The Implementation of Visual Comfort Evaluation in the Evidence-Based Design Process Using Lighting Simulation

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Abstract: Validation of the EBD-SIM (evidence-based design-simulation) framework, a conceptual framework developed to integrate the use of lighting simulation in the EBD process, suggested that EBD’s post-occupancy evaluation (POE) should be conducted more frequently. A follow-up field study was designed for subjective–objective results implementation in the EBD process using lighting simulation tools. In this real-time case study, the visual comfort of the occupants was evaluated. The visual comfort analysis data were collected via simulations and questionnaires for subjective visual comfort perceptions. The follow-up study, conducted in June, confirmed the results of the original study, conducted in October, but additionally found correlations with annual performance metrics. This study shows that, at least for the variables related to daylight, a POE needs to be conducted at different times of the year to obtain a more comprehensive insight into the users’ perception of the lit environment.

Keywords: building performance simulation; lighting simulation; lighting quality; visual comfort; office field study; evidence-based design

1. Introduction

In the field of architecture, evidence-based design (EBD) is defined as the process of basing design decisions about the built environment on credible research and learning from previous evidence to achieve the best possible outcomes [1,2]. One of the easiest, quickest, and inexpensive methods to provide evidence for predicting or evaluating values in a built environment is using computational modeling. In a framework for evaluating evidence in EBD developed by Pati [3], computer simulation is categorized under ‘experiment level’, which confirms the application of simulation for providing evidence. For example, in the study by Jakubiec and Reinhart [4], simulation tools were used for the prediction of occupants’ visual comfort within daylit environments. The results illustrated that it is possible to use current simulation-based visual comfort predictions to predict occupants’ long-term visual comfort assessments in a complex daylit space.

Investigation regarding the application of simulation tools in the EBD process is ongoing [5–9]. A conceptual framework was developed to integrate the use of lighting simulation within the EBD process in a systematic way: the EBD-SIM framework [6]. The study concluded that the translation between the user evaluation and the simulation-based evaluation was a critical step in the integration of lighting simulation with EBD. Therefore, an initial validation study [7] was dedicated to a first application of the EBD-SIM framework in a post-occupancy evaluation (POE) step.

POE is defined as ‘the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time’ [10] (p.3). POE’s purpose and methodology are varied, often depending on the type of building. For example, POEs of office buildings are, in most cases, interested in occupants’ comfort and productivity, utilizing both subjective and objective evaluations of indoor environmental quality (IEQ) [11]. The recent literature review conducted by Dam-Krogh et al. [12] investigated
methods applied in previously performed POEs in office buildings with special attention to IEQ and productivity to compare and evaluate successful practices of POEs in office buildings. In more specific and recent POE studies, lighting quality of office buildings was investigated by [13–17]. These studies were concerned with obtaining better insight on occupant satisfaction and acceptance about daylighting by conducting POEs while using photosensors, shading, and/or control systems. This is a key factor for proper lighting design by utilizing daylighting without neglecting human comfort and achieving responsive buildings. Having more information available about occupants’ behaviors, needs, and preferences enables architects to design better responsive elements of a building for optimal rates, scales, and types of changes.

While POEs are popular tools for the evaluation of different aspects of building from the occupant’s point of view, most POEs are one-off studies [11]. Additionally, using POEs in a framework of EBD is not studied well (yet). One attempt to strengthen the EBD knowledge base by developing standardized POE tools was conducted by [18]. In this study, based on a review of over 100 research publications, a conceptual framework and a set of standard tools were established to comprehensively evaluate building performance in terms of eight key design areas, including air quality, visual environment, thermal comfort, acoustic environment, hazardous materials, conservation of resources, overall climate response, and building envelope (façade).

A real-time case study in a fully operational office building was conducted to analyze visual comfort from a subjective (‘the user’) and an objective (‘the simulation’) point of view to provide a systematic performance evaluation using the EBD-SIM framework [7]. It covered both long-term and short-term evaluations of the light environment. The results showed that, although illuminance preference varies significantly among individuals, there was a positive correlation between the overall lighting quality perceived by the occupants and the amount of light on the task area. Regarding performance metrics, the results showed the highest correlation with point-in-time horizontal illuminance ($E_h$), especially on the task area ($E_{h\text{-task}}$) and human perception. The implementation of the study results in the EBD-SIM process model is schematically illustrated in Figure 1.

**Figure 1.** Study results [7] implementation in the EBD-SIM model addressing the workflow during the post-occupancy evaluation steps.

The initial validation study [7] suggested that a POE should be conducted more frequently to obtain a better insight into user perception of daylight and, subsequently, the use of the new evidence to improve the design of the EBD-SIM model further. Therefore, the field study was repeated to perform a POE for a second time, including the same
participants but at a different time of year to investigate the possible improvement in the reliability of a POE study (within-subjects study [19]). In addition, a larger sample with a similar procedure was selected in which users experienced only one condition each (between-subject-study [19]) to investigate if previous findings are confirmed with a larger sample or that results are just a coincidence and more detailed simulation of the actual/intended use of a space is required to forecast the visual comfort.

Even though a long-term goal is to show how the EBD-SIM framework can be used to incrementally develop evidence through several projects, the research questions for this project were as follows:

1. How do the most frequently used visual comfort metrics correlate with perceived occupant visual comfort?
2. To what extent do instantaneous and annual human visual comfort perceptions correlate with simulated comfort assessment?
3. How much would the usefulness of a POE improve if its frequency were increased?

Note that the first two questions are repeated from the preceding study [7], though with a larger sample. The most frequently used visual comfort metrics were identified based on the state-of-the-art literature review conducted by [7].

The third question was added specifically for the follow-up POE study.

2. Materials and Methods

2.1. Research Design

A study in a fully operational office building focusing on visual comfort analysis was conducted to explain the application of the EBD-SIM framework in the POE step. Objective data were collected via computational modeling and subjective data by using an online questionnaire. Calculated performance metrics and questionnaire results were collected similarly to the previous study [7]. Previously collected data were included in the study as part of the repeated measures method.

2.2. Procedure

At first, the physical environment was modeled, and performance metrics were calculated. The simulation results were compared against a limited and randomized set of illuminance measurements in the real building to check if they were in the same range. The results showed a difference between simulated and real values of 20 ± 11%, which is within normal variability levels for simulated objects [20]. Secondly, using an online questionnaire, occupant characteristics were recorded, and their feedback regarding visual comfort was gathered. Finally, user feedback and simulation output were compared. This comparison was performed to investigate how metrics measured by simulation tools (to assess visual comfort) correlate with actual visual comfort perceived by the users, and to answer the research questions. The first sample of the population (N = 15) filled out the questionnaire in October, and the second sample of the population (N = 46) filled it out in June. For N = 10 of these people, all working in one wing of the survey location, the questionnaire was a repetition. In total, N = 51 unique people participated in the study, which means, in total, N = 61 complete survey results were gathered.

An overview of the three research questions and the results of the comparison between POE and the performance metrics (PM) for different groups of participants at different data collection moments is illustrated in Figure 2.
2.3. Site

The study was carried out in a four-story academic building (with a basement) located in Jönköping, Sweden (lat. 57.778168° N, long. 14.163526° E). To the left and right of the building are buildings of comparable height. Physical data were collected from 51 private office rooms on the second, third, and fourth floors. Most of the rooms are approximately 15 ± 5 m² and are furnished mainly by a large desk, a chair, and one or more bookshelves. The rooms have windows in the north-east (21), south-west (19), north (9), and south-east orientations (7). Three rooms on the north-east and south-west side have a second window in the same direction. Five rooms on the south-west side have a second window on the south-east side. The number of rooms with two windows is highlighted in the parenthesis in Table 1. The size of the windows on the second floor on the north-east side is one third larger compared to that on the third and fourth floors. There is permanent solar shading at the building’s south and south-west sides (see Figure 3). All rooms are equipped with conventional suspended luminaires and were used according to the users’ needs during the survey, but they were not modeled nor further included in the study.

Table 1. Number of rooms based on the location of the windows; rooms with two windows are shown within parenthesis.

| Window Location       | Frequency | Percentage |
|-----------------------|-----------|------------|
| North-East (NE)       | 21(3)     | 41.2       |
| South-West (SW)       | 14(3)     | 37.3       |
| North (N)             | 9         | 17.6       |
| South-East (SE)       | 7(5)      | 3.9        |
| Total                 | 51        | 100        |
2.4. Survey Participants

Occupants of four wings of the building were invited to participate in the survey. They were all academic employees whose work involves research and teaching/education, mainly using computers. The invitation email was sent to 150 people, of which 61 people (39 male/22 female, average age 45 ± 20 years) responded (response rate 40.7%). For \( N = 36 \) participants, this was the first time they filled out the survey; \( N = 15 \) people answered during the first study in early October [7], and \( N = 10 \) of this group participated for the second time in this study, see Table 2. (in parenthesis: the respondents who were inquired twice). Most participants in this study worked for more than one year in their current office room, and more than half of the participants (\( N = 36 \)) reported wearing vision aids (near vision = 13, distance vision = 10, both = 11, trifocal = 1, other = 2).

Table 2. Number of respondents per floor and wing—within parenthesis: the respondents who were inquired twice.

| Floor | Wing 1 | Wing 2 | Wing 3 | Wing 4 | Total |
|-------|--------|--------|--------|--------|-------|
| Floor 2 | 12 (5) | 4 | 3 | 4 | 23 |
| Floor 3 | 16 (5) | 4 | 2 | 8 | 30 |
| Floor 4 | 1 | 1 | 2 | 4 | 8 |
| Total | 29 | 9 | 7 | 16 | 61 |

2.5. Performance Metrics for Visual Comfort

Seven currently used performance metrics for visual comfort were obtained, including five metrics related to illuminance values (\( E_{v\text{-eye}}, E_{h\text{-room}}, E_{h\text{-task}}, \text{Daylight Autonomy DA}, \text{Spatial Daylight Autonomy sDA} \)) and two glare indicators (Daylight Glare Probability DGP, Annual Sunlight Exposure ASE), see Table 3. Further details are explained in [7].
Table 3. Collected visual comfort metrics (daylighting).

| Criteria | Metrics | Time |
|----------|---------|------|
| **Illuminance (under CIE Standard Clear Sky, CIE Intermediate Sky, and CIE Standard Overcast Sky)** | Mean/maximum/minimum illuminance value on the task area (Eh-Task) | Moment |
| | Mean/maximum/minimum illuminance value on room surface (Eh-Room) | Moment |
| | Vertical eye illuminance (Ev-eye) | Moment |
| | Daylight Autonomy (DA) | Annual |
| | Spatial Daylight Autonomy (sDA) | Annual |
| **Glare (under CIE Standard Clear Sky, CIE Intermediate Sky, and CIE Standard Overcast Sky)** | Daylight Glare Probability (DGP) | Moment |
| | Annual Sunlight Exposure (ASE) | Annual |

2.6. Simulation Model

The building was modeled in Autodesk Revit. For detailed daylight analysis, the model was exported to Rhinoceros 3D to perform lighting analysis with the DIVA plugin. In addition to the simulated building wing, direct surroundings were also modeled to consider potential shading. The material properties and simulation parameters used for the calculations are described in Table 4.

Table 4. Material properties and simulation parameters.

| Material | Reflectance/Visible Light Transmittance (Tvis) in % |
|----------|---------------------------------------------------|
| Walls    | White interior wall 70%                           |
| Floor    | Generic floor 20%                                 |
| Ceiling  | Generic ceiling 70%                               |
| Desk     | Generic furniture 50%                             |
| Glazing  | Glazing double pan 80%                            |
| External Shading | Metal sheet                             |
| Surrounding Building | Outside faced 35%                               |
| Ground   | Outside ground 20%                                |

| Simulation Parameters for Daylight Autonomy |
|---------------------------------------------|
| Weather Data | Goteborg—Landvetter Airport, Sweden |
| Occupancy Schedule | 8–18 with Daylight Saving Time (DST) 60 min 300 lux |
| Target Illuminance | -ab2 -ad 1000 -as 20 -ar 300 -aa |
| Radiance Parameters | Grade sensor—750 mm above 450 mm distance |
| Sensor Density | No automated shading |
| Shading | No electric lighting |
| Electric Lighting | No electric lighting |

For each workplace area on the second, third, and fourth floors, a grid of $1.45 \times 1.45 \text{ m}$ at workplace height ($h = 0.75 \text{ m}$) was used to calculate the mean, minimum, and maximum horizontal illuminance under CIE Standard Clear Sky, CIE Intermediate Sky, and CIE Standard Overcast Sky conditions [21]; for the rest of the paper, these are referred to as ‘clear’, ‘overcast’, and ‘intermediate’ sky conditions. The same setting was applied for the room area of each room for horizontal illuminance ($E_{h-room}$), ASE, and DA calculations. One point in the middle of each room with a viewing direction towards windows was selected for the vertical eye illuminance ($E_{v-eye}$) and DGP calculations under clear, intermediate, and overcast sky conditions. As the questionnaires were filled out in early October and early June, a day in early October (11) and early June (4) was chosen for the simulation to have a comparable day length and sun path. In total, 67.2% of the questionnaires were filled out in the morning; hence, for the simulation, a time in the morning was selected (10 a.m.).
2.7. Questionnaire

The questionnaire was a web-based form in English to collect feedback regarding the visual comfort perception of office occupants. It contained questions regarding office characteristics, satisfaction with the lit environment in general (‘annual’), satisfaction with the lit environment at the time of response (‘momentary’), user preferences, and personal information. For 15 satisfaction variables of the lit environment ‘in general’ (annual) and ‘at the time of response’ (momentary), a 7-point Likert satisfaction scale [22] was used (1 = very satisfactory to 7 = very unsatisfactory). All variables were included in the analysis, see Table 5.

Table 5. Description of the variables included in the analysis with their variable name. Satisfaction variables are all on a 7-point Likert scale (1 = very satisfactory to 7 = very unsatisfactory).

| Variable Description                                  | Variable Name |
|-------------------------------------------------------|---------------|
| Momentary                                             |               |
| Satisfaction with light at the desk area               | Light desk    |
| Satisfaction with natural light (daylight)             | Natural       |
| Satisfaction with artificial (electric lighting)       | Artificial    |
| Satisfaction with glare from sunlight                 | Glare sun     |
| Satisfaction with glare from artificial lighting      | Glare artificial |
| Satisfaction with lighting quality                    | Lighting quality |
| Annual                                                |               |
| Satisfaction with light at the desk area               | A-Light desk  |
| Satisfaction with natural light (daylight)             | A-Natural     |
| Satisfaction with artificial (electric lighting)       | A-Artificial  |
| Satisfaction with glare from sunlight                 | A-Glare sun   |
| Satisfaction with glare from artificial lighting      | A-Glare artificial |
| Satisfaction with lighting quality                    | A-Lighting quality |
| Satisfaction with the view to outside                  | A-View        |
| Satisfaction with overall indoor environmental quality (i.e., thermal, acoustic) | A-IEQ |
| Satisfied with job                                    | A-Job         |

2.8. Analysis

The correlation of all 15 satisfaction variables as well as the correlation among these variables with seven groups of performance metrics was explored by calculating Pearson correlation coefficients using IBM SPSS Statistics 24. To determine whether there is statistical evidence that the mean difference between paired observations on a particular outcome is significantly different from zero, a paired sample t-test was run for ten participants who filled out the questionnaire two times during early October and June. Only significant correlations are reported.

3. Results

In this section, the objective, subjective, and correlation analysis of the follow-up POE study for ten participants who filled out the questionnaire two times during early October and June as well as the larger sample (N = 46) who filled out the questionnaire only once in June is reported.

3.1. Within-Subject Analysis (Follow-Up POE Investigation)

3.1.1. Objective Comparison

1. Horizontal illuminance on a room area ($E_{h\text{-room}}$)—The overview of the results for the mean value of horizontal illuminance $E_{h\text{-room}}$ of the calculated sensor points of the ten rooms’ areas at the work plane height is shown in Figure 4a,b. Where the mean $E_{h\text{-room}}$ values in October were below 200 lux for all sky conditions, the amount of daylight increased, as expected, during the second POE in June. On average, the rooms received 200 lux or more horizontal illuminance during June. Since the participants mostly worked under the clear sky condition, more details of the results for the clear sky condition are illustrated in the right image.
2. Horizontal illuminance on a task area (E\textsubscript{h-task})—Based on the position of the desk area in each room, the mean horizontal illuminance received on task area E\textsubscript{h-task} was calculated. As presented in Figure 4c,d, on average, the amount of daylight received at the task area in June was approximately 100 lux higher compared to October. Under the clear sky condition, the areas received, on average, 300 lux with a variation between 100 and 800 lux (see Figure 4d).

3. Vertical eye illuminance (E\textsubscript{v-eye})—Vertical eye illuminance E\textsubscript{v-eye} was calculated at the center point of each room with a viewing direction towards the daylight opening. The results of E\textsubscript{v-eye} under three different sky conditions are illustrated in Figure 4e.

4. Daylight Autonomy (DA) and Spatial Daylight Autonomy (sDA)—The highest value for DA was found for the rooms on the second floor, with an average of 44 ± 8%. The rooms on the third floor at the north-east side had DA values around 29 ± 3%, and the south-west side had the lowest DA values around 2 ± 0.3%. sDA values of all rooms were lower than 50% of the space area.

5. Daylight Glare Probability (DGP)—The center point of each room with a direction towards windows was elected for DGP analysis. The results of this analysis show that, under the ‘clear’ sky condition, DGP values were in the range of intolerable glare (DGP > 0.45) for 70% of the rooms in October and for all the rooms in June. Under ‘overcast’ and ‘intermediate’ sky conditions, DGP values were below the ‘imperceptible’ level (DGP < 0.35) in October and at the ‘perceptible’ level (0.40 < DGP < 0.35) in June. The mean DGP values for the rooms under the three sky conditions are presented in Figure 5. The variations in DGP values under the clear sky condition are presented in the right image.

6. Annual Sunlight Exposure (ASE)—For all rooms, less than 10% of the areas had an illuminance value higher than 1000 lux/250 h per year, which means that, according to the LEED certification, the rooms are categorized as ‘a room with not too much direct sunlight during the year’ [23].

Figure 4. Cont.
Figure 4. Overview of the results for the mean value of (a) horizontal illuminance of the calculated sensor points of the ten rooms’ areas at the work plane height ($E_{h\text{-room}}$), (b) mean value of horizontal illuminance on the task area of the calculated sensor points of the ten rooms’ areas ($E_{h\text{-task}}$), and (e) mean value of vertical illuminance in the center point of each room with viewing direction towards the daylight opening of the ten rooms ($E_v$) under three different sky conditions for 11 October and 4 June both for 10 a.m. (a,c,e). The details of the mean values under clear sky condition (b,d,f).

Figure 5. (a) DGP values under clear sky (blue), overcast sky (red), and intermediate sky (green) conditions: imperceptible level ($DGP < 0.3$), perceptible level ($0.3 < DGP < 0.35$), disturbing glare ($0.35 < DGP < 0.4$), intolerable glare ($DGP > 0.45$); (b) The details of the mean values under clear sky condition.

3.1.2. Subjective Comparison

Descriptive statistics—Descriptive statistics analysis for all 15 satisfaction variables shows that the mean values of all variables except ‘Glare sun’ (satisfaction with glare from the sun at the moment) and ‘A-artificial’ (annual satisfaction with artificial lighting) were a bit lower for the second POE in June compared to October. On average, for the satisfaction values, the change was 0.4 points. This means people were more satisfied with the built environment in general in June (1 = very satisfactory, 7 = very unsatisfactory). Similarly, in October, the highest satisfaction belonged to ‘satisfaction with the job’, which increased slightly in June. Then, ‘satisfaction with daylight’ (both ‘annually’ and ‘at the moment’) had the highest satisfaction rate in June ($M = 3.5, SD = 1.58$). Satisfaction with daylight ‘at the moment’ with a 1.8 point improvement from October shows the highest increase in satisfaction. The least satisfaction in June belonged to artificial light ($M = 3.5, SD = 1.58$). See Table 6 for more details on other variables.

Paired samples t-test—To determine whether there is statistical evidence that the mean difference between paired observations on a particular outcome is significantly
different from zero, a paired sample t-test was run for ten participants who filled out the questionnaire two times during early October and June. The results show that, although the mean satisfaction values are increased from October to June for almost all variables, a significant difference was only found in scores for natural light from October to June (sig = 0.016, $M = 1.80$, $SD = 1.93$). In addition, a marginally significant difference was found for ‘A-Glare sun’ (sig = 0.052, $M = 0.50$ $SD = 0.71$) and ‘Light desk’ (sig = 0.053, $M = 0.80$ $SD = 1.13$).

Table 6. Descriptive statistics analysis of all 15 satisfaction variables (1 = very satisfactory, 7 = very unsatisfactory) of the first POE in October ($N = 10$) and the second POE in June ($N = 10$) of within-subjects study.

| Variable       | Mean ± Std. Deviation (October) | Mean ± Std. Deviation (June) |
|----------------|----------------------------------|------------------------------|
| A-light desk   | 3.5 ± 0.97                       | 3.2 ± 1.23                   |
| A-Natural      | 3.0 ± 1.33                       | 2.3 ± 0.48                   |
| A-Artificial   | 3.4 ± 1.17                       | 3.5 ± 1.72                   |
| A-Glare sun    | 3.4 ± 1.58                       | 2.9 ± 1.52                   |
| A-Glare artificial | 3.5 ± 1.65                | 3.0 ± 1.63                   |
| A-View         | 3.7 ± 2.58                       | 3.4 ± 2.50                   |
| A-Lighting quality | 3.5 ± 1.35               | 3.3 ± 0.95                   |
| A-Overall IEQ  | 3.3 ± 1.06                       | 2.8 ± 1.23                   |
| A-Job          | 2.1 ± 2.08                       | 1.9 ± 1.85                   |
| Light desk     | 3.9 ± 0.99                       | 3.1 ± 1.45                   |
| Natural        | 4.1 ± 1.73                       | 2.3 ± 1.50                   |
| Artificial     | 3.5 ± 0.97                       | 3.5 ± 1.58                   |
| Glare sun      | 2.6 ± 1.35                       | 2.9 ± 1.45                   |
| Glare artificial | 3.3 ± 1.70                  | 2.8 ± 1.62                   |
| Lighting quality | 3.5 ± 1.18                  | 3.0 ± 1.49                   |
| Valid N (listwise) | 10                                | 10                           |

Correlation analysis—The results show that there were ‘very strong’ ($0.8 < r < 1$) to ‘strong’ ($0.6 < r < 0.79$) degrees of correlations for all the variables between annual and at the moment evaluations except for ‘Natural light’ in October. In June ($N = 10$), the highest correlation was found for ‘Glare sunlight’ ($0.95$, $p < 0.01$) and ‘Glare artificial light’ ($0.92$, $p < 0.01$). This means that participants either perceived glare as similar all year round or found it hard to recall the difference between glare at the moment and annually.

3.2. Between-Subjects Analysis

All participants who responded to the survey in June ($N = 46$) worked in individual office rooms. These rooms are located on the second, third, and fourth floors of the building’s four wings. Based on the location of the window, these rooms are categorized into four groups which are presented in Table 7.

Table 7. Number of rooms based on the location of the windows—within parenthesis: the rooms with two windows.

| Window Orientation   | Frequency | Percentage |
|----------------------|-----------|------------|
| North-East (NE)      | 19(3)     | 41.3       |
| South-West (SW)      | 11(1)     | 23.9       |
| North (N)            | 9         | 19.6       |
| South-East (SE)      | 7(5)      | 15.2       |
| Total                | 46        | 100        |

There are three rooms at the north-east side and one room at the south-west side with two windows on the same side. Five rooms at the south-east side have a second window at the south-west side. These rooms are highlighted in parenthesis in Table 7.
3.2.1. Objective Evaluation Using Light Simulation

1. Horizontal illuminance in a room area (E_{h-room})—The overview of the results for the mean value of horizontal illuminance $E_{h-room}$ of the calculated sensor points of the room areas at work plane height is illustrated in Figure 6. On average, the rooms received more than 300 lux light under the clear sky condition. Since most of the rooms on the south-east side have two windows, they receive the highest value of illuminance compared to the others. There is no surrounding building on the north side; therefore, this side received the second highest values with low variance for all three sky conditions.

2. Horizontal illuminance in a task area (E_{h-task})—Based on the position of the desk area in each room, one sensor point was selected to calculate the horizontal illuminance incident on task areas. As illustrated in Figure 7, on average, the amount of daylight incident at the task areas is slightly higher compared to the mean illuminance value of the rooms under the clear sky condition.

3. Vertical eye illuminance (E_{v-eye})—In the center point of each room with a viewing direction towards the daylight opening, the vertical eye illuminance was calculated under three different sky conditions, and the results are illustrated in Figure 8.

4. Daylight Autonomy (DA) and Spatial Daylight Autonomy (sDA)—The rooms on the north sides had DA values with a mean of (67.2 ± 3.5)%. The rooms on the south-east side had a mean DA value of (63 ± 13)%. At the north-east side, the mean value of DA was around (31.5 ± 9)%. The south-west side had the lowest mean DA value of (20 ± 14)%. The average of sDA values of all rooms was lower than 50% of the space area, but there are a few rooms on the south-east side with sDA values of around 70%.

5. Annual Sunlight Exposure (ASE)—None of the rooms at the north-east, north, and south-west sides exceed 1000 lux for more than 250 h per year for more than 10% of the space area of each room. The mean value of ASE for the rooms at the south-east side, however, received more than 1000 lux for 243 ± 156.5 h in a year, which means that some of the rooms on this side are categorized as ‘rooms which receive too much direct sunlight during the year’ (USG) [23].

6. Daylight Glare Probability (DGP)—The center point of each room with a viewing direction toward the windows was selected for DGP analysis. The results of this analysis show that for all rooms under the ‘overcast’ and ‘intermediate’ sky conditions, the DGP value is below the ‘perceptible’ level (0.30 < DGP < 0.35). The DGP values under the clear sky condition for the rooms on the north-east, south-west, and south-east side are in the range of ‘intolerable glare’ (DGP > 0.45). For more details, see Figure 9.

Figure 6. Overview of the results for the mean value of horizontal illuminance of the calculated sensor points of the room areas at work plane height.
Figure 6. Overview of the results for the mean value of horizontal illuminance of the calculated areas: imperceptible level (DGP < 0.3), perceptible level (0.3 < DGP < 0.35), disturbing glare (0.35 < DGP < 0.4), intolerable glare (DGP > 0.45).

Figure 7. Comparison of the amount of daylight incident at the task area against the mean value of E_h-room.

Figure 8. The overview of the results for the mean value of vertical illuminance in the center point of each room with viewing direction towards the daylight opening of the ten rooms under three different sky conditions on 4 June at 10 a.m.

Figure 9. DGP values under clear sky (blue), overcast sky (red), and intermediate sky (green) conditions: imperceptible level (DGP < 0.3), perceptible level (0.3 < DGP < 0.35), disturbing glare (0.35 < DGP < 0.4), intolerable glare (DGP > 0.45).
3.2.2. Subjective Evaluation Using Questionnaires

Descriptive statistics—The sample of all participants in June (N = 46) shows a similar trend to the smaller sample. This means that the highest satisfaction in June belonged to satisfaction with ‘A-Job’ (M = 2.4, SD = 1.87). After that, daylight (both annually: ‘A-Natural’, and moment: ‘Natural’) with (M = 2.9, SD = 1.75 and M = 2.8, SD = 1.72) and ‘Glare artificial’ (M = 2.8, SD = 1.6) had the highest satisfaction rates. For more details, see Table 8.

Table 8. Descriptive statistics analysis of all 15 satisfaction variables (1 = very satisfactory, 7 = very unsatisfactory).

| Variable          | Mean ± Std. Deviation (JUNE, N = 46) |
|-------------------|---------------------------------------|
| A-Light Desk      | 3.0 ± 1.56                            |
| A-Natural         | 2.9 ± 1.75                            |
| A-Artificial      | 3.3 ± 1.71                            |
| A-Glare Sun       | 3.4 ± 1.76                            |
| A-Glare Artificial| 3.0 ± 1.72                            |
| A-View            | 3.3 ± 2.23                            |
| A-Lighting Quality| 3.4 ± 1.60                            |
| A-Job             | 2.4 ± 1.87                            |
| Light Desk        | 3.0 ± 1.63                            |
| Natural           | 2.8 ± 1.72                            |
| Artificial        | 3.1 ± 1.66                            |
| Glare Sun         | 3.3 ± 1.72                            |
| Glare Artificial  | 2.8 ± 1.59                            |
| Lighting Quality  | 3.0 ± 1.61                            |
| Valid N (listwise)| 46(42)                                |

Correlation analysis—The correlation of all fifteen satisfaction variables was explored by calculation of Pearson correlation coefficients, and only significant correlations are reported here. The results of correlation analysis for the larger samples (N = 46 and N = 61) show that there were ‘very strong’ (0.8 < p < 1) degrees of correlations for all the variables between annual and at the moment variables. Similarly, for the smaller samples (N = 10 for both studies in June and October), the highest correlation was found for ‘Glare artificial light’. For daylight (A-Natural vs. Natural), a correlation was found only for June in both small and large samples. For more details, see Table 9.

Table 9. Correlation analysis for variables between ‘annual’ and ‘at the moment’.

| Annual/Moment Variables | POE1-Oct. (N = 10) | POE2-Jun. (N = 10) | Jun. (N = 46) | Oct. + Jun. (N = 61) |
|-------------------------|--------------------|--------------------|--------------|----------------------|
| A-Light Desk vs. Light Desk | 86 **              | 68 *               | 84 **        | 84 **                |
| A-Natural vs. Natural | not significant    | 78 **              | 87 **        | 80 **                |
| A-Artificial vs. Artificial | 88 **              | 84 **              | 86 **        | 86 **                |
| A-Glare Sun vs. Glare Sun | 81 **              | 95 **              | 87 **        | 85 **                |
| A-Glare Artificial vs. Glare Artificial | 97 **      | 92 **              | 89 **        | 89 **                |
| A-Light Quality vs. Light Quality | 94 **      | 71 *               | 86 **        | 87 **                |

* p ≤ 0.05; ** p ≤ 0.01.

All the samples consistently showed the strongest correlation between ‘Light quality’ and ‘Light desk’ for both annual and moment situations. For the large sample in June (N = 46), all correlations of the variables for the moment situation were stronger than the same annual situation. For example, the correlation of ‘Light desk’ with ‘Light quality’ was \( r = 0.87, p < 0.01 \), and the correlation of ‘A-Light desk’ with ‘A-Light quality’ was \( r = 0.85, p < 0.01 \).

Both daylight and artificial light seem to contribute to the user assessments of the light quality in the room, with the correlation between ‘Artificial light’ and ‘Lighting
quality (r = 0.81, p < 0.01) being slightly higher than the correlation between 'Natural light' and 'Lighting quality' (r = 0.77, p < 0.01). Both sources of glare also contributed to the assessments of the lighting quality in June with the same weight (r = 0.71, p < 0.01).

Unlike in October, when the assessments of the amount of light on the desk area ('Light desk') seem to only be linked to the amount and quality of artificial lighting, in June, both light sources seem to have contributed to the assessments of the 'Amount of light on desk area'. For both light sources, the correlations were stronger for at the moment assessments compared to the annual assessments. 'Amount of artificial light (moment)' and 'Amount of daylight (moment)' showed strong correlations with the 'Amount of light on desk area' (r = 0.80, p < 0.01 and r = 0.71, p < 0.01, respectively). 'Glare from artificial light' and 'Glare from sunlight' showed a lower correlation with 'Light desk' (r = 0.76, p < 0.01 and r = 0.64, p < 0.01, respectively).

3.3. Objective–Subjective Correlation Analysis

The correlation between performance metrics and perceived visual comfort for the sample in June (N = 46) shows that, in total, eight subjective variables including satisfaction with 'Glare sun', daylight (both annual and at the moment: 'A-Natural' and 'Natural' variables, respectively), 'A-View', total light at the desk (‘A-Light desk’ and ‘Light desk’), and lighting quality (‘A-Light quality’ and ‘Light quality’) had a moderate (0.3 < r < 0.5, p < 0.001) relationship with at least one of the simulated performance metrics. All variables except glare had positive correlations with user satisfaction. Note that it is shown as negative numbers since user satisfaction was defined in inverse order, with 1 being the highest satisfaction level and 7 being the lowest satisfaction level.

The variable ‘Glare sun’ had the highest correlation with point-in-time horizontal illuminance (momentary) at task area (E_{h-task}) for mean values under the clear sky condition (r = 0.38, p < 0.01) and the intermediate sky condition (r = 0.33, p < 0.01).

Satisfaction with daylight for both the annual and momentary situations (‘A-Natural’ and ‘Natural’) showed a significant correlation with E_{h-room}, ASE, and DGP. The highest correlations for E_{h-room} with ‘A-Natural’ were for the mean value of illuminance under clear sky and intermediate sky conditions (r = −0.30, p < 0.01), both classified as moderate correlations. Additionally, ‘Natural’ and ‘A-Natural’ showed a moderate correlation with DGP (r = −0.41, p < 0.01).

Since the view to the outside is often inextricably linked to daylight, it was included in the analysis as well. The ‘A-View’ variable correlated with vertical illuminance (E_{v-eye}), horizontal illuminance at task area (E_{h-task}), and horizontal illuminance for the room area (E_{h-room}) as well as with DA, sDA, and ASE. The highest correlation was found for the mean value of E_{h-room} under ‘clear’ sky conditions (r = −0.46, p < 0.01).

'A-Light desk' and 'Light desk' showed correlations with the horizontal illuminance at task area (E_{h-task}) and room area (E_{h-room}) as well as with DA and sDA. Additionally, ‘Light desk’ correlated with vertical illuminance (E_{v-eye}) and ‘A-Light desk’ with ASE. The highest correlation for ‘A-Light desk’ was found for the minimum value of E_{h-room} under intermediate sky conditions (r = −0.47, p < 0.01). The highest correlation for ‘Light desk’ was found for the minimum value of E_{h-room} under ‘intermediate’ sky conditions (r = −0.47, p < 0.01).

Finally, ‘Light quality’ and ‘A-Light quality’ had significant correlations with E_{h-room}, sDA, and ASE. The highest correlation for ‘Light quality’ was found for the minimum value of E_{h-room} under ‘clear’ sky conditions (r = −0.36, p < 0.01).

4. Discussion

This follow-up study, conducted in June, is the second validation test of the EBD-SIM framework to provide new evidence to obtain better insights about the lit environment, specifically concerning visual comfort in office rooms. The effects of a larger sample size and having two POE studies in two different seasons (October, June) were investigated to find out if previous findings are confirmed (research questions 1 and 2), and to elucidate
the usefulness of having two continuous POE studies for better analysis of visual comfort in office environments (research question 3). The results are categorized into two groups: within-subject study and between-subject study.

The main purpose of conducting a between-subject study in June with a larger sample ($N = 46$) was to verify previous findings in October ($N = 15$) and provide new or updated evidence for the EBD-SIM framework. Comparison between the two measurement moments showed similarities as well as differences.

The correlation analysis of subjective variables for both studies shows a ‘strong’ to ‘very strong’ degree of correlations for all annual and momentary variables except daylight (A-Natural vs. Natural), for which a correlation was not found in October. These strong to very strong correlations can be interpreted in that it is difficult for people to remember a lighting situation throughout the year, and the current situation dominates their feeling regarding the lit environment. Additionally, for daylight (A-Natural vs. Natural), it seems that occupants can better distinguish the difference between annual and momentary situations during dark seasons. From a subjective point of view, for all variables, it was consistently observed that the overall lighting quality perceived by the occupants had the highest correlation with the amount of light on the task area. While in October, the assessment of ‘light quality at the task area’ seemed to only be linked to the ‘amount and quality’ of artificial lighting, in June, in addition to artificial lighting, a strong correlation was found with ‘Natural light’ and ‘Glare sun’.

Regarding the first question related to the correlation between visual comfort metrics and perceived occupant visual comfort, similar to the results obtained in October, the results confirm the previous finding that point-in-time-horizontal illuminance had the highest correlation with perceived visual comfort by occupants. Moreover, in the larger study (June), annual performance metrics showed some degrees of correlation. This means that it is worth calculating sDA, DA, and ASE to provide a moderate forecast on occupant perception of lit environments, especially for ‘Light desk’, ‘Light quality’, and ‘Natural’. This analysis is in agreement with other studies, e.g., [15,24]. Since the results of vertical eye illuminance ($E_v$) and DGP are sensitive to the point of view of the occupants [25], the calculation of data specifically for the occupants’ position and viewpoint improves the accuracy of the data.

Regarding the second question related to instantaneous and annual visual comfort perception and simulated comfort assessment metrics, it was found that for the large sample in June, all correlations of the subjective variables for the moment situation were stronger than the equivalent annual situation. Additionally, $E_h$, which measures the instantaneous situation, showed the highest number of correlations with perceived variables compared to the annual performance metrics. This could be interpreted in that human visual comfort perception for instantaneous situations and modeled comfort performance metrics have a higher agreement than human perception for annual estimations and modeled performance. In the future, POEs can be integrated into, e.g., (artificially) intelligent building control systems, providing direct feedback to the control agent so that each occupant is provided with their preferred lighting and, in a broader sense, with other desired IEQ conditions. Additional input from occupants such as user characteristics (e.g., age, gender, light sensitivity), user behavior, and user preferences can be collected to analyze the effects of the built environment on occupants in greater depth. Logging this feedback data and storing it in a database can provide a set of valuable evidence from the instantaneous feedback of occupants, which in turn can help with better prediction of human comfort and improvement of lighting design. For example, in an innovative study conducted by Newsham et al. [26], along with lighting simulation tools, a humanoid robot was used to attract the attention of the occupant about their real environmental situation and provide them with personalized suggestions to improve their well-being. If a building is responsive to the requirements and behavior of occupants and organizations, either via a POE and/or via continuous monitoring, it can become a truly intelligent building. Conducting metadata analysis on all data collected from evidence and designing building
interfaces or (self-)learning systems based on this evidence-based knowledge would make the interaction of occupants with buildings more convenient.

Regarding the third research question related to the usefulness of a POE with an increased frequency, the results show that in June, people were generally more satisfied with the lit environment compared to answers given in the original study performed in October. As daylight levels are higher in June, it seems that having more daylight has a positive impact on user satisfaction in general. The importance of daylight on user satisfaction was also shown by other researchers, e.g., [27–30]. For example, a study was conducted by Day, Futrell, Cox, and Ruiz [28] that measured physical data and surveys to assess occupants’ subjective visual comfort. The results of their survey study \(N = 1068\) showed that occupants who were more pleased with (their access to) daylight were also more likely to have a higher level of satisfaction. This finding also indicates that, depending on the time of year, a single POE study can overestimate or underestimate different lighting quality metrics. The paired sample \(t\)-test analysis shows a significant difference for the daylight ‘Natural’ variable and a marginally significant difference for the daylight ‘A-Glare sun’ and ‘Light desk’ variables, which means at least for these variables, it is worth running a POE at least twice at different times of the year.

5. Conclusions

This study addressed implementing subjective–objective results in the evidence-based design process using lighting simulation tools in a POE step of the EBD-SIM framework. The POE focused on assessing occupant visual comfort in an individual office space to provide a systematic approach to repeatedly gather evidence in this field and build a knowledge database that can help improve how the results are analyzed, presented, and interpreted. As this study shows, running the EBD-SIM framework each time can provide new evidence. In the meantime, it helps to tailor the next run based on lessons learned in the previous run.

The results confirm the previous finding that the overall lighting quality perceived by the occupants had the highest correlation with the amount of light on the task area. In parallel, \(E_{hi}\) (point-in-time horizontal illuminance) showed a consistently positive correlation with the highest number of subjective variables. Moderate correlations between annual performance metrics and some of the subjective variables were also observed during June, which were non-existent in the October study.

This study suggests that, at least for daylight-related variables (e.g., ‘Natural’, ‘A-Glare sun’, and ‘Light desk’), it is worth running the POE more than once at different times of the year to obtain a better insight into user perception of the lit environment.

As described in the EBD-SIM framework [6], it is preferable to use the simulation output in the POE step so that the situation present at the time of conducting a POE study can be approximated using lighting metrics, and so that the result of the survey can be analyzed in greater depth.

The scope of this research was limited to the visual aspects of lighting quality, and the simulation results included only daylight aspects. In the future, the study can be extended to include both electric lighting and daylight as well as visual effects and light effects beyond vision through a long-term evaluation.

Author Contributions: Conceptualization, A.D., P.J., and M.A.; methodology, A.D., P.J., and M.A.; software, A.D.; validation, A.D., P.J., and M.A.; formal analysis, A.D.; investigation, A.D., P.J., and M.A.; resources, A.D. and M.A.; data curation, A.D.; writing—original draft preparation, A.D.; writing—review and editing, A.D., P.J., and M.A.; visualization, A.D.; supervision, P.J. and M.A.; project administration, M.A.; funding acquisition, P.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Region Jönköpings Län’s FoU-fond Fastigheter and the Bertil and Britt Svenssons Stiftelse för Belysningsteknik.
Institutional Review Board Statement: Ethical review and approval were not requested for this study as collection and analysis of data could not be used to identify participants, did not collect any sensitive personal data, did not include physical contact with participants, would not provide any risk of discomfort, inconvenience, or psychological distress to participants or their families, did not recruit from vulnerable groups, and did not include data collection undertaken overseas. Participants were asked to give informed consent.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data not available. The authors do not have permission to share data.

Acknowledgments: The authors would like to acknowledge the survey participants’ cooperation in this study as well as the valuable comments by the reviewers and editors of the journal of Applied Sciences.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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