

Predicting the Daylit Area - A Comparison of Students Assessments and Simulations at Eleven Schools of Architecture

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Abstract

In recent years climate-based metrics, in particular daylight autonomy, have found their way into North American standards and green building rating systems. The authors showed in an earlier pilot study that subjective space evaluations by architecture students correlated well with daylight-autonomy-based daylit area simulations in a single north-facing studio space in Boston. For this manuscript the authors collaborated with educators at 11 schools of architecture and applied the method consistently to 13 spaces within the participating schools. The schools are located in Brazil (2), Canada (1), Egypt (1) and the United States (7). The authors also introduce the concept of a “partially daylight area” metric based on a minimum illuminance threshold for daylight autonomy of 150lux. The two metrics correctly determined in 18 out of 24 cases which parts of the study space are fully or partially daylit. The authors accordingly propose a two-tier evaluation system to rate the daylight availability in spaces.

1 Introduction

Illuminance-based daylighting metrics have been in use for close to a century to evaluate the daylighting performance of interior spaces. Early examples such as the daylight factor and/or minimum work plane illuminances under select clear sky conditions can be calculated during design but also directly measured in real spaces if outside sky conditions resemble the relevant reference skies. More recently, building standards and green building rating systems have moved towards climate-based daylighting metrics (CBDM) examples being daylight autonomy [Reinhart and Walkenhorst 2001], which is promoted through the Illuminating Engineering Society of North America’s (IESNA) Lighting Measurement #83 (LM-83) [2012] and useful daylight illuminance [Nabil & Mardaljevic 2005]. CBDM consider illuminance distributions under all sky conditions appearing in a space during “regularly occupied hours”. Given that any effort to directly measure a climate-based metric requires a whole year, these metrics realistically have to be determined using a validated dynamic daylight simulation engine such as Daysim [2014] and/or the Five Phase Method in RADIANCE [McNeil & Lee 2013]. LM-83 defines a point in a space to be “daylit” if the daylight autonomy at the point for a target illuminance of 300lux and for occupancy from 8am to 6pm including daylight savings time is over 50% (in short $DA_{300lux}[50\%]$). Daylight Autonomy is defined as the percentage of the occupied hours in a year when the illuminance is above a given target level.

Several studies have suggested that CBDM are conceptually stronger than static daylighting metrics since they are based on a holistic analysis of the daylighting conditions at a site throughout a year [Reinhart et al. 2006; Mardaljevic et al. 2009]. The authors thus welcome the proliferation of CBDM in codes and standards. At the same time, they cautiously observe that the shift towards CBDM moves daylighting design theory and practice away from quanti-

ties that a designer or building occupant can directly experience. It is therefore critical to understand how building occupants rate the daylight availability in spaces vis-à-vis the spaces' $DA_{300\text{lux}}[50\%]$ distribution. The first such inquiry was conducted by the IESNA's Daylighting Metrics Committee during the development of LM-83. In a field study of 61 real spaces building occupant and daylighting expert evaluations were correlated to multiple daylighting metrics of these same spaces via regression analysis [Saxena 2010]. $DA_{300\text{lux}}[50\%]$ yielded the statistically "best fit" within a pool of competing daylight availability/sufficiency metrics. It is important to stress that in the IESNA study test subjects evaluated the daylight availability of the *overall study spaces* whereas a key attraction of the $DA_{300\text{lux}}[50\%]$ concept for design is that it *spatially divides* any building's interior into daylit and non-daylit areas. As an example, Figure 1 shows a perspective view of an imaginary space located in Boston that is daylit by a skylight as well as a west and an east-facing window. The $DA_{300\text{lux}}[50\%]$ distribution shows sufficient daylight availability below the skylight and next to the windows. While the skylight and the larger, east-facing window adequately daylight their portions of the space, the southwest corner seems to be somewhat too dark. This information is "actionable" providing a designer with direct information where within a space daylighting levels are insufficient.

Alas, the just described ability to use $DA_{300\text{lux}}[50\%]$ distributions to spatially distinguish daylit from non-daylit areas was not explicitly tested in the initial IESNA study. The authors therefore saw a need to further investigate whether $DA_{300\text{lux}}[50\%]$ simulations do in fact correlate sufficiently well with spatially resolved occupant evaluations. To advance this question the authors previously devised a classroom exercise called the "daylit area study" in which students of architecture, at the beginning of a course or module on lighting, are asked to subjectively evaluate and draw the daylit area in a partially daylit space on a floor plan of the space provided [Reinhart & Weissman 2012]. $DA_{300\text{lux}}[50\%]$ and other daylight availability metrics can then be compared to the subjective evaluations. The exercise was first used in a 2011 pilot study on the second floor studio of the Carpenter Center at Harvard University. For that space $DA_{300\text{lux}}[50\%]$ simulations exhibited superior spatial agreement with 60 occupant evaluations than other daylighting metrics. Encouraged by the results from the pilot study the authors set out to test the general validity of their findings by repeating the experiment in multiple schools of architecture. To this ends, the authors collaborated with educators at eleven schools of architecture and applied the method consistently to thirteen spaces located within the participating schools. This manuscript reports on the findings of this cross-institutional study.

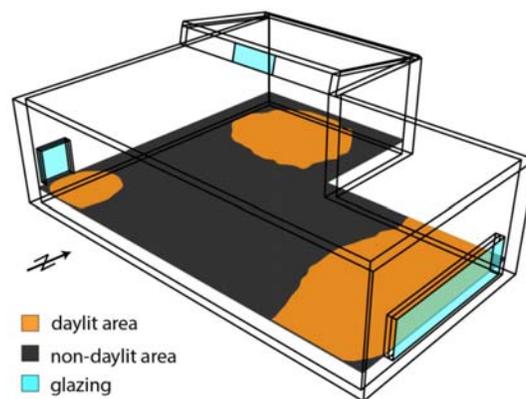


Figure 1: Daylit area distribution in an imaginary top- and sidelit space in Boston according to $DA_{300\text{lux}}[50\%]$
Daylit area distribution in an imaginary top- and sidelit space in Boston according to $DA_{300\text{lux}}[50\%]$

2 Methodology

Participant Recruitment

In September 2011, following the publication of the daylit area pilot study, the authors reached out to fellow building science educators via the Society of Building Science Educators (SBSE) list server (<http://sbse.org>) as well as personal contact lists inviting them to repeat the daylit area study exercise in their classes and to share digital scans of the resulting student assessments and a detailed study space description with the authors. Optical properties of the surfaces and glazings within the scene also had to be provided. Participants had to be university-level building science instructors offering a class or module on daylighting at some point within the 2012 calendar year. In “exchange” the authors offered to provide daylighting analysis results for all study spaces for participating instructors to share with the students. Table 1 lists the instructors and schools that contributed their results to this study.

Table 1: Overview of study participants and spaces

School	Instructor	Course title	Space Type	Size [m ²]	# of students	Surface properties based on	Sky conditions
Ain Shams University, Egypt	Ashraf Nessim	Environmental Control	Classroom	1083	11	Illuminance Meter	Clear
Concordia, Canada	José Candanedo	Building Illumination and Daylight	Classroom	77.5	20	Spectrophotometer	Clear
Federal University of Paraíba, Brazil	Solange M. Leder	Architecture & Urbanism	Complete Floor	308.6	31	CIBSE Chart	Clear
Federal University of Santa Catarina, Brazil	Fernando Rutt-kay Pereira	Architecture & Urbanism	Classroom	45.4	13	Illuminance Meter	Clear
Harvard University, USA	Christoph Reinhart	Environmental Technologies in Buildings	Studio	403.1	60	CIBSE Chart	Clear & Overcast [#]
Iowa State University, USA (ground floor)	Ulrike Passe	Environmental Forces in Architecture	Studio	856.7	21	CIBSE Chart	Clear
Iowa State University, USA (upper floor)	Ulrike Passe/ Kris Nelson	Environmental Forces in Architecture	Studio	802.3	21	CIBSE Chart	Clear
Miami University, USA	Mary Ben Bonham	Environmental Systems II	Studio	449.3	35	CIBSE Chart	Overcast
MIT, USA	Christoph Reinhart	Daylighting	Studio	83.5	18	CIBSE Chart	Clear
MIT, USA	Christoph Reinhart	Architectural Building Systems	Classroom	75.2	18	CIBSE Chart	Clear
Parsons the New School for Design, USA	Matthew Tanteri	Daylight & Sustainability	Studio	616.1	54	CIBSE Chart	Overcast
University of Idaho at Boise, USA	Kevin V.D. Wymelenberg	Daylight Design and Simulation	Lab Room	174.1	13	Macbeth Color Charts	Overcast
University of Southern California, USA	Karen Kensek/ Tyler Tucker	Advanced Environmental Systems	Classroom	48.4	16	CIBSE Chart	Overcast

[#]) Two visits by different classes

Experimental Setup

Participating instructors were informed that study spaces had to be sufficiently deep so that parts of them would in all likelihood be considered to be “non daylit”. To be in line with LM-83, study spaces had to qualify as “common workplace environments” such as open offices, classrooms, meeting rooms, multi-purpose rooms, and service areas in libraries and lobbies. Studio spaces were also included. When in doubt, participating instructors were encouraged to send the authors photographs of potential study spaces.

Same as during the pilot study, students were provided with floor plan printouts to complete the daylit area study exercise. Instructors were encouraged to provide large printouts (e.g. in A3 format) and to mark objects on the floor plan that students could use as a spatial reference such as furniture or large floor tiles. During their visit of the study space, students were asked to draw the daylit area in the space following their intuition and to record illuminance meter readings at selected locations within the space. The suggested wording of the student assignment is shown in Table 2. A completed daylit area study sample is shown in Figure 2. During the assignments the electric lighting in the study space had to be switched off and any movable shading systems fully retracted. The only study space in which the blackout shades were partially lowered during the experiment is the classroom at Concordia University. The instructor conducted the daylit area study under these conditions to ensure that participating students would actually consider parts of the study space to be non-daylit. For the simulation the shades were statically set to the exact same position as during the daylit area study.

Table 2: Wording of student assignment

*A key architectural concept is to divide the floor plan of a building or space into a ‘daylit’ and a ‘non-daylit’ area. Within the daylit area indoor illuminances levels due to natural light should be adequate, useful and balanced for most of the year. In this exercise you are asked to follow your own intuition and divide the ‘taped’ area of **name of study space or spaces** into a daylit and a non daylit area. Please visit the **name of study space or spaces** on **date and time range** and individually conduct your assessment without consulting with the other students. During your visit you will be asked to carry out a series of illuminance measurements and to mark the daylit area on a floor plan of the space that you will be given.*

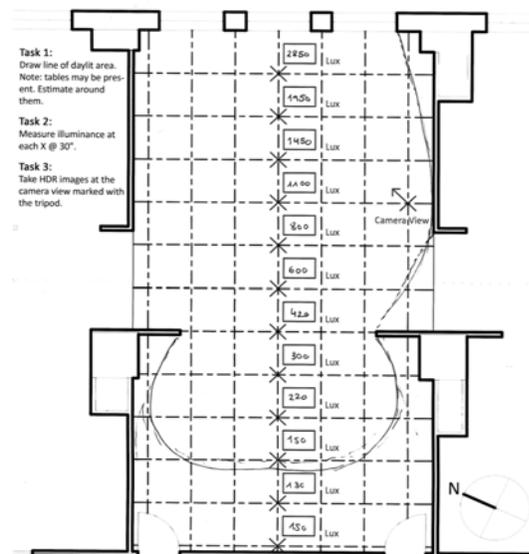


Figure 2: Example of a completed daylit area study form

In addition to the scanned daylit area study forms instructors were asked to provide an accurate three dimensional model of their study space, preferably in the Rhinoceros 3D format as well as multiple photographs [McNeill 2013]. The motivation for requesting Rhinoceros files

was that all daylight simulations in this study were conducted by the second author using the DAYSIM-based DIVA-for-Rhino simulation environment which is a plugin for Rhinoceros [Solemna 2014]. To help participating schools to provide good quality daylighting models, instructors were provided with

- an authorized pre-print of LM-83 which includes specific modeling instructions,
- DIVA help files of how to set up a Rhinoceros model for daylighting analysis¹ as well as
- the “Daylight Simulation Checklist” from the *Building Performance Simulation for Design and Operation* book [Reinhart 2011]

In addition to the scene geometry, optical properties of all relevant surfaces and glazings also had to be provided for the simulations. To determine these properties the authors recommended that participating instructors purchase a reflectance sample card from the Chartered Institution of Building Services Engineers [CIBSE 2001] or an equivalent. Reflectance charts present a low-cost method to determine the visual light reflectance of Lambertian surfaces. Each chart consists of a multicolored reference surfaces of varying known reflectance that are punctured in the center to allow for visual comparison with a sample surface of unknown reflectance below. By placing the reflectance chart on a sample surface, an observer can visually determine which reference surface the unknown surface is closest to. The reflectance of the sample roughly corresponds to that of its closest reference surface. As shown in Table 1, CIBSE reflectance sample cards were used to determine material surface properties in nine out of the thirteen study spaces. One instructor used a Macbeth color chart in combination with a digital camera and a Radiance calibration routine to determine the diffuse reflectance of scene surfaces.² Two instructors approximated the reflectance of surfaces with two illuminance meter readings, one facing towards and another away from the surface in question. One instructor used a Konica Minolta CM-2500D Spectrophotometer to determine the reflectance all scene surfaces. All instructors estimated the visible light transmittance of glazing units in their scene by placing an illuminance meter under diffuse sky conditions first inside and then outside of the glazing facing outwards. The resulting estimated direct glazing transmittance is the ratio of the inside to the outside illuminance meter readings.

Survey Evaluation

All paper-based daylight area study evaluations were scanned and forwarded to the authors. The daylight area boundary lines for each evaluation were then added to the Rhinoceros model of the space. Figure 3(a) shows an example set of evaluations for the top and sidelit study space from Miami University (Figure 4). As one would expect all student evaluations indicate a daylight area that is somewhat concentric with the area underneath the central clearstories. The challenging task for the authors was to find a generalized way of how to average the daylight area evaluations from multiple individuals. The space for the pilot study is sidelit from one side only and the mean of multiple evaluations was simply determined by calculating the mean difference of the daylight area boundaries lines from the window. This concept works well for the pilot study space but becomes ambiguous in more general situations. For this and future studies the authors hence propose to use an “area-based” averaging function. The idea is to overlay all daylight area evaluations on top of each other and to identify the area for which at least 75% of all evaluations state that it is daylight. This area is in the following termed “fully daylight”. Similarly, one may determine the area within a space for which at least 25% of evaluations assume that it is daylight. This becomes the “partially daylight area”. The partially daylight area necessarily includes the fully

¹ URL: <http://diva4rhino.com/user-guide/getting-started/model-setup> Accessed Jan 6 2014

² G. Ward, Radiance script to compute color compensation based on measured Macbeth chart, URKL http://radsite.lbl.gov/radiance/man_html/macbethcal.1.html

daylit area. An advantage of this definition is that it may unambiguously be applied to any possible space geometry. It is also easy to motivate: “The daylit and partially daylit areas within a space correspond to areas for which either the majority (>75%) or a sizable portion (>25%) of occupants vote that the space is daylit. The remaining area is ‘non daylit’”. Figure 3(b) shows the resulting distribution for the study space at Miami University. The advantage of introducing a partially daylit area for design purposes is that it provides a sense of how abrupt the transition from daylit to non-daylit is. If the daylight falls off dramatically within a space then one is likely to also find that different occupants will draw very similar daylit area boundaries. If on the other hand the lighting falloff is more gradually, it is less likely that different individuals will draw the same boundary line between daylit to non-daylit. One of the study goals for the authors was to identify a simulation-based equivalent for partially daylit areas similar to the earlier described $DA_{300lux}[50\%]$ concept for fully daylit areas.

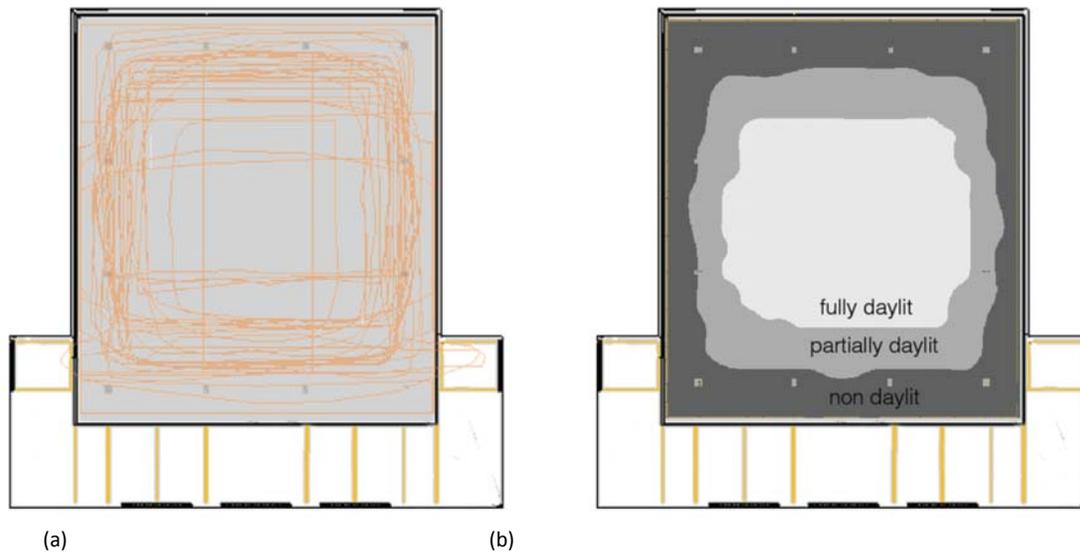


Figure 3: (a) Scanned in daylit area study evolutions for Miami University; (b) resulting fully and daylit areas (up is North)

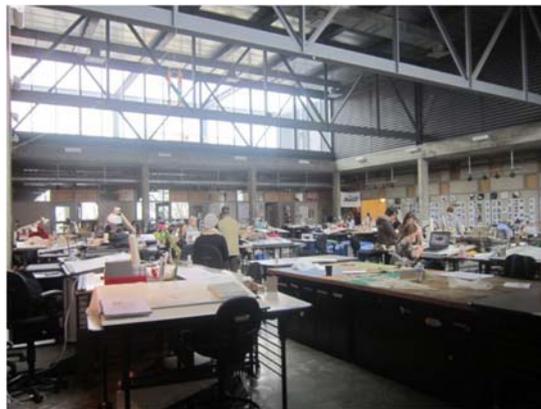


Figure 4: Photo of toplit study space at Miami University

Daylight Simulations

To ensure consistency between simulation results across all spaces, the second author conducted all daylight simulations for this study using the Rhinoceros files plus measured material surface properties and photographs provided by the participating schools. For each study space

the second author initially compared the Rhinoceros models with the provided photographs as well as Google Earth aerial images of surrounding buildings and landscape. This proved to be a fast and effective way to detect inconsistencies or missing elements in the models such as surrounding context, hung ceilings and vegetation. Other initial models were either BIM models that included unnecessary details that had to be simplified such as door knobs, ceiling fans or multiple surfaces for glazing materials, or were too basic with no ground surfaces or massing for neighboring buildings and trees. In most cases these model shortcomings for daylighting analysis were effectively resolved by going back and forth once or twice between the second author and participating instructors. Once all models and materials seemed “plausible” and consistent with the photos, a set of daylight metrics were calculated using Radiance and Daysim in DIVA-for-Rhino. The simulation parameters used in all simulations are documented in Table 2.

Table 2: Radiance simulation parameters used for all study spaces

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold
7	1500	20	0.05	300	0

In order to also determine what might be a simulation-based partially daylit area in the above described sense, the authors proposed a variation of spatial daylight autonomy with a target illuminance of 150lux. The ensuing hypothesis going forward is that the $DA_{150lux}[50\%]$ area is a good simulation-based metric to mimic the partially daylit areas according to the daylight area evaluations. Figure 5 shows the simulation-based fully and partially daylit areas for the example space from Figure 1.

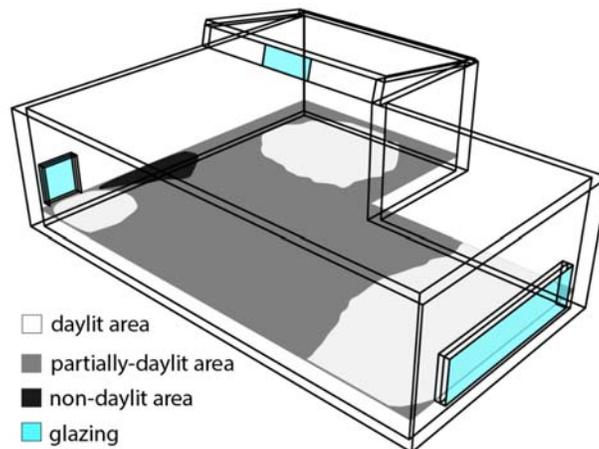


Figure 5 Fully and partially daylit area in a top- and sidelit space in Boston according to $DA_{300lux}[50\%]/DA_{150lux}[50\%]$

3 Results

Fully and Partially Daylit Areas

Figure 6 shows the fully daylit (white), partially daylit (light gray) and non daylit (black) areas in all thirteen study spaces based on student evaluations and $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ simulations. In 11 out of 13 spaces the conceptual shapes and sizes of the partially and fully daylit areas according to evaluations and simulations largely coincide. For two spaces there are fundamental differences: Ain Shams University and Federal University of Santa Catarina. In Ain Shams the students identified two substantial fully daylit areas next to the window bands along the west and east facades whereas the simulations predict a large, partially daylit area extending

across the whole length of the space from the west facing façade three quarters into the space with only minimal stripes of fully daylighted areas. For the Federal University of Santa Catarina the students found fully and partially daylighted areas near the openings whereas the simulations suggest that the space is fully daylighted throughout.

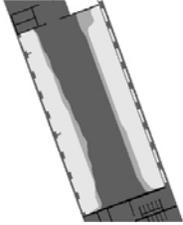
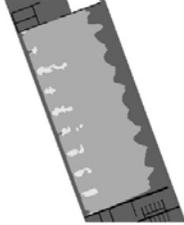
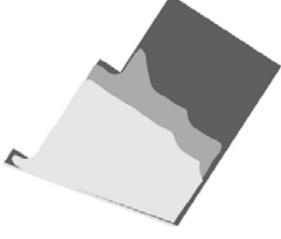
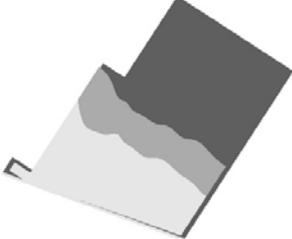
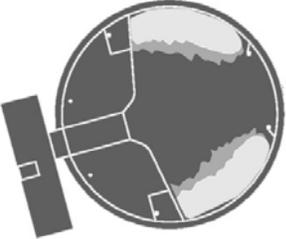
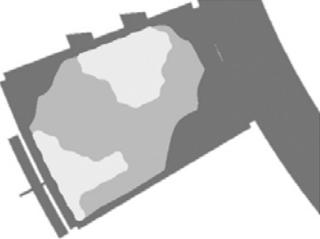
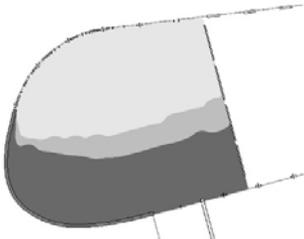
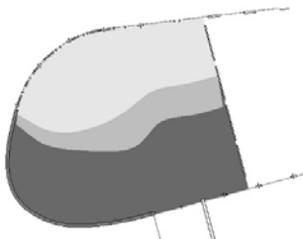
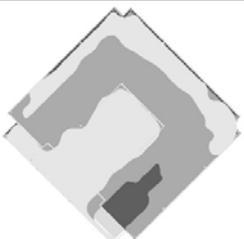
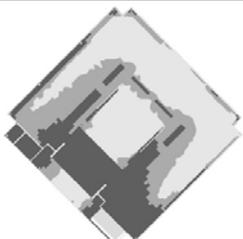
Apart from these two “outlier spaces”, two other spaces show notable differences between student evaluations and simulations. For the Federal University of Paraíba the fully daylighted area according to student evaluations is considerably smaller than for the simulations but the partially daylighted areas largely coincide. A potential explanation for that discrepancy is that for the large empty space without furniture direct sunlight patches on the floor were interpreted by some students as “the daylighted area”. A second notable difference can be found in a rectangular area on the ground floor of Iowa State University near the Southwest façade which the students evaluated as fully daylighted but which is non-daylighted according to the simulations. Further inspection of that area revealed that it is a glazed staircase. What might have happened is that the students logically evaluated the daylighted on the staircase whereas the simulations referred to a grid of illuminances under the staircase.

As far as owners and green building rating systems such as the US Green Building Council’s LEED system are concerned, a key performance indicator for daylight is the overall percentage of regularly occupied zones within a building that are daylighted. Figure 7 hence compares the percentage of fully and partially daylighted areas in all thirteen study spaces according to student evaluations and simulations. The values for partially and fully daylighted areas for each space are connected with lines to guide the readers eyes. The lines for the two outlier spaces are dashed to visually separate them from the remaining spaces. Figure 7 further shows a gray area around the identity line. For points within this area simulations predict the size of the fully and partially daylighted areas within 15 percentage points. These 15 percentage points were chosen by the authors to represent an “acceptable” error range for a rating system credit. In 8 and 10 out of 13 spaces the fully and partially daylighted area are estimated by the simulations within this error range which corresponds to a success rate of 69% (16/26). Without the two outlier spaces the ratio of acceptable predictions increases to 8 (fully daylighted) and 9 (partially daylighted) out of 11 spaces or a success rate of 77% (17/22). While these findings are encouraging, the question arises why the $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ method failed in two spaces.

Analysis of Outlier Cases

The study space at Ain Shams is a long studio with narrow vertical band of glazed openings facing Northeast and Southwest. Anecdotal evidence suggests that the electric lighting is typically always switched on. The simulations indicate that between 8am and 6pm daylighting levels half of the time hover between around 150lux and 300lux and are even lower otherwise. This space does accordingly not seem to be fully daylighted. So, how may one explain the student evaluations? Effectively, these individuals were asked as part of a course assignment to indicate where a study space is daylighted. This question strongly suggests that the space is in fact daylighted. So instead of looking for truly adequate daylighting levels the students probably selected areas where they detected any daylight during the time of the assignment.

On the other end of the spectrum the Federal University of Santa Catarina space is completely daylighted throughout the year according to the simulations whereas many students only marked the areas right near the windows to be daylighted. The situation might have been similar to Ain Shams, i.e. in absence of insufficient daylighting levels many students started to mark illuminance contrast distributions instead.

North 	Student Evaluations  75%  25%	Simulations  DA300lux[50%]  DA150lux[50%]
Ain Shams University, Egypt 		
Concordia University, Canada 		
Federal University of Paraiba, Brazil 		
Federal University of Santa Catarina, Brazil 		
Harvard University, USA 		
Iowa State University, USA (ground floor) 		

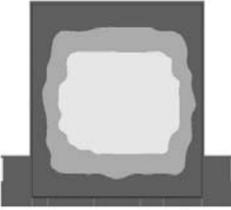
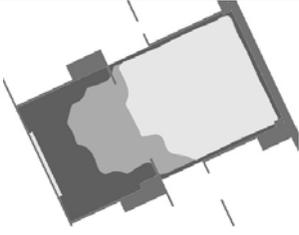
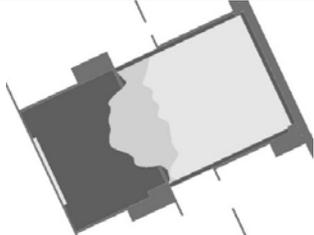
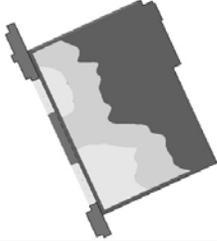
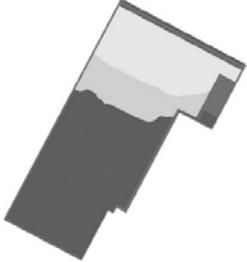
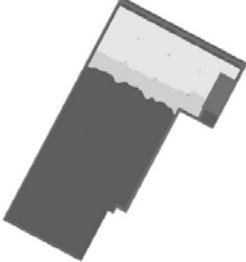
<p>Iowa State University, USA (upper floor)</p> 		
<p>Miami University, USA</p> 		
<p>MIT, USA</p> 		
<p>MIT, USA</p> 		
<p>Parsons the New School for Design, USA</p> 		
<p>University of Idaho at Boise, USA</p> 		
<p>USC, USA</p> 		

Figure 6 Fully and partially daylit areas in the twelve study space according to student evaluations (left) and DA_{300lux}[50%]/DA_{150lux}[50%] simulations (right)

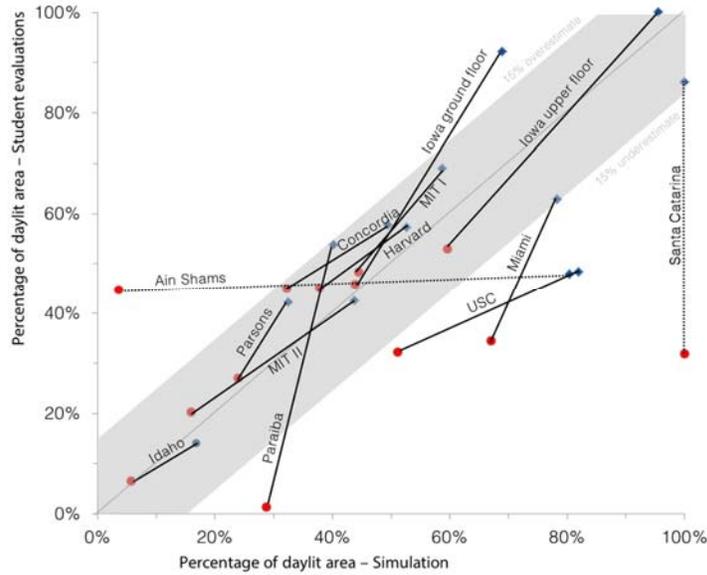


Figure 7 Percentage of study space areas that are fully and partially daylight according to student evaluations and $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ simulation

Using $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ Simulation for Design

As noted in the introduction, a particular charm of the $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ concept for design purposes is that (if it works) it allows designers to focus their attention to areas with insufficient daylight. To test the validity of this design procedure, Table 3 shows for all study spaces the percentages of the simulation-based fully and partially daylight areas that overlap with the areas that were determined to be fully and partially daylight by the students. For the fully daylight areas the numbers in brackets indicate that an area was considered by the students to be partially daylight. A percentage of 100% indicates that all areas within a space which the simulations qualified to be fully or partially daylight was also voted as such by the students. On the other hand, a percentage of zero indicates that there is no overlap between the student evaluations and the simulations. In a worst case scenario half of a space could be determined to be fully daylight by the simulations while the students vote the other half to be daylight. In that case the area sizes in Figure 7 would be identical but the overlap in Table 3 would be zero.

Table 3 shows that in 8 out of 13 spaces over 80% of the daylight area according to $DA_{300lux}[50\%]$ are also fully daylight according to the student responses. For 4 of the remaining 5 spaces over 80% of the $DA_{300lux}[50\%]$ areas are least partially daylight according to the students. The only space where only 67% of the $DA_{300lux}[50\%]$ area is determined to be at least partially daylight by the students is Paraisba. Similarly, in 8 spaces at least 80% the $DA_{150lux}[50\%]$ areas overlap with the student evaluations. The lowest overlap is found for Ain Shams and USC.

4 Discussion

Implications for Rating Systems and Standards

The Result section has revealed that using $DA_{300lux}[50\%]$ and $DA_{150lux}[50\%]$ simulations to determine which parts of a space are fully or partially daylight lead in about 70% of all investigated situations to an agreement with student evaluations within 15% of the overall size of a space. The authors feel that this finding supports the use of the $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ concept for two tier evaluations of daylight spaces: A green build-

Table 3: Overlap between Simulation and Student Evaluations

School	Overlap between Simulation and Student Evaluations [% of area]	
	Full Daylit	Partially Daylit
Ain Shams	86 (92)	44
Concordia (Canada)	98 (98)	98
UFSC (Brazil)	32 (86)	86
Harvard	100 (100)	90
Idaho	89 (98)	74
Iowa State - G.F	63 (100)	99
Iowa State - 1st. F	68(100)	103
Miami	52 (88)	80
MIT – I	97 (100)	100
MIT – II	84 (100)	83
Parsons	99 (100)	100
USC	61 (93)	59

ing rating system or building standard could accordingly provide say one credit point if at desired proportion of a space is “partially daylit” and a second credit point if that proportion is also fully daylit. The goal of the present study was not to determine what this desired proportion should actually be but rather what the relationship between a $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ simulation and occupant/student evaluations is. It was hence shown that in 11 out of 13 spaces the simulation-based fully and partially daylit areas largely corresponded to areas for which either the majority (>75%) or a sizable portion (>25%) of occupants voted that the space is daylit.

For the two outlier spaces the authors formulated the hypothesis that the spaces can indeed (as the simulations indicate) be considered to be largely non-daylit (Ain Shams) or completely daylit (Santa Catarina) and that the student evaluations were biased due to the need to complete an assignment. This hypothesis is thus mostly concerned with validity of the daylit area study method itself, suggesting that the method can only be reliably applied in spaces that are neither fully nor under-daylit. How can a designer determine whether this is the case? Under-daylit spaces can be identified with $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ simulations. For completely daylit spaces simulation methods concerned with glare and illuminance contrast have to be employed in combination with the daylight availability simulations.

Considering that the $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ concept worked this well for the 13 study spaces, the authors encourage design professionals to apply it to their design projects in combination with the above mentioned glare and contrast simulations. The authors further recommend that code officials and technical committee members for green rating systems consider the concept as an additional compliance path for credits related to daylight availability. The adoption of the $DA_{150lux}[50\%]$ concept, albeit new, also seems worth considering given its appeal for design which is discussed in the following section. It is further worthwhile pointing out that the effort and time required to run only a $DA_{300lux}[50\%]$ simulation or a combined $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ simulation is identical since both cases are based on the exact same annual illuminance time series.

Design Implications

Moving beyond the standards and rating systems, the authors first and foremost support the use of $DA_{300lux}[50\%]/DA_{150lux}[50\%]$ simulation for iterative spatial design investigations. Table 3 shows that areas that are fully, partially or non daylit overlapped to a high degree with those of the student evaluations and that simulation results can hence be applied to vary window size

and layout as well as to modify material finishes. One particular benefit of floor diagrams such as in Figures 5 and 6 is that they show a gray transition area between daylit and non-daylit which starts to account for the subjective nature of light evaluations of spaces.

Open Questions

One caveat related to this study is that the use of dynamic shading systems has not been addressed thus far even though methods to model the use of movable shading systems have been proposed in the past [Reinhart 2004; Haldi & Robinson 2010; O'Brien et al. 2013]. The reason for this shortcoming is that it is doubtful whether students and or in fact any non-expert visiting a space for a single time could possibly predict the implications of a shading device and control situation over a whole year. A potential way to still link occupant evaluations to simulations is to have the occupants visit multiple times when the shading device is set to different positions. This caveat does not imply that the authors discourage the use of dynamic shading models to predict the daylit area in a space. In fact, the Concordia space in which the blinds were partially lowered showed that student evaluations matched well a climate based simulation in which the blinds were always in the same position. Modeling the space with the blinds in different positions throughout the year hence seems justifiable if indeed the dynamic shading model used either models an automated shading system or – in the case of a manually controlled system – adequately accounts for visual comfort and overheating.

5 Conclusion

In closing, this manuscript confirms that research on daylight availability metrics has matured, and daylight autonomy based simulations should be adopted by both designers and rating systems. Going forward, daylighting research should turn towards evaluating visual comfort and its relationship to the control of dynamic shading systems, which can optimize occupant comfort as well as reduce energy use from electric lighting and space conditioning. Pedagogically, the study offers a method of teaching architecture students the relationship between their intuition and perceptions of the physical world, and the digital analytical methods described. On a larger level, this study demonstrates the benefit of cross-university collaboration of instructors at schools of architecture across the world on matters related to environmental performance evaluation of buildings and spaces. In fact, as building standards and rating systems have become increasingly stringent and far-reaching, this type of collaboration has become increasingly important as an efficient method of testing multiple environmental conditions simultaneously. At the end of the day, architects, with the help of consultants, design building layouts and facades. Architects therefore must be aware of the performance metrics imposed on their designs, understand them, and have a say in their selection and deployment. The LORAX project, which supported the writing of this manuscript, serves as a leader of this charge, namely to give architectural students and educators a voice in the development of green building rating systems.

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