SENSITIVITY STUDY OF ANNUAL AND POINT-IN-TIME DAYLIGHT PERFORMANCE METRICS: A 24 SPACE MULTI-YEAR FIELD STUDY

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ABSTRACT

With the latest published version LEED (v4), and the IES codifying two recommended annual-climate-based daylighting metrics and performance criteria, annual daylighting simulation has become even more important to the design professions than ever before. However, interpretation and application of annual-climate-based daylighting data are still relatively novel. This paper documents a 8-year human factors daylighting field research project using students' qualitative assessments of daylight sufficiency and corresponding point-in-time and annual-climate-based daylighting simulation in a variety of building types (n=24) in order to provide insight to the building performance simulation community about application of these new annual daylighting metrics.

INTRODUCTION

During the last decade, the architecture industry has experienced many metrics for measuring daylighting in built environment. Static daylight metrics measured at a single point in time have recently fallen out of favor and instead annual dynamic daylighting metrics such as Daylight Autonomy (Reinhart et al. 2006), Useful Daylight Illuminance (Mardaljevic and Nabil, 2005), continuous Daylight Autonomy (Rogers, 2006), were promoted in order to better incorporate project design parameters, climate, and the annual variability of daylight. In 2012, the Illuminating Engineering Society (IES) formalized this evolution when they adopted spatial daylight autonomy (sDA) and annual sunlight exposure (ASE), which were the first human-factors evidence-based daylight metrics approved by IES. And consequently in 2014, sDA and ASE were codified by the latest version of LEED as one of two modeling compliance paths for Indoor Environmental Quality (EQ) Daylight Credit, offering more potential credits than the other compliance pathways. However, interpretation and application of annual-climate-based daylighting data are still relatively novel and the better understanding is essential.

According to LEED V4, acceptable spaces are those with at least 55% of floor area exceeds 300Lux for 50% of annual occupied hours (spatial Daylight Autonomy$_{300Lux/50\%\ time}$ (sDA$_{300/50\%}$)) and no more than 10% of analysis points in a space exceeds 1000 Lux of direct sunlight for 250 hours as measured from 8AM-6PM (annual sunlight exposure$_{1000\ Lux,\ 250\ hours}$ (ASE$_{1000,\ 250}$)). Nezamdoost and Van Den Wymelenberg (2015) examined LEED V4 criteria for the EQ Daylight Credit on 22 spaces but only eight spaces passed. Fourteen of the 22 spaces met the sDA (LM-83) portion of the LEED V4 EQ Daylight Credit, but six of the 14 failed due to the ASE 10% threshold criteria. The ASE criteria adopted by LEED appears to be too restrictive and may result in many good daylighting designs failing to meet the credit. This suggests that ASE 1000 Lux 250 hours at 10% threshold warrants refinement.

Given the need for data sets to test the viability of current annual daylight performance metrics, a substantial human factors field study was conducted. This field study included qualitative assessment of 24 real daylit spaces by graduate architecture students and annual and point in time simulation of daylight performance.

METHODS

The research plan was conducted to address one primary goal and several secondary objectives. The primary purpose of this paper was to understand how well annual simulated daylight results for daylight sufficiency and excessiveness correlate with students' qualitative assessments within 24 study spaces. This paper follows up on a previous study conducted by Lisa Heschong (HMG-PIER Review 2012, Heschong and Van Den Wymelenberg, 2012). The secondary objectives were to test correlations of subjective responses with alternative point-in-time illuminance thresholds (ranging from 100-5000 Lux), illuminance thresholds for annual analysis, alternative thresholds for annual sunlight exposure, and whether continuous (spatial) daylight autonomy performs better or worse than standard spatial daylight autonomy. There was also interest to determine if any other illuminance metrics or modifiers improve correlation of annual simulation results with subjective responses.

Data Collection

Experiment Setup

This paper documents an eight year long experiment (2007-2015) conducted with architectural graduate students (n=81) under 30 years of age at the University of Idaho in Boise who took course "Daylighting Design and Simulation" to evaluate 24 real study spaces by documenting their own intuition about daylight performance using questionnaires.

Human factors evaluations were conducted during 43 field trip observations in 24 spaces within 14 buildings in Boise, Idaho and Seattle, Washington. The field trips occurred during class time, generally between the hours of 11 AM and 3:30 PM, with median time at 1:45pm. The research protocol (project 15-724) was reviewed by the Institutional Review Board at the University of Idaho and was certified as exempt.

In order be inclusive of a broad range of daylight conditions, study spaces were chosen with diverse building geometry, space type, orientation, size, daylight strategy (toplight/sidelight), sky condition, window glazing characteristics, and exterior obstructions. In order to ensure consistency with previous researches (HMG-PIER Review 2012, Heschong and Van Den Wymelenberg 2012) and address common space types that employ daylight, field study spaces were selected in three common space types: Office space type (n=12), Classroom space type (n=6), and Other space type (n=6).

Questionnaire items

Each participant completed a three-page questionnaire, focusing on visual interest, daylight sufficiency, lighting conditions, visual comfort and glare, and thermal/ acoustic privacy.

Among all questions, the authors decided to focus more on a few specific qualitative questions which best represent the goals of this study. Each was given a letter and descriptor, as follows for analysis purposes:

A - I enjoy being in this room.

B - I can work happily in this room with all the electric lights turned off.

C - The daylight in this room is sufficient.

D - The daylight in this room is not too bright.

E - I like the daylight uniformity.

F - I like the vertical surface brightness.

G - I am able to do my work here without any problems from daylight induced glare.

H - I am happy with how the blinds are positioned.

I - There is no glare from direct sun penetration.

Simulation Parameters

Accurate three-dimensional digital models of each study space and surrounding exterior obstructions (within 100' of study space) were generated in SketchUp (version 2014). All relevant architectural details were included in digital models based on the simulation protocol outlined in LM-83 (IESNA-Daylight Metrics Committee 2012). Each geometry model was double checked with floor plans, site photographs and Google Earth. Once approved, the geometry was exported into RADIANCE daylight simulation engine using a two-foot by two-foot (2'*2') illuminance analysis grid (looking toward ceiling and located 32" above the floor) to generate horizontal illuminance point data sets.

In order to provide a relevant basis of comparison between the point-in-time simulations and the conditions present when the students conducted the evaluations during the field trips, a simulation data set with the same clock time, from the same week and with a matching sky condition from the annual simulation results was selected from within the annual hourly simulation results. For annual dynamic climate-based daylight simulation, the three-phase RADIANCE method was employed (McNeil and Lee, 2013), per LM-83 (IESNA-Daylight Metrics Committee 2012) with TMY3 weather file (analysis time period from 8AM to 6PM local clock time). Light source contributions were computed in RADIANCE by Rcontrib ambient calculations.

Data Analysis

In this step, 448 questionnaires – 64 items each, were organized in spreadsheets. Scripts were used to conduct data cleaning; sanity checks were scripted for the entire data set, and redundant data entry was conducted for 10 percent of data to ensure accuracy. The approved data were imported as a single matrix to use in statistical analysis software (R). Inferential statistics were employed as follows: (1) one-way and two-way, paired and unpaired t-test (95% confidence interval) to determine statistical significance between groups of continuous data. (2) Pearson Correlations were calculated to find the relationship between variables of interest. For the comparisons between simulations output and students qualitative assessments, simulation data set was categorized into two major metric types: (1) daylight sufficiency and (2) daylight excessiveness.

Daylight Sufficiency

An illuminance indicator value and a percent of time value are fixed, for LM-83 it is 300 lux for 50% of the time between 8AM and 6PM, and the metric reports a percent area that meets these criteria. It is written sDA300, 50%. Given the increased implementation of the new metric, for example in LEED v4, and the resultant scrutiny placed upon it in the design research and professional communities, a follow up sensitivity analysis was warranted. This study examined simulation results using several illuminance levels (100- 5000 Lux) and correlated results with students' qualitative assessments.

Daylight Excessiveness

The IES DMC voted that a metric for daylight sufficiency should be paired with and balanced by a metric of daylight excessiveness so as to help reduce potential of occupant's perceived glare. So, the DMC developed a metric called Annual Sunlight Exposure (ASE) to serve as a visual comfort proxy by measuring annual potential for sunlight penetration. It is described as the percent of sensors that exceeds 1000Lux of direct sunlight illuminance, as measured by a computationally simulated "zero-bounce" solar disc analysis, for more than 250 hours per year with blinds open. Given feedback from the research and design professional community regarding the 1000Lux threshold, other high illuminance thresholds (700, 800, 1000, 2000, 3000 and 5000 Lux) were examined as candidates for the "daylight excessiveness" threshold in both point in time and annual simulations.

RESULTS

This section reports the findings of correlation coefficient analysis between annual simulated daylight results for daylight sufficiency and excessiveness, and students' qualitative assessments within 24 study spaces.

Occupant Visual Brightness Perception Phenomena

A few spaces were identified to have the potential to be influenced by a moderating variable defined as "occupant Visual Brightness Perception" phenomena, potentially increasing differences in simulated illuminance plots relative to students' subjective responses. According to Nezamdoost and Van Den Wymelenberg (2015), Students' evaluations show a possible impact of human brightness perception increasing error which generally happens when vertical glazing or clerestory openings provide high levels of daylight washing vertical surfaces and/or the ceiling of the study space. Consequently, this surface brightness can impact students' perception of daylit/non-daylit areas in a room while the horizontal task illuminance (simulation grid) does not necessarily exceed the required threshold to designate that area as daylit.

In order to test this idea, correlational analyses were run between related question items and the results show that the question, "I like vertical surface brightness" is highly correlated (R^2= 0.625) to question "The daylight in this room is always sufficient". The question, "I like vertical surface brightness" also shows strong correlation (R^2= 0.7) with question "I like the daylight uniformity". These findings support the hypothesis of "Occupant Visual Brightness Perception". This additional support suggests that annual daylight metrics should consider brightness of vertical surfaces.

Accordingly, the correlation coefficients values were plotted for both point-in-time (table 1) and annual (table 3) evaluations in two groups: The first category (Group 1) consists of all of the 24 study spaces and the second category (Group 2) includes only those spaces do not have characteristics likely to bias responses based upon the human brightness perception phenomena.

Point in Time Metrics

In general, looking at correlation coefficients of students' assessments, point-in-time simulation results showed considerably stronger correlations with students' subjective responses than did annual simulation results. This finding confirms the previous work (Nezamdoost and Van Den Wymelenberg, 2015) that showed point-in-time simulation results had less average percent of difference between student daylit area evaluations than did annual simulation results.

Accordingly, a wide varied range of illuminance indicators (ranging from 50-500 Lux) were chosen and examined in the 24 study spaces in order to understand the most correlated threshold based on students' qualitative assessments for point-in-time evaluations.

Looking at table 1 in Group 1 (all study spaces), the most promising indicators in predicting view quality (A1), daylight sufficiency (B1 and C1), and daylight uniformity (E1) are 125 and 150 Lux together. While in Group 2 (those spaces with less potential for occupant visual brightness perception to impacted results) the percent floor above higher illuminances (175 Lux, 200Lux, 250Lux and arguably 300Lux) correlate more strongly with daylight sufficiency questionnaire items.

As was expected based upon previous work (Nezamdoost and Van Den Wymelenberg, 2015) the two groups showed statistically significant differences, and the average correlation values improved from R^2=0.44 to R^2=0.60, specifically at high illuminance levels.

Table 1 Correlations of point in time illuminance indicators with students' evaluation

% of Area> X Lux	Group	A1	B1	C1	D1	E1	I 1
50 Lux	1	0.443	0.464	0.534	0.091	0.364	0.003
	2	0.445	0.461	0.535	0.078	0.369	0.002
75 Lux	1	0.491	0.514	0.596	0.099	0.428	0.004
	2	0.494	0.513	0.600	0.086	0.436	0.003
100 Lux	1	0.526	0.556	0.651	0.104	0.474	0.003
	2	0.531	0.555	0.657	0.090	0.484	0.002
125 Lux	1	0.553	0.582	0.694	0.110	0.510	0.002
	2	0.558	0.581	0.702	0.095	0.522	0.001
150 Lux	1	0.560	0.581	0.704	0.104	0.519	0.001
	2	0.570	0.588	0.718	0.097	0.538	0.001
175 Lux	1	0.535	0.549	0.676	0.087	0.497	0.001
	2	0.573	0.591	0.728	0.096	0.545	0.001
200 Lux	1	0.479	0.489	0.614	0.064	0.454	0.000
	2	0.567	0.587	0.728	0.093	0.544	0.000
250 Lux	1	0.423	0.436	0.565	0.046	0.417	0.000
	2	0.546	0.585	0.732	0.085	0.533	0.000
300 Lux	1	0.402	0.409	0.543	0.037	0.394	0.001
	2	0.540	0.559	0.723	0.078	0.526	0.000
350 Lux	1	0.374	0.368	0.510	0.026	0.361	0.003
	2	0.529	0.533	0.712	0.066	0.506	0.001
400 Lux	1	0.353	0.338	0.485	0.019	0.335	0.007
	2	0.509	0.501	0.691	0.055	0.478	0.004
450 Lux	1	0.338	0.316	0.468	0.015	0.314	0.009
	2	0.488	0.469	0.665	0.047	0.447	0.006
500 Lux	1	0.329	0.293	0.431	0.012	0.290	0.011
	2	0.467	0.426	0.638	0.041	0.421	0.007

Finally, the translation of the point-in-time simulation results into occupants' preferred values is plotted in figure 1. This figure takes point-in-time simulation output, organizes it in a two-way table, percent area versus illuminance indicator thresholds, and color-codes it by students' responses (Likert scores 1-9) to question C "The daylight in this room is sufficient". Accordingly, students' scores were classified into three categories: Preferred (Likert scores 7-9), Acceptable/Nominal (Likert scores 5-6) and unacceptable (Likert scores 1-4). Then, linear trendlines were plotted to show the proportional relationship between acceptable range of percent area and illuminance level based on students' evaluations. The blue trendline interprets the boundary between the unacceptable and acceptable ranges, meaning that a study space would not be designated as "acceptably" daylit if less than the specified percent area was achieved, as shown by the values below the blue trendline, when referencing a particular illuminance threshold. The purple trendline shows the transition between the "acceptable" and "preferred" range of percent area for each illuminance threshold. In other words, an analysis area will be rated as preferred, if it meets or exceeds the area corresponding to the purple trendline when referencing each illuminance indicator threshold.

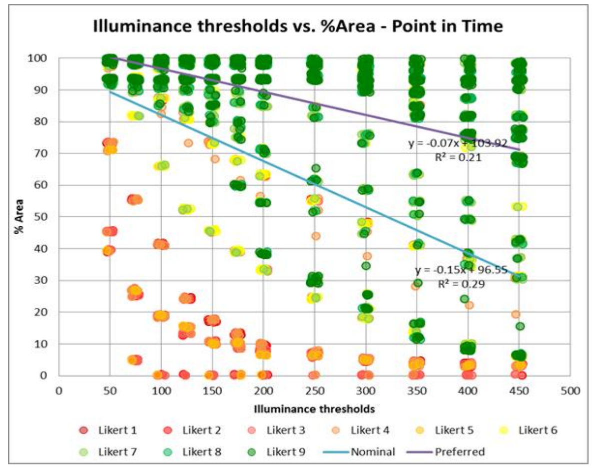

Figure 1 Comparing Point-in-time correlation results of percent area and illuminance thresholds color coded by students' responses (Likert scores 1-9) based on question C

Table 2 Correlation of point-in-time simulation results at high level of illuminance indicators with students' evaluation

% of Area> X Lux	Group	A1	B1	C1	D1	E1	I 1
800 Lux	1	0.260	0.217	0.385	0.002	0.218	0.026
	2	0.354	0.306	0.513	0.013	0.294	0.022
1000 Lux	1	0.219	0.175	0.344	0.000	0.173	0.053
	2	0.292	0.243	0.447	0.004	0.230	0.049
1500 Lux	1	0.134	0.101	0.252	0.005	0.094	0.094
	2	0.175	0.139	0.317	0.001	0.123	0.091
2000 Lux	1	0.097	0.071	0.208	0.010	0.065	0.101
	2	0.126	0.097	0.258	0.004	0.085	0.099
3000 Lux	1	0.116	0.094	0.165	0.003	0.095	0.040
	2	0.138	0.115	0.194	0.008	0.112	0.038
5000 Lux	1	0.116	0.090	0.167	0.006	0.087	0.025
	2	0.125	0.097	0.179	0.007	0.093	0.025

Table 2 shows the correlation coefficient results of six candidate indicators at the high level of illuminance with six major questions, color-coded with strength of values. Again, Group 2 (those spaces with less potential for occupant visual brightness perception to impacted results) better matched with subjective responses rather than all study spaces (Group 1).

Looking at the table 2, very poor R^2 values in glare questions confirm the previous studies (HMG PIER 2012; Heschong and Van Den Wymelenberg, 2012) that there is not substantial evidence for an upper limit being defined. However, at high level of illumination, correlation values slightly increased based on question I

"There is low probability of glare from direct sun penetration"; where the students' visual discomfort peaked at 2000Lux; yet still were not very compelling ($R^2 = 0.1$).

Annual Metrics

Sensitivity studies were also conducted in annual simulations to determine which illuminance indicator thresholds (ranging from 100-5000 Lux) best predict students' subjective responses to questions pertaining to the entire year. Table 3 shows correlation values of six major questions with spatial Daylight Autonomy using a range of lux levels (100-5000), and using 50% of the time between 8AM and 6PM as the time threshold, in two categories (Group 1 and 2).

Table 3 Correlations of annual illuminance indicators (Blinds Open) with students' evaluations

Dependant	Group	A2	B2	C2	D2	E2	I 2
sDA100/50%	1	0.320	0.283	0.278	0.016	0.245	0.009
	2	0.566	0.511	0.505	0.025	0.484	0.018
sDA125/50%	1	0.284	0.258	0.249	0.015	0.220	0.010
	2	0.563	0.521	0.507	0.026	0.491	0.022
sDA150/50%	1	0.291	0.268	0.258	0.015	0.231	0.011
	2	0.556	0.519	0.503	0.026	0.493	0.022
sDA175/50%	1	0.294	0.274	0.262	0.014	0.237	0.012
	2	0.544	0.516	0.497	0.024	0.489	0.024
sDA200/50%	1	0.289	0.277	0.264	0.013	0.241	0.012
	2	0.522	0.510	0.489	0.022	0.482	0.025
sDA250/50%	1	0.266	0.263	0.253	0.009	0.233	0.011
	2	0.488	0.498	0.480	0.020	0.468	0.023
sDA300/50%	1	0.206	0.212	0.206	0.003	0.192	0.009
	2	0.428	0.462	0.449	0.014	0.432	0.019
sDA350/50%	1	0.178	0.192	0.187	0.001	0.174	0.007
	2	0.376	0.423	0.412	0.009	0.392	0.016
sDA400/50%	1	0.156	0.175	0.173	0.000	0.157	0.005
	2	0.331	0.386	0.378	0.005	0.351	0.012
sDA500/50%	1	0.136	0.151	0.153	0.000	0.131	0.001
	2	0.293	0.342	0.342	0.001	0.301	0.005
sDA600/50%	1	0.129	0.138	0.146	0.002	0.112	0.000
	2	0.267	0.302	0.312	0.000	0.250	0.000
sDA700/50%	1	0.127	0.127	0.138	0.004	0.098	0.001
	2	0.252	0.269	0.286	0.001	0.215	0.001
sDA800/50%	1	0.116	0.111	0.126	0.006	0.084	0.004
	2	0.220	0.228	0.249	0.002	0.179	0.004
sDA1000/50%	1	0.072	0.075	0.076	0.028	0.045	0.022
	2	0.133	0.145	0.146	0.022	0.096	0.024
sDA2000/50%	1	0.029	0.030	0.040	0.029	0.015	0.023
	2	0.050	0.055	0.070	0.026	0.032	0.025
sDA3000/50%	1	0.000	0.000	0.003	0.089	0.002	0.097
	2	0.000	0.002	0.007	0.092	0.001	0.111
sDA5000/50%	1	0.001	0.000	0.001	0.068	0.004	0.078
	2	0.000	0.000	0.003	0.071	0.002	0.088

As shown in table 3, by excluding those spaces demonstrating characteristics consistent with occupant visual brightness perception issue, average correlation values significantly improved from $R^2=0.21$ to $R^2=0.43$ in annual simulation results (almost doubled).

Looking at table 3, the strongest correlation values in all study spaces were reported in range of 100 lux to 300 lux. However, high R^2 value for the low illuminance thresholds could not be reliable enough due to not normal distribution data. According to the Pearson R correlation, both variables should be normally distributed (Daniel W.W. 1990 and Kowalski, D. J. 1972). To illustrate this issue, two correlation scatterplots in 100 lux and 300 lux were plotted in figure 2 based on question C "The daylight in this room is always sufficient", where the horizontal axis is percent area above 100 lux or 300 lux compared with the Likert scores along vertical axis. As it was expected, in low illuminance level (100 lux) most answers were provided in one little quadrant of the filed (saturated) and a few answers where there is no stimulus (black room) and the line between the two chunks of data makes for a stronger R^2 value.

It was found that in high level of illumination, R^2 values gradually decreased (negative trend) and no upper limit can be found in daylight sufficiency (B and C) questions. It means students feel visually comfortable in low level of illuminance than bright conditions. Although the findings support the previous researches (HMG PIER 2012; Heschong and Van Den Wymelenberg, 2012) that no upper limits to annual daylight autonomy values were found, but at high level of illumination (sensor*hours) an increase in correlation values were reported based on question I "There is low probability of glare from direct sun penetration"; where the students' dissatisfaction from brightness increased at 1000Lux and peaked at 3000Lux; yet still were not very compelling ($R^2 = 0.09$).

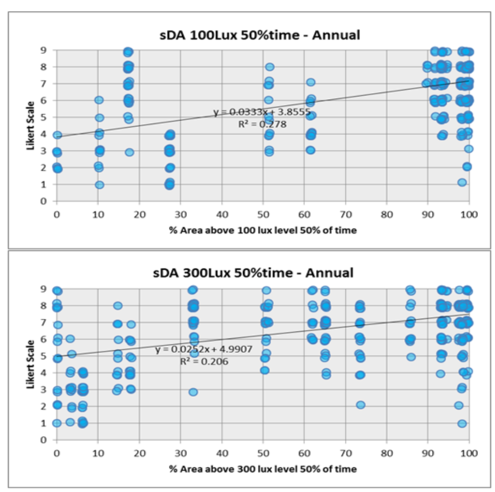

Figure 2 Comparing annual correlation results of percent area above 100 lux and 300Lux (top to bottom respectively) and students' responses to question C, in all study spaces (Group 1)

Similar to point-in-time simulation, in figure 3, annual simulation result is illustrated in a two-way table, percent area versus illuminance indicator thresholds, and is color-coded by students' responses (Likert scale 1-9) to question C "The daylight in this room is always sufficient". Again, students' assessments were divided into three groups based upon Likert scores: Preferred (Likert scores 7-9), Acceptable/Nominal (Likert scores 5-6) and unacceptable (Likert scores 1-4). Then linear trendlines were plotted to show the proportional relationship between acceptable range of percent area and illuminance level based on students' evaluations. The blue trendline interprets the boundary between the unacceptable and acceptable ranges, meaning that a study space would not be designated as daylit if less than the specified percent area, as shown according to the blue trendline, was achieved when referencing a particular illuminance threshold. The purple trendline shows the transition between the acceptable and preferred range of percent area for each illuminance threshold. In other words, an analysis area will be rated preferred, if it meets or exceeds the purple trendline when referencing each illuminance indicator threshold.

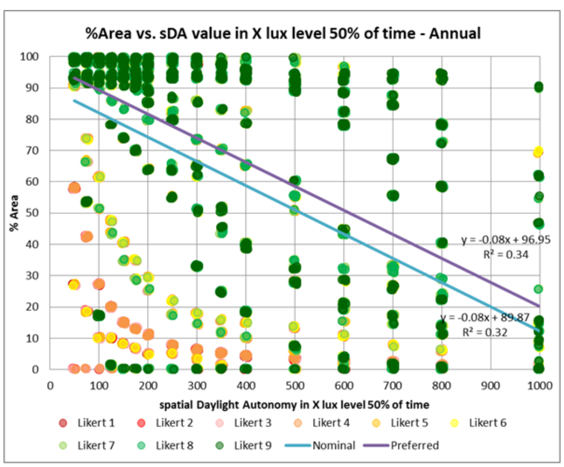

Figure 3 Comparing annual correlation results of percent area and spatial daylight autonomy in different illuminance levels color coded by students' responses (Likert scores 1-9) based on question C

The LM-83 defined parameters for ASE calculation produces a value that represents the percent of an analysis area that exceeds 1000 Lux of "direct sunlight" illuminance for more than 250 hours per year. According to LM-83, preliminary data suggest that if the ASE exceeds 10%, the space will be judged to have unsatisfactory visual comfort. ASE is considered as one of two modeling compliance paths for Indoor Environmental Quality (EQ) Daylight Credit in recently updated version of LEED (V4). According to LEED V4, acceptable spaces are those with at least 55% spatial Daylight Autonomy300/50% (sDA300/50%) and no more 10% annual sunlight exposure1000,250 (ASE1000,250). Preliminary analysis suggests that this ASE criteria may be too restrictive and may result in seemingly well-daylit and visually comfortable spaces not achieving the metric. Nezamdoost and Van Den Wymelenberg (2015) examined LEED V4 criteria for the Indoor Environmental Quality (EQ) Daylight Credit on 22 spaces, but only eight spaces passed. Fourteen of the 22 spaces met the sDA (LM-83) portion of the LEED V4 Indoor Environmental Quality (EQ) Daylight Credit, meaning that 6 of the 14 failed due to the ASE 10% threshold criteria required by LEED V4.

Therefore, a case study analysis of 19 study spaces was conducted and compared several alternate performance criteria. We studied alternate nHours (250, 300, 600 and 900 hours) criteria as proposed by HMG-PIER Review 2012, as well as the maximum number of hours that any one single point in entire room received of direct sunlight (simulated 1000 Lux). Figure 4 illustrates this case study, whereas the primary vertical axis (left) is the percent area above 1000 Lux and the solid colored lines represent alternate numbers of hours; and whereas, the secondary vertical axis (right) is ASE max (maximum number of hours that one single point in entire room achieved direct sunlight) represented by the orange dashed line.

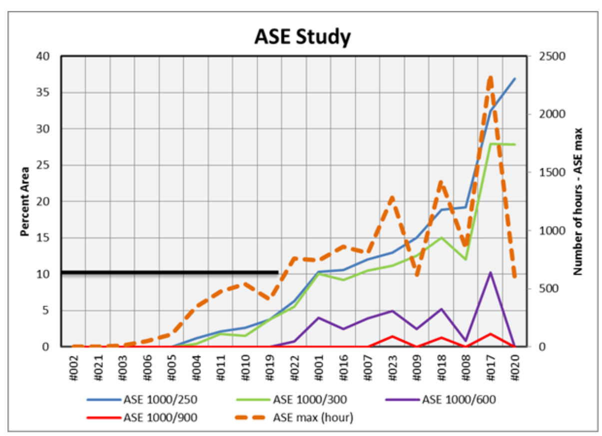

Figure 4 Comparing Annual Sunlight Exposure (ASE) in 250, 300, 600 and 900 nHours indicators plus ASE max; ordered by ASE 1000Lux250hours; the red horizontal line pertains to the left axis and indicates the current LM-83 preliminary criteria (1000/250)

Looking at figure 4, at 250 and 300 hours exceeding 1000 Lux direct sunlight, almost half of study spaces failed, having results higher than 10%. Conversely, the values recorded at 900 hours are too unresponsive to the amount of sunlight - mostly hovering at or just about zero % of the space, and therefore, it does not provide useful information. Interestingly, the 600-hour values show more fluctuation and show variation in rank order as compared to ASE 1000/250. The same can be said for the ASE Max line (orange dashed line, right axis). The IES LM-83 preliminary criteria may need more nuance, but given the greater diversity in results for ASE 250, ASE 300, ASE 600 and ASE Max, one of these indicator values is likely to produce the most discernment in results. However, it appears as though ASE 1000 Lux 250 hours at 10% threshold warrants refinement.

Comparing spatial continuous Daylight Autonomy and spatial Daylight Autonomy

Continuous Daylight Autonomy (cDA) is a variation on Daylight Autonomy that awards partial credit for grid-point-hours less than the target threshold. Although cDA can be said to have greater discernment in spaces with lower illuminances and better sensitivity to small changes, it also suffers from less discernment at higher illuminances. Furthermore, it can be more difficult to interpret differences when comparing two potential designs since two options could potentially have similar cDA values, or both change the cDA by 10%, but it's not clear whether that is due to 300 lux for 10% of the time, or 30 lux 100% of the time. Figure 5 is a compelling representation of the strength and limits of the spatial cDA300Lux/50% time, spatial cDA 500Lux/50% time and sDA 300Lux/50% time in both blinds open and operated using LM-83 blind logic.

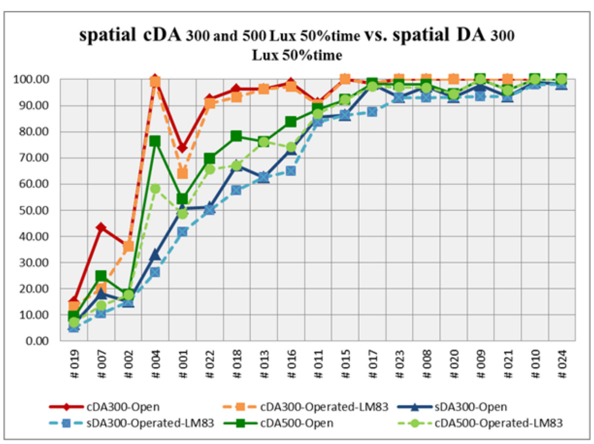

Figure 5 Comparison plot of spatial cDA 300Lux/50%, cDA500Lux/50% and spatial DA 300Lux/50% with blinds open and operated (LM83)

As expected, high values for spatial cDA 300Lux/50% time (Blinds open) were reported. In 15 out of 19 spaces, spatial cDA300/50% is above 90%, which confirms the idea that average daylit spaces report high results for cDA making it more difficult to differentiate between spaces or design options of well daylit spaces.

DISCUSSION

The research plan was conducted to understand how well alternative point-in-time illuminance thresholds and annual simulated daylight results for daylight sufficiency and excessiveness correlate with students' qualitative assessments within 24 study spaces.

The strongest correlations of annual simulation results to students' qualitative assessments were reported in range of sDA100Lux/50% to sDA300Lux/50%; however choosing low illuminance thresholds are not statistically reliable due to not normally distributed data. According to the Pearson R correlation, both variables should be normally distributed (Daniel 1990, Kowalski 1972), but scatter plots in low illuminance thresholds revealed that the results were clustered together, i.e. the median is too close to the maximum value and the sample is not normally distributed.

It was found that a moderating variable defined as "Occupant Visual Brightness Perception" had statistically significant impact on students' responses. By excluding those spaces with high potential for occupant visual brightness perception to impacted results, average correlation values improved from R^2=0.44 to R^2=0.60 in point-in-time, and from R^2=0.21 to R^2=0.43 in annual simulation results, specifically at illuminance thresholds greater than 250Lux. The reason it shows up more at higher illuminances is because at lower illuminance thresholds, spaces are more likely to saturate the low threshold. At higher illuminance levels, spades are less likely to have large portions of the horizontal work plan achieve the higher thresholds, thus there is more opportunity for the vertical surface brightness perception to bias the students' evaluations and result in differences between the subjective responses (Likert scores) and the simulated horizontal illuminance. Additionally, strong correlation results between vertical surface brightness and daylight sufficiency questions confirms the significant impact of vertical surface brightness on occupant visual perception. Therefore, counting only on horizontal grid points is enough for accurate dynamic daylight simulations or not?

The paper has also provided evaluations using equivalent point-in-time daylighting results. The result section reveals that point-in-time simulation outcomes show considerably higher correlation values between students' subjective responses than did annual simulation results. This is possibly due to the relatively better ability of people in evaluating spaces in the observation time than predicting whole year. The higher correlation for point-in-time results could open up a discussion to the question proposed by Van Den Wymelenberg (2014); is there an important difference between visual comfort research results obtained from naïve versus expert participants or occupants versus visitors? For point-in-time analyses, the illuminance indicator value, 250 Lux has the strongest students' opinions about daylight sufficiency. On the other side, at high levels of daylight illumination, very poor R^2 values in glare questions confirm the previous studies that there is not substantial evidence for an upper limit being defined.

Preliminary analysis suggests that the ASE 10% threshold criteria may be too restrictive and may result in seemingly well-daylit and visually comfortable spaces not achieving the metric. Therefore, a case study analysis of 19 study spaces was conducted and compared several alternate nHours (250, 300, 600 and 900 hours) criteria as proposed by HMG-PIER Review 2012, as well as the maximum number of hours that any one single point in entire room received of direct sunlight (simulated 1000 Lux). At 250 and 300 hours exceeding 1000 Lux direct sunlight, almost half of study spaces failed, having results higher than 10%. While a few study spaces face northwest and the sun only comes in to small part of the space in the late afternoon and is not really a problem. Two of study spaces are reading rooms where people can choose where to sit. This suggests that perhaps temporal or space type sensitivity should be applied to these criteria. Given the greater diversity in results for ASE 250, ASE 600 and ASE Max, one of these indicator values is likely to produce the most discernment in results. However, it appears as though ASE 1000 Lux 250 hours at 10% threshold warrants refinement.

Two variations of daylight autonomy, spatial continuous DA300/50% and spatial DA300/50% were analyzed and compared. Generally, most of the study spaces produce very high values for spatial continuous DA300/50%. In fact, 15 out of 19 spaces produce values higher than 90% of the floor area as "daylit" using this metric. This means that study spaces may produce very similar cDA values despite important performance differences making it a difficult metric to use for codes, reach standards, or design decision making. It is possible that a higher illuminance indicator value used with continuous DA could prove more useful at providing this important discernment ability.

CONCLUSION

Some big research gaps can still be seen. Based on this study, still, the better understanding of annual-climate-based daylighting metrics is essential. It seems there is a need to conduct further validation studies of these annual daylighting metrics and criteria in order to increase designers' confidence in their use and to help improve the science of annual-climate-based daylight simulation in the future. Future work should continue to update the proposed illuminance thresholds based on additional human factors and post occupancy studies.

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