Towards Subjectivity in Annual Climate-Based Daylight Metrics

J. Alstan Jakubiec[1], Geraldine Quek[1], Thanyalak Srisamranrungruang[1]
[1] Singapore University of Technology and Design, Singapore

Abstract

This paper presents a post-occupancy study of 543 participants in 10 daylit office buildings in Singapore. Calibrated daylighting and electric lighting simulation models of each building were created and verified. HDR photographs and vertical and horizontal illuminance measurements were taken at each participant's workspace, and a survey on their long-term and instantaneous subjective evaluations of lighting were collected. For the first time, this study compares climate-based daylighting metrics (CBDM's) to occupant's long-term subjective impressions. The authors find that simulated mean annual horizontal illuminance correlates strongly with occupants' satisfaction with access to daylight. 50% occupant satisfaction with daylight begins at levels as low as 80 lx, far below current lighting sufficiency standards. Vertical illuminance measures did not exhibit strong correlations with reported discomfort. These results are an initial investigation of CBDM's use for more than lighting sufficiency and illustrate the need for further study of overlighting metrics.

Introduction

Recent work in daylighting analysis includes human factors more than ever before. New focus is being placed on physical reactions to light such as circadian health and alertness as well as subjective assessments such as visual discomfort, occupants' definition of daylit, and the relationship between global contrast and emotive perception. This exciting and mostly recent work has a critical issue—that it is based entirely on instantaneous or very short exposures to lighting conditions; therefore, there is no clear method to interpret the results beyond based on the frequency of occurrences.

Several authors have dealt with instantaneous subjective lighting measures in annual climate-based daylighting simulations. Wienold (2009) proposed that when analysing annual visual discomfort, practitioners should follow EN 15251 (2007), a thermal comfort standard. Under Wienold's translational proposal, discomfort should not be predicted for more than 5% of the year, and the mean of the top 5% of visual discomfort results should also fall below a goal-based threshold. Reinhart and Wienold (2011) proposed a 5% temporal limit as well when adding an illuminance-based overlighting provision in the daylight availability metric which is meant to correlate with increased probability of visual discomfort. IES-LM-83 (2012) proposes a slightly looser threshold by recommending avoiding direct sunlight without dynamic shading devices for 6.8% of the year, but they also note that more and less stringent criteria could be used instead. Rockcastle, et al. (2014) and Jakubiec and Reinhart (2012) among others opted to display a temporal map of the results rather than provide any hard thresholds.

This paper describes an alternate approach to those authors above by directly correlating subjective long-term occupant impressions with calibrated annual daylighting models of the spaces in which the occupants are seated. First, the process of measurement and daylight model calibration for 10 office buildings with 543 survey participants is described and validated. Then the survey presented to each participant is described. Finally, correlations (and lack thereof) are reported.

This study is exploratory, such that the data collected is not intended to test any specific hypothesis but instead explores where statistically-strong correlations exist between subjective and objective data. The initial results reported reduce degrees of data processing freedom and inclusion of covariates in the analysis to minimize false positives (Simmons et al. 2011).

Methodology

Space measurement and lighting model calibration

Ten office spaces in Singapore were visited between October 2016 and August 2017. During each visit, 3D scan data was collected throughout the building interiors and exteriors to document the layout and exterior obstructions. In addition, glass transmittance was field-measured by comparing interior and exterior illuminance measurements. Material reflectances were also collected using a spectrophotometer (Jakubiec 2016). In most cases, glazing transmittance data and building information models were available to the research team. Using this measured information, best-practice daylighting models were created. Figure 1 shows an example 3D scan of 1 measured building (Building 10), and Figure 2 shows the resulting 3D model, which includes the building fabric—walls, windows, mullions, etc.—in addition to luminaires, furniture, computer screens of participants, and window shades. Luminaire photometric information was input via IES files based on specifications where available, and based on HDR photography combined with illuminance measurements compared to IES data catalogues where not available (an arduous process).

Figure 1: 3D scan (with roof removed) of Building 10.

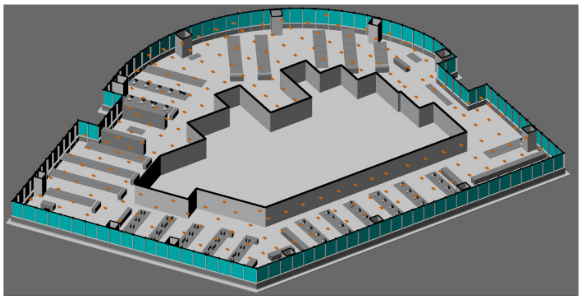

Figure 2: Resulting simulation model of Building 10.

While visiting the 10 spaces, instantaneous measurement data was also collected. The time of measurements were recorded, and their location on a building floorplan was logged. Horizontal illuminance data at the desk was measured, and a high dynamic range (HDR) photograph was taken from the eye position of the occupant following Jakubiec, et al. (2016, 2016b). This means that vertical illuminance measurements were taken at the camera lens as well. Approximately half of the photographic measurements were calibrated based on luminance measurements from a grey card while the other half were calibrated based on the illuminance measurements. All HDR images were vignetting corrected and transformed into the Radiance angular fisheye (-vta) format (Ward 1994).

Custom 5-minute Daysim-format weather files were created based on a weather station at the authors' home institution in Singapore for the year of data before the measurement and survey period concluded in each building. In this way, measured data can be compared to instantaneous simulation results or specific climate-based daylight simulation timesteps accounting for the time of measurement.

Model calibration is assessed based upon root mean square error (RMSE) and mean bias error (MBE) using horizontal and vertical illuminance measurements compared to calculations. In terms of process, a single calculation is made for all luminaire and monitor contributions using Radiance (Ward 1994), and a 5-minute annual climate-based calculation is performed using Daysim (Reinhart and Walkenhorst 2001). The annual daylight calculation is ran twice—first with and then without window shades. This is done to have reasonable data for calibration (with shades) and to compare against typical design models (without shades). Both sets of electric and daylit calculations use high-quality ambient parameters with 7 ambient bounces.

The initial simulation of all 10 models was not perfect. Errors and biases were found; however, through an iterative process comparing illuminance and luminance renderings to measurements, an overall horizontal illuminance RMSE of 123.4 lx (26.0% of the mean) and MBE of 5.2 lx was achieved Figure 3 shows the horizontal measured (red line) values compared to the simulated electric and daylit values for Building 10, the same as depicted in Figures 1 and 2. Vertical illuminance had far greater relative variance due to the variety of monitor types, brightness settings, and the desire of some participants to turn off their workplace monitor before the photographic capture process—vertical RMSE is 123.5 lx (46.4% of the mean), and vertical MBE is 66.7 lx.

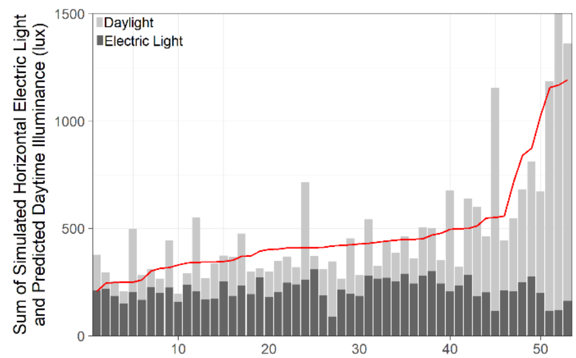

Figure 3: Field-measured workplane illuminance of Building 10 depicted as a red line, and simulated lighting levels represented as stacked areas.

The result of this entire process of measurement, simulation, and calibration is that the authors have reasonable certainty that when a climate-based daylight metric (CBDM) is calculated, its result corresponds accurately to what the occupant experiences**.** Figure 4 further shows the diversity of daylight levels experienced in this study by depicting the average mean daylighting level in each building using the standard IWEC weather data for Singapore and no operable shades.

Subjective survey

Each of the 543 participants filled out a 5-minute, 3-page survey, and this section reports the questions within the survey. Broadly, the authors collected demographic, instantaneous subjective, and long-term subjective data. The long-term questions present improvements on Jakubiec's (2016) study. Wienold and Christoffersen's (2006) Daylight Glare Probability study, Van Den Wymelenberg's thesis work (Van Den Wymelenberg and Inanici 2014), and the UC Berkeley CBE survey (Zagreus et al. 2004) also provided references for the format of the questions. The complete survey eschewing instructions to the participants is included in Table 1. Instructions included information such as definitions, of glare for example, and instructions for how to answer the questions. In addition, an open comment section was included at the end of the survey.

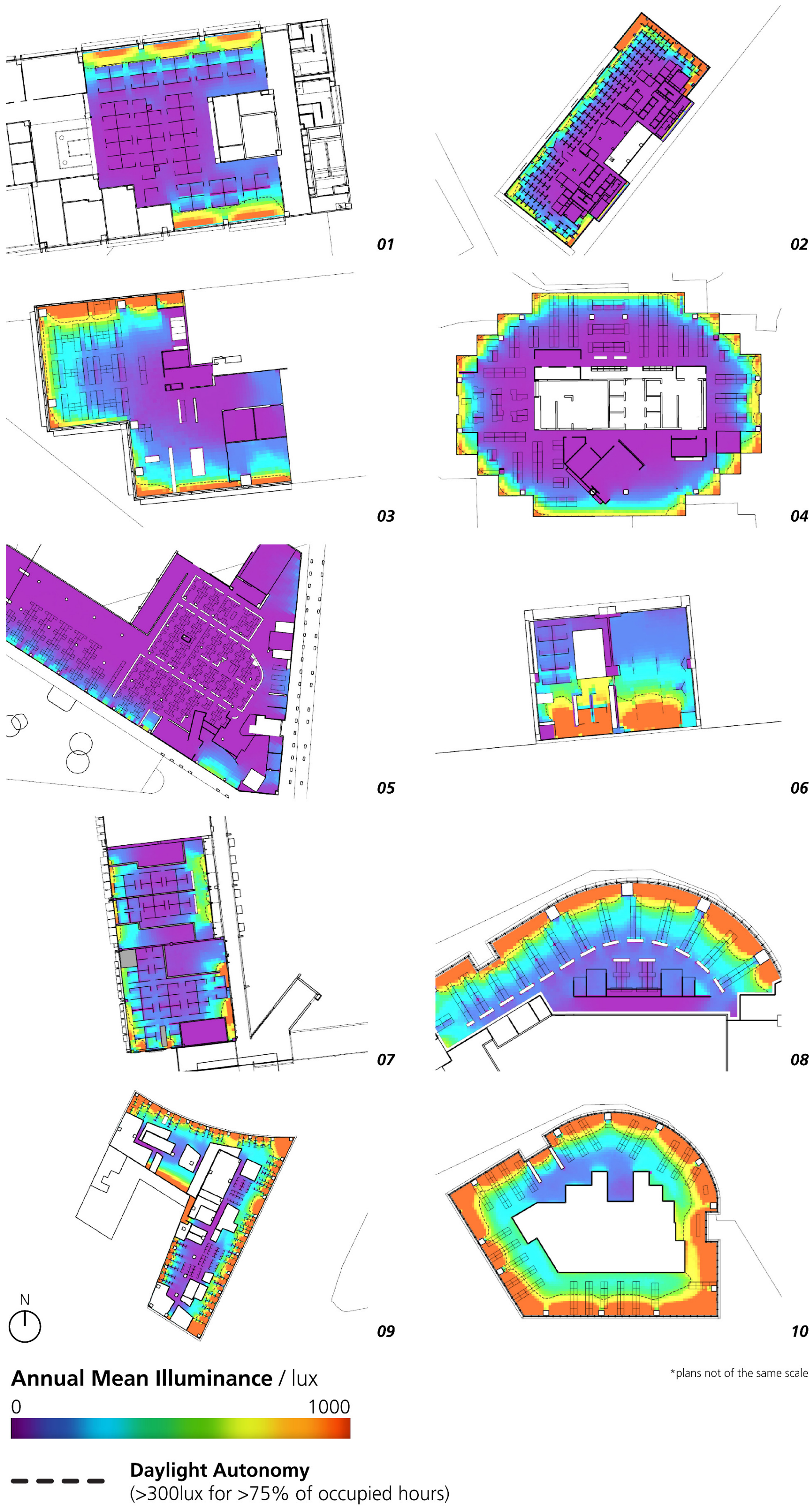

Figure 4: Simulated mean annual horizontal illuminance of 10 studied buildings.

Table 1: Questions and response options included in the subjective survey

Question	Response Range
Demographic Questions	
1. What is your age?	≤20 years, 21-30 years, 31-40 years, 41-50 years, 51-65 years, or ≥ 65 years
2. How long have you been working at your present workspace?	≤ 1 week, < 1 month, < 6 months, < 12 months, or ≥ 1 year
3. In a typical week, how many hours do you spend in your workspace?	≤ 10 hours, 11−30 hours, ≥ 30 hours
4. What is your gender?	Make or Female
5. Are you wearing corrective eyewear at the time of this survey?	Glasses, Contacts, No
6. Does your working day consist of predominantly screen-based tasks?	Yes or No
7. Do you use a desk lamp regularly?	Yes, No, or I do not own a desk lamp.
Long-term Questions	
8. How satisfied are you with your access to daylight?	Range from Very Satisfied, to Neutral, to Very Dissatisfied
9. For the length of time you have been using this workspace, how do the combined lighting conditions from daylight and electric light make you feel?	Range from Clearly Comfortable, to Neutral, to Clearly Uncomfortable
10. Take a moment and look around your workspace. How do you rate your view through exterior windows?	Very Interesting, Interesting, Not Interesting, No View, or Don't Know
11. The total amount of light from daylight and electric lighting systems in this space is often too high.	Range from Strongly Agree to No Opinion to Strongly Disagree
12. The total amount of light from daylight and electric lighting systems in this space is often too low.	
13. I am often bothered by glare from the electric lighting systems.	
14. The lighting quality in the space positively influences my productivity at work.	
Current Impressions Questions	
15. Right now, assess the amount of light—including daylight and electric lighting—in this space. Check a single box corresponding to your answer.	Too bright, Adequate, Inadequate, or Too dark
16. How would you adjust electric lighting in this space to improve the current lighting environment?	Turn off, Reduce a lot, Reduce a little, Do not change the lighting, Increase a little, or Increase a lot
17. Mark the degree of glare you experienced while taking this survey.	Imperceptible (No glare), Noticeable (Little glare), Disturbing (Significant glare), or Intolerable (Extreme glare)
18. Assuming you have to conduct your daily work under the current conditions, do you feel that the lighting is,	Range from Clearly Comfortable, to Neutral, to Clearly Uncomfortable
19. If you are experiencing glare or visual discomfort, please indicate the cause(s) or source(s).	Multiple choice: Reflections in Computer Screen, Window, Shading Device, Electric Lighting, Personal Desk Lamp, and Other (Indicate)
20. Currently, which adjectives describe the lighting in your current location?	Multiple choice: Gloomy, Dim, Comfortable, Bright, Glary

Results

Demographics

In the interest of showing the diversity of the participant pool, the authors wish to disclose some demographic information of the 543 study participants. Figure 5 shows the age of those participating in the study. It is interesting to note that most (343, 63.6%) participants use corrective eyewear of some sort. Male and female participants were evenly split (53% and 47% respectively), and more than three-quarters (76.7%) of participants had been seated at their workspace for more than 6 months.

Measurements and Simulations

Figure 6 illustrates the ranges of horizontal and vertical illuminance values measured during the study. Horizontal illuminance values are clustered within the 300 lx to 600 lx range, and vertical illuminances fall primarily within the 150 lx to 300 lx range.

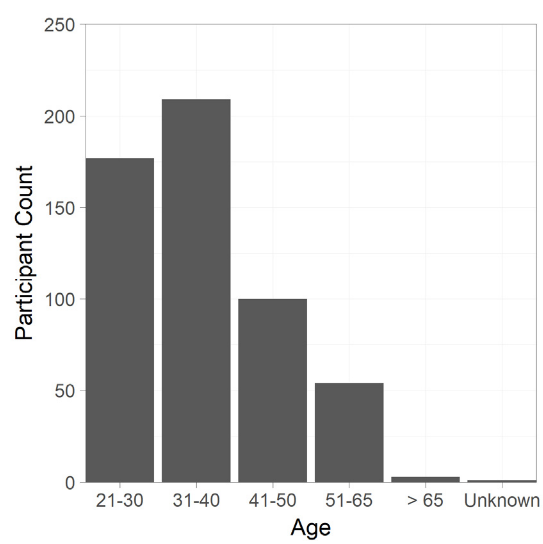

Figure 5: Histogram of participant ages.

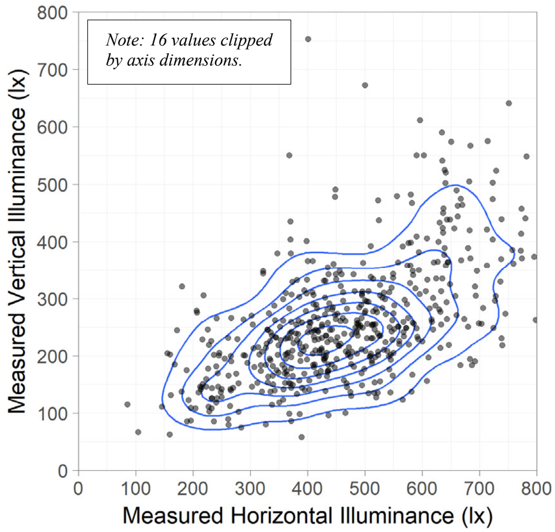

Figure 6: Density comparison of measured horizontal and vertical illuminance levels.

Measured Daylight Glare Probability (DGP) and Unified Glare Rating (UGR) values are very low compared to published guidelines. No single DGP value is above 0.35 (perceptible). UGR values, which are contrast-based, show greater detectible levels of visual discomfort as illustrated in Figure 7.

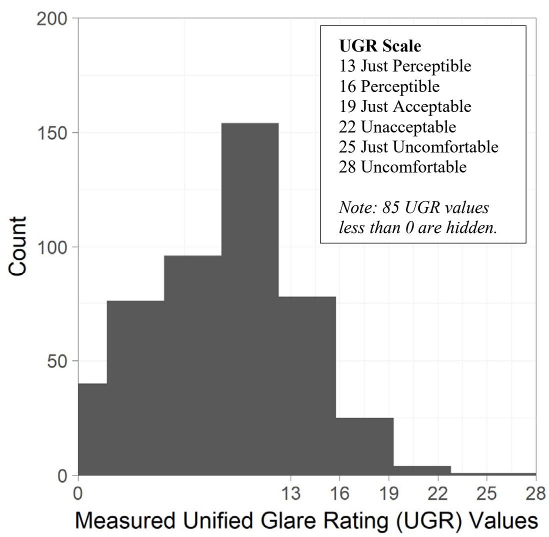

Figure 7: Histogram of field-measured UGR values.

For brevity, the authors refer the reader to Figures 3 and 4 to partially illustrate the simulated daylighting and electric levels inside without shades. In addition, Figure 8 depicts the mean daytime illuminance levels throughout the year from the 543 occupant desks within the 10 simulation models.

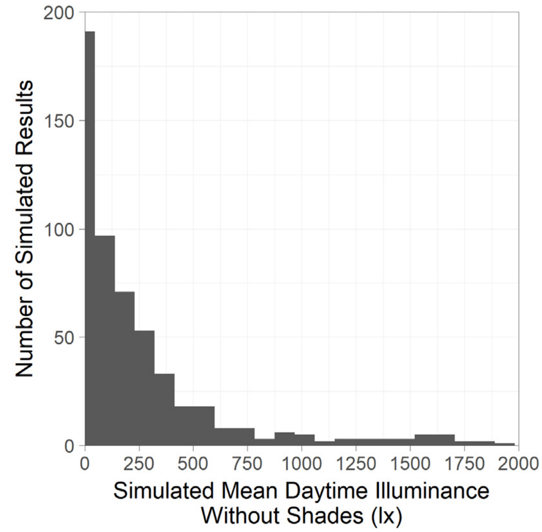

Figure 8: Histogram of mean annual simulated workplane illuminance for all 543 participants.

Inferential statistics

Alluded to in the introduction, the authors sought simple correlations between a single simulation or measurement output and occupant question. As seen in other studies (Wienold and Christoffersen 2006; Hirning et al. 2014 for example), results are analysed between groups of participants, because individual subjective differences fluctuate wildly. When there is a real impact of a measured variable on a subjective output, it is expected for the percentage of persons within that group responding in a certain manner to increase or decrease accordingly. In this study 23 groups of approximately 23 participants ($\sqrt{543}=23.3$) are used for group analysis. Groups are always divided based on quantiles of the predictor data, which is measured or simulated and used to predict the subjective response.

One very strong correlation that was found is the relationship between the $\log_{10}$ of the mean simulated daytime illuminance from daylight without shades and the percentage of occupants satisfied with their access to daylight—Question 8 in Table 1 with a response better than 'Neutral.' By way of example of the grouping methodology, Figure 9 shows the distribution of the 23 groups for analysis using a box plot. Figure 10 illustrates the relationship between the $\log_{10}$ mean daylight illuminance (although the axis is labelled in linear space) and the percentage of occupants satisfied with access to daylight. Eighty-one percent of the variance between groups in satisfaction with daylight access is explained by the mean daylight illuminance (R^2), and the p-value is 2.681e-09, many times smaller than the 0.05 value typically held as a guard against false positives in other studies.

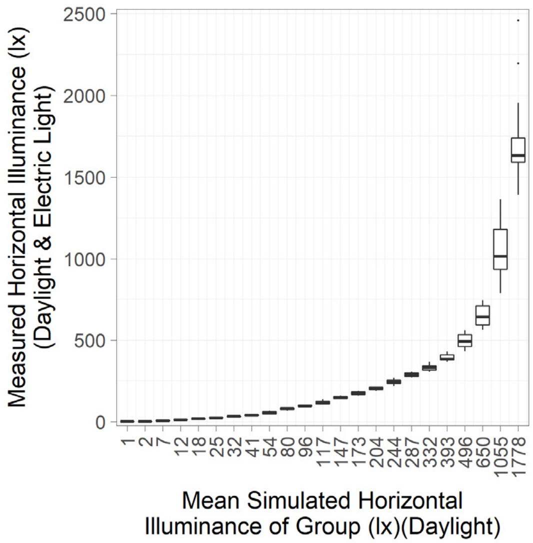

Figure 9: Quantile groupings of mean illuminance for group analysis (n=23).

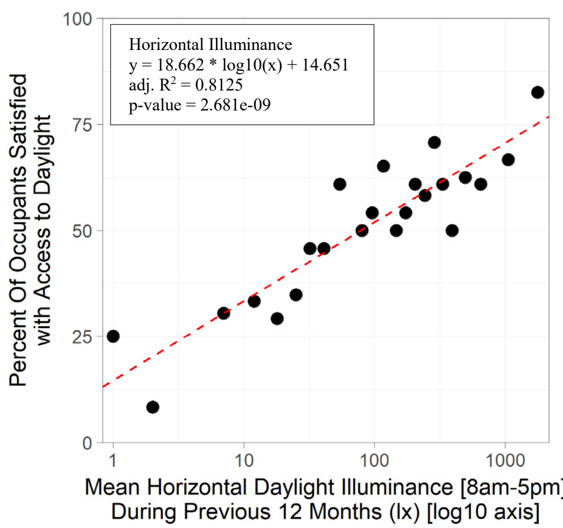

Figure 10: Correlation between mean simulated horizontal daylight illuminance and the percentage of occupants satisfied with access to daylight.

On the other hand, typical daylight metrics such as Daylight Autonomy at 300 lx (DA300 lx) do not correlate as well with the subjective question of satisfaction with daylight access. This is depicted in Figure 11 and should not come as a surprise—a mean daylight illuminance of only 80 lx is required for 50% of occupants to feel satisfied with their access to daylight. The starting point of 300 lx, designed to be a threshold at which electric lighting can be turned off, misses a significant portion of occupants who would describe their daylight access as 'satisfactory.' However, some relationship can still be observed at higher levels of DA300 lx, and the R^2 correlation coefficient is 0.4851 with a low p-value.

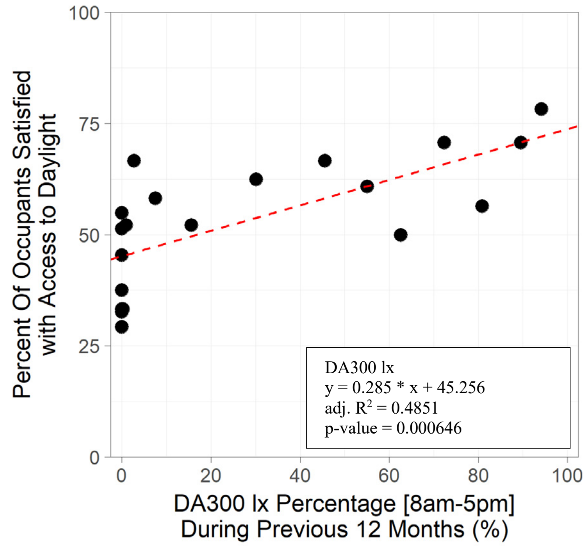

Figure 11: Correlation between DA300 lx and the percentage satisfied with access to daylight.

Correlations with discomfort can be examined as well. Figure 12 illustrates the relationship between the $\log_{10}$ mean vertical daytime illuminance, a measure which would likely correspond to discomfort, and the typical impressions of visual comfort in the space—Question 9 from Table 1 with a value worse than 'Neutral.' Only 4.6% of the variance in the percentage of uncomfortable occupants is explained by mean vertical eye illuminance levels. Several other correlations were tested—with UDI-exceeded levels, with the frequency of vertical illuminance levels greater than 1500 lx, and with negative Daylight Availability levels—but none presented a strong correlation.

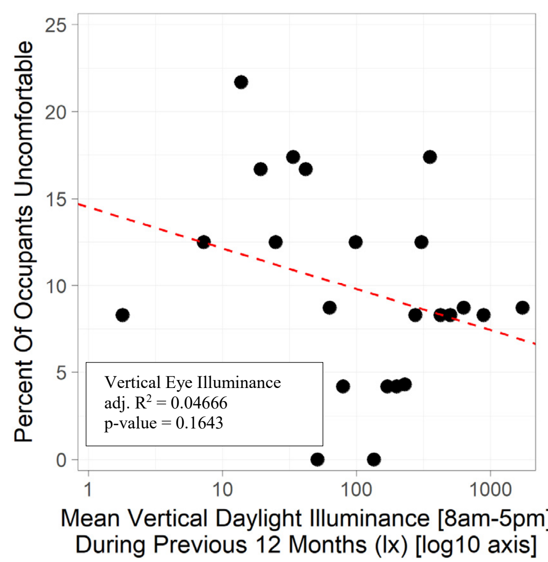

Figure 12: Correlation between mean vertical eye illuminance and the percent of uncomfortable occupants.

Discussion and Conclusion

The novelty of this work is twofold. Primarily, this is the first field study where calibrated lighting models were created and verified with instantaneous measured data. Therefore, it is also the first time where common annual lighting performance measures used in practice such as Spatial Daylight Autonomy (sDA), Daylight Autonomy (DA), and Useful Daylight Illuminance (UDI) can be compared to the impressions of people that occupy the space full-time, interrogating the metrics veracity as a performance measure. Secondarily, preliminary results show correlations between subjective experience and long-term simulated data that enable the creation of novel lighting performance metrics predicting human factors such as satisfaction with access to daylight, not simply whether a space is fully daylit or not. Simple correlations were not identified between typical overlighting metrics (UDI-exceeded and Daylight Availability) and reported discomfort. Neither were correlations found between vertical eye illuminance measures and reported discomfort, at least in the context of Singapore. Further work is needed to understand the application of these metrics at least in the tropical location of this study.

The authors have shown that Daylight Autonomy and similar metrics are less useful at predicting subjective satisfaction with daylight access. This is not to say that lighting sufficiency metrics are not useful, but rather that they are designed for another purpose. Perhaps a certain level of daylight access based on the mean daily amount of daylight received should be mandated by code or used as a prerequisite in green building rating systems such as Singapore's Green Mark or the US's LEED. On the other hand, the authors have also shown that measures currently accessible in many commercial and open-source building performance simulation tools—mean annual illuminance—can do an adequate job at correlating with subjective satisfaction with access to daylight.

Limitations and future work

There are several limitations to this work. Primarily, the effort has been carried out in one cultural and climactic location—Singapore. While this has not stopped other studies from gaining broader acceptance, previous hypothesis and observations from the authors have identified this as a potential problem. Carrying out similar studies to this one, even if limited in scope, would be beneficial in finding true global subjective lighting quality metrics, if they even exist.

The amount of data relationships identified in this manuscript are obviously small compared to the sheer magnitude of the subjective questions (Table 1) and simulation outputs, so this paper serves as an initial presentation of the methodology and early results. In addition, annual visual discomfort calculations have not yet been included in the paper; however, they are forthcoming in future work and should prove useful to compare to reported long-term occupant discomfort.

Acknowledgements

The work was supported by the Singapore Building Construction Authority (BCA), Green Building Innovation Cluster (GBIC) Research and Development Grant under grant number GBIC-R&D / DCP 05. The authors further acknowledge support for measurement equipment from the SUTD-MIT International Design Centre (IDC). Any opinions expressed herein are those of the authors and do not reflect the views of the IDC. The authors are extremely grateful to Denise Kwok from the BCA's Green Mark Department for facilitating access to many of the buildings studied herein. The authors additionally thank the 10 building or office managers who granted us access to their buildings.

References

EN 15251. (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

Hirning, M. B., Isoardi, G. L., & Cowling, I. (2014). Discomfort glare in open plan green buildings. Energy and Buildings, 70, 427-440.

IES. (2012). LM-83-12 IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). New York, NY, USA: IESNA Lighting Measurement.

Jakubiec, J. A., & Reinhart, C. F. (2012). The 'adaptive zone'–A concept for assessing discomfort glare throughout daylit spaces. Lighting Research & Technology, 44(2), 149-170.

Jakubiec, J. A. (2016). Building a Database of Opaque Materials for Lighting Simulation. In PLEA 2016–Cities, Buildings, People: Towards Regenerative Environments, Proceedings of the 32nd International Conference on Passive and Low Energy Architecture.

Jakubiec, J. A., Van Den Wymelenberg, K., Inanici, M., & Mahic, A. (2016). Accurate measurement of daylit interior scenes using high dynamic range photography. In Proceedings of the CIE 2016 Lighting Quality and Energy Efficiency Conference.

Jakubiec, J. A., Van Den Wymelenberg, K., Inanici, M., & Mahic, A. (2016). Improving the accuracy of measurements in daylit interior scenes using high dynamic range photography. In Proceedings of the 32nd PLEA Conference, Los Angeles, CA, USA.

Jakubiec, J. A., & Reinhart, C. F. (2016). A concept for predicting occupants' long-term visual comfort within daylit spaces. Leukos, 12(4), 185-202.

Reinhart, C. F., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and buildings, 33(7), 683-697.

Reinhart, C. F., & Wienold, J. (2011). The daylighting dashboard–A simulation-based design analysis for daylit spaces. Building and environment, 46(2), 386-396.

Rockcastle, S., & Andersen, M. (2014). Measuring the dynamics of contrast & daylight variability in architecture: A proof-of-concept methodology. Building and Environment, 81, 320-333.

Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. Psychological science, 22(11), 1359-1366.

Van Den Wymelenberg, K., & Inanici, M. (2014). A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight. Leukos, 10(3), 145-164.

Ward, G. J. (1994). The RADIANCE lighting simulation and rendering system. In Proceedings of the 21st annual conference on Computer graphics and interactive techniques (pp. 459-472). ACM.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and buildings, 38(7), 743-757.

Wienold, J. (2009). Dynamic daylight glare evaluation. In Proceedings of Building Simulation 2009, Glasgow, Scotland.

Zagreus, L., Huizenga, C., Arens, E., & Lehrer, D. (2004). Listening to the occupants: a Web-based indoor environmental quality survey. Indoor Air, 14(8), 65-74.