher than 900 lx are in the last category, and the values between these are classified into 100 lx intervals. Then, to determine the more precise range, the values were classified into 14 categories in the 50 lx range (Fig. 5).

The highest satisfaction from the environmental lighting level is provided in the illumination range of 600–700 lx. The illumination more than this range results in more satisfaction compared to lower ranges of lighting. Fig. 5 shows that occupants were more satisfied by the illumination above 550 lx, and illumination between 600 and 650 lx provides the highest satisfaction levels. Thus, there is an optimal range of satisfaction with lighting level, and the most preferred lighting comfort range for these office spaces is 600–650 lx. But the illumination above 550 lx is acceptable for most of the occupants.

3.3. Step 3

In this step, the influence of individual variables on occupants’ response to lighting conditions was first examined. ANOVA analysis was processed between individual variables as independent and perceived lighting as the dependent variable to test the effect of distinct groups (such as different age groups) on visual perception (Rockcastle et al., 2017). The relationships between occupants’ lighting comfort perceptions and nominal physical parameters such as type of building and opening adjacencies (one or two windows to the outside, window to the atrium, or
rooms without window) were determined by ANOVA ordinal parameters using bivariate correlations.

ANOVA analysis results indicated that the response to the lighting condition varies according to the occupants’ age group and their work type (Table 4). It is worth mentioning that there is no significant difference in lighting comfort range between male and female groups and different working hours during the day and presence duration in the office space, as indicated by a deficient value of F (Ferguson, 2009) and having the \( p > 0.05 \).

To define the acceptable lighting level based on the participant’s age, first, occupants are divided into four groups based on their age: under 30, between 30 and 39, between 40 and 49, and above 50 years old. Then the mean satisfaction level of lighting on their desk is calculated, which is presented below:

- Under 30 years old, 716 lx,
- between 30 and 39, 582 lx,
- between 40 and 49, 456 lx,
- above 50 years old, 467 lx.

The results show that the older occupants prefer a lower illumination rate.

Table 5 represents the relationship between the lighting comfort and the type of lighting source by the Spearman rank correlation coefficient. The lighting source includes daylight, artificial lighting, and a combination of both. In all three cases (\( p\text{-value} < 0.01 \)), there is a meaningful relationship between the source of light and people’s satisfaction. Based on the correlation coefficient, there is a stronger relationship between employees’ satisfaction with both lighting sources compared to only natural or artificial lighting (correlation coefficient of 0.52). Among the natural and artificial lighting, the correlation coefficient between the level of satisfaction and daylighting (correlation coefficient of 0.48) is higher than the artificial lighting (correlation coefficient of 0.29). Thus, both natural and artificial lighting sources are more effective on the occupants’ lighting comfort than natural or artificial lighting alone.

Comparing people’s response to illumination and temperature in different seasons determines the season’s effect on people’s perception of these two factors (Table 6). In general, 23.1% of people were dissatisfied with the lighting level, while people’s dissatisfaction was 27.3% with ambient air temperature.

Most studied rooms and participants who filled out the questionnaire in winter were the same as the summer. Therefore, different subjective perceptions caused by season should be analyzed to compare the occupant’s perception in winter.
A paired-samples t-test is conducted to compare the satisfaction ratings for both conditions. Table 6 shows the t-test result for both thermal and visual satisfaction for the effect of the season on occupants' satisfaction. It shows that the season affects the sensation of visual and thermal satisfaction. Since the season affects occupants’ perception of light, Fig. 6 shows the mean and standard deviation of the occupants’ perception concerning the light level and air temperature in summer and winter to compare satisfaction level of lighting in these seasons. The mean and standard deviation of light satisfaction in winter is higher than in summer (3.1 ± 0.95 for winter, 2.8 ± 0.7 in summer). This may happen due to the simultaneous effect of sunlight and heat in space throughout the summer. In summer, the mean and the standard deviation of satisfaction with temperature is higher than in winter (2.6 ± 0.89 for summer, 2.3 ± 0.82 for winter). This means that the satisfaction with lighting level in winter and summer is higher than temperature satisfaction because it was already satisfactory. The satisfaction of the light level in winter is more than that in summer, while the satisfaction with the ambient air temperature in summer is higher.

The available daylight available in a room is proportional to the amount of light the window receives, depending on how heavily obstructed it is. The external obstruction is the angle between the normal normal to the glazing center and the line intercepting the building or tree’s edge (Lo et al., 2017; British Standards Institution, 2007). The obstruction angle in the studied buildings is divided into five intervals which depend on the floor on which the room is located. So, in the same building, obstruction varies in the studied rooms. In building A, the obstruction level for the studied rooms was mostly 2, while in buildings B, C, D, E, and F, the obstruction levels were mostly 2, 3, 3, 2, 2, respectively.

The linear regression is used to assess whether the obstruction level and the floor affect the visual perception responses. The linear regression for the correlation between obstruction level and lighting satisfaction shows that $R^2 = 0.015$, and for obstruction level and visual satisfaction correlation, $R^2 = 0.018$, which means the correlations are very low. So, the room’s floor and obstruction level makes not much difference to occupants’ satisfaction with lighting.

The evaluation of other environmental parameters’ effect on the visual satisfaction of occupants (Table 7), shows a significant correlation between occupants’ lighting satisfaction and type of the building, window orientation, and openings adjacencies, that influence people’s lighting comfort.
The mean and standard deviation of occupants' comfort ratings have been analyzed using the descriptive analysis to investigate staff satisfaction with lighting and temperature. Here, the parameters that have a significant relationship with occupants' comfort are examined to determine each group's impact (each building, window orientation, etc.) on employees' satisfaction. Fig. 7a shows the mean and standard deviation of the user's satisfaction with ambient air temperature and lighting level are based on the studied office windows' orientation. The higher satisfaction with these two parameters in spaces without windows (2.81 ± 0.73) is minimum. Satisfaction with the temperature in windowless spaces is the highest (2.83 ± 0.96), and the minimum temperature satisfaction level is in space with west-oriented windows (2.44 ± 0.85) (Fig. 8).

Fig. 7b shows the mean and standard deviation in the occupants' perception of light level and air temperature in different adjacencies. The mean and standard deviation of both lighting and temperature satisfaction in rooms adjacent to the atrium on one side with one window on the other side is the highest (3.45 ± 1.14 for lighting level satisfaction, 3.16 ± 0.81 for satisfaction with temperature), and in spaces without any windows, mean and the standard deviation of satisfaction with temperature and lighting level is the lowest (2.54 ± 0.94 for lighting, 2.42 ± 0.85 for temperature).

Fig. 7c shows the mean and standard deviation of the occupants' satisfaction with each building's office spaces' lighting and thermal conditions. The mean and standard deviation of satisfaction from building B's lighting environment (3.14 ± 0.95) is higher than the other buildings, and the lowest satisfaction is in building F (2.79 ± 0.82). Satisfaction with building A's temperature is the highest (2.8 ± 0.72), and the minimum satisfaction level is in building F (2.44 ± 0.85). Thus, it could be concluded that people's satisfaction with temperature and lighting varies based on different buildings.

Table 7 ANOVA analysis of physical variables and subjective comfort evaluations.

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<td>2.499</td>
<td>3.693</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Bold signifies correlation is significant at the 0.05 level (2-tailed).

4. Discussions

In this study, the occupants' response to illumination level suggests that lighting levels between 600 and 650 lx in office spaces could lead to a visually comfortable condition for most occupants. This is in line with an earlier study by Kim and Kim (2007) in which the task illumination in Michigan should not be less than 650 lx. However, in the Netherlands, people prefer to have an average of 800 lx at desk height (Boubekri, 2008). In France, the desk's preference for lighting level is 300–600 lx (Escuyer and Fontoymont, 2001). In Oakland, it is desired to raise the lower bound of illuminance range from 510 to 560 lx (Vine et al., 1998). In Hong Kong, the average lighting level of 518 lx leads to 86% of users' acceptance; however, if the illuminance level is more than 750 lx, 96% of office occupants would be satisfied (Mui and Wong, 2011). In Italy, a study showed that with a maximum of 413 lx, 74% of occupants confirmed to have neutral visual sensation (Castaldo et al., 2017). It can be concluded that people's preferences for lighting levels are not the same in different countries and cities. This variation among acceptable ranges could depend on climate and culture (Boyce, 2003; Nicol et al., 2006), the function of building, and architecture (Tregenza and Wilson, 2011).

There are some essential points in this study worth mentioning.

- In this study, the measurement was done in the summer and winter because of the field study limitations. The further measure needs to be performed to discuss the results better. Many questionnaires were completed in different environments and in two seasons, which could provide useful information.
- The effort was to select the spaces and participants in the winter the same as summer. But for some reasons, such as employees leave of absence from the work or limited access to some spaces, in some cases, it was not possible to repeat the study in the same conditions in some cases. We mention this as a limitation of our study. Around 64% of participants in winter were the same as the summer.
- Among the various physical parameters that affect visual and thermal comfort, only the illumination and temperature in this study are examined.
As this study was conducted only in six buildings, the result could be case-specific. Further studies could be helpful to generalize the findings and conclusion of the present study. Results show that illumination level has a very low impact on thermal satisfaction. As this study is a survey, and data collection was in the real office spaces. Many other parameters affect the correlation of these two factors; more studies are needed to investigate this correlation in a controlled room. Other affecting parameters controlled be constant.

5. Conclusions

In this study, employees’ visual and thermal comfort limits in Tehran’s various office spaces during winter and summer were investigated through field measurements. Measurements consisted of illuminance on work surfaces, air temperature, and relative humidity in offices in six buildings in Tehran. The analysis of these measurements leads to the following conclusions:

- The measured desktop illuminance was between 77 and 1298 lx in summer and 35–1150 lx in winter. The highest air temperature was 33 °C, and the lowest was 17 °C. The mean air temperature in summer and winter was 25.3 °C. The indoor relative humidity was 17.2%–55.1%, with a mean of 34.7% in summer and 25.8% in winter.
- There is a meaningful correlation between occupants’ response to thermal and visual conditions and overall satisfaction in office spaces. It means that the overall comfort highly depends on the visual and thermal comfort of occupants. But the overall comfort depends more on the thermal situation than the lighting level.
- According to the linear regression, the correlation between illumination level and lighting satisfaction is moderate. To define an acceptable range for illumination, the satisfaction level in each illumination range is assessed. The comparison between lighting ranges shows that occupants were more satisfied by the illumination above 550 lx, and illumination between 600 and 650 lx provides the highest satisfaction.
- There is a significant correlation between occupants’ lighting satisfaction and season (season affects the sensation of visual and thermal satisfaction).
- Type of building, window orientation, and openings adjacencies are other environmental factors that impact visual comfort. External obscurations and the floor level do not correlate substantially with the occupants’ lighting satisfaction.
- Both natural and artificial lighting sources are more effective in the occupants’ lighting comfort than daylighting. While artificial lighting as the only lighting source is not acceptable by the occupants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Appendix A. Questionnaire

<table>
<thead>
<tr>
<th>Table A1</th>
<th>Summary of the survey questionnaire.</th>
</tr>
</thead>
</table>

### Section A- Demographics

<table>
<thead>
<tr>
<th>Overall</th>
<th>age</th>
<th>sex</th>
<th>Right hand/left hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kind of work</td>
<td>Paper-based</td>
<td>With computer</td>
<td>Both of them</td>
</tr>
<tr>
<td>Working hours</td>
<td>&gt; 8 hours</td>
<td>7-8 hours</td>
<td>4-6 hours</td>
</tr>
</tbody>
</table>

For how long you have been working in this room (in a month)?

<table>
<thead>
<tr>
<th>Visual problems</th>
<th>Do you sometimes have a severe headache?</th>
<th>Do you have light sensitivity?</th>
<th>Do you use glasses?</th>
</tr>
</thead>
</table>

### Section B- Lighting perception

<table>
<thead>
<tr>
<th>Perceived lighting level</th>
<th>Please specify the overall assessment of the lighting level in your office:</th>
</tr>
</thead>
<tbody>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>How do you assess the lighting level at your desk height?</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>How much is the lighting level of the scene when you look frontward?</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>When you look at your right side, how much is the lighting level of the scene?</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>When you look at your left side, how much is the lighting level of the scene?</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Satisfaction of lighting</th>
<th>Please rate your satisfaction with the room lighting:</th>
</tr>
</thead>
<tbody>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>Please rate your satisfaction with lighting when working with a computer:</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>Please rate your satisfaction with lighting when writing/reading a paper:</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
</tbody>
</table>

### Section C- Thermal perception

<table>
<thead>
<tr>
<th>The tendency to change the amount of light</th>
<th>What is your desire to increase the amount of light?</th>
</tr>
</thead>
<tbody>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>What is your desire to reduce the amount of light?</td>
<td></td>
</tr>
<tr>
<td>very little</td>
<td>little</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lighting distribution</th>
<th>Please rate your satisfaction with lighting distribution throughout the room:</th>
</tr>
</thead>
<tbody>
<tr>
<td>very little</td>
<td>little</td>
</tr>
<tr>
<td>Light source preferences</td>
<td>Which one of these lighting sources do you prefer?</td>
</tr>
<tr>
<td>Daylighting</td>
<td>Artificial lighting</td>
</tr>
</tbody>
</table>

### Section D- Other activities

<table>
<thead>
<tr>
<th>Other activities</th>
<th>Both of them</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper-based</td>
<td>With computer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>About the work</th>
<th>Kind of work</th>
<th>Paper-based</th>
<th>With computer</th>
<th>Both of them</th>
<th>Other activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working hours</td>
<td>&gt; 8 hours</td>
<td>7-8 hours</td>
<td>4-6 hours</td>
<td>&lt; 4 hours</td>
<td></td>
</tr>
</tbody>
</table>
Table A2  Building and room data.

<table>
<thead>
<tr>
<th>Building name:</th>
<th>Building type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>Building B</td>
</tr>
<tr>
<td>Building C</td>
<td>Building D</td>
</tr>
<tr>
<td>Building E</td>
<td>Building F</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date:</th>
<th>Floor level</th>
<th>Window orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;3</td>
<td>North</td>
</tr>
<tr>
<td>Time:</td>
<td>3-6</td>
<td>South</td>
</tr>
<tr>
<td></td>
<td>6-9</td>
<td>West</td>
</tr>
<tr>
<td></td>
<td>9-12</td>
<td>East</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No window</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjusted to atrium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>External obstructions</th>
<th>Almost much</th>
<th>Much</th>
<th>A half</th>
<th>Little</th>
<th>Almost none</th>
</tr>
</thead>
</table>

References


Boyce, P.R., 2003. Human Factors in Lighting, third ed.


