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The daylit area — Correlating architectural student assessments with current and emerging daylight availability metrics

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**Abstract**

This paper proposes a method for testing current and emerging daylight availability metrics such as daylighting factor, daylight autonomy, useful daylight illuminance and LEED 3.0 requirements against building occupant assessments of a daylit space. During spring 2011 the method was tested as a classroom exercise by 60 architectural students enrolled in two graduate level building science courses in the second floor studio space of le Corbusier’s Carpenter Center in Cambridge, MA, USA. The results from this test yielded that the Lighting Measurement protocol for Spatial Daylight Autonomy, that is currently being developed by the Illuminating Engineering Society of North America (IESNA) daylighting metrics committee, reproduced the student assessments of the daylit area in the space more reliably than the other tested daylight availability metrics. These findings are preliminary and still need to be validated and refined in other spaces. Apart from providing valuable data points for scientific experiments, the method also has substantial educational value as a teaching exercise for architectural students to develop an intuitive understanding of contemporary daylight performance metrics, as well as a feeling of how their personal lighting preferences compare to these metrics.

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1. Introduction

What is daylighting, why are we pursuing it, and what is a well daylit space? The answers to these questions are complex and subjective. A rather unambiguous response to the first question is that daylighting describes the controlled use of natural light in and around buildings. Several drivers exist for why one might want to implement daylighting. A starting point for most explorations on daylighting describes the amount of daylight available in a space over the course of a year. A starting point for most explorations on daylighting describes the amount of daylight available in a space over the course of a year. A starting point for most explorations on daylighting describes the amount of daylight available in a space over the course of a year. A starting point for most explorations on daylighting describes the amount of daylight available in a space over the course of a year. A starting point for most explorations on daylighting describes the amount of daylight available in a space over the course of a year.

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1 The first author previously used the term daylight availability to describe “how much daylight is available in a space over the course of a year” whereas the IESNA Daylighting Metrics committee has started to use daylight sufficiency to name the same concept. In the following, both terms are considered interchangeable.

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2. Review of daylight availability metrics

A variety of daylight availability metrics based on rules of thumb and computer simulations have been proposed in the past. The most common rule of thumb used to rate daylight availability in...
a sidelit space is the window-head-height rule of thumb. The rule relates the distance from floor to the head of a window to how far “adequate, useful and balanced daylight enters the spaces for most of the year” [2]. A simulation-based validation study of this rule of thumb for unobstructed facades yielded that “in a standard, office-type sidelit space equipped with venetian blinds, the depth of the daylit area usually lies between 1 and 2 times the size of the window-head-height. For spaces such as atria or circulation areas that are not equipped with movable shading devices, the ratio range can increase up to 2.5” [2].

The most common computer-based evaluation of daylight availability to date begins by defining a grid of upward facing sensors offset from the floor (usually at desk height) followed by an evaluation of the daylight at these sensors using various criteria/metrics. The oldest daylight availability metric is daylight factor, defined as the ratio between the illuminance at a sensor point inside the space to the illuminance at an unshaded, upward facing exterior reference point, under CIE standard overcast sky conditions [3]. Since 2001, substantial effort has gone toward the development of climate-based daylighting metrics [4-7]. Similar to daylight factor, these metrics employ a grid of sensor points, but the daylight availability evaluation is based on illuminance levels under multiple sky conditions, usually all sky conditions appearing during hours of the year when a space is occupied.

In order to be of direct use for design evaluations, daylight availability metrics are usually coupled with a benchmark, or cutoff level, above which a point in a space is defined to be “daylit”. The usefulness of benchmarks is that a space can be divided into a daylit and a non-daylit area. For example versions 2.2 and earlier of the popular LEED green building rating system from the US Green Building council, promoted a daylight, or glazing factor of 2% as a minimum benchmark level [8]. LEED Version 3.0 requires a minimum light level of 25 footcandles (269lux) on the equinox at 9 am and 3 pm under CIE clear sky conditions [9]. At the time of writing, the Daylight Metrics Committee of the Illuminating Engineering Society of North American (IESNA) was in the process of completing a new Lighting Measurement (LM) protocol that promoted a daylight autonomy (DA) type metric to characterize daylight availability/sufficiency in spaces [10]. Daylight autonomy is a climate-based metric defined as the percentage of occupied times in the year during which minimum, program-specific illuminance levels can be met by daylight alone [4]. The IESNA committee currently favors a target illuminance 300lux for offices, classrooms and library type spaces, occupied hours from 8 am to 6 pm local clock time. If applicable, venetian blinds are operated hourly to block any direct sunlight into the space. According to the IESNA LM, a point is considered to be “daylit” if the daylight autonomy exceeds 50% of the occupied times of the year. The LM is partly based on expert and building occupant surveys in 61 daylit spaces [11]. However, the surveys only addressed overall daylight levels in the test spaces, without addressing the spatial distribution of daylight within these spaces.

Fig. 1. (a) Outside view looking South of the 2nd floor studio space of the Carpenter center. (b) Inside view looking North of the 2nd floor studio space of the Carpenter center.

Fig. 2. Assignment given to the students; floor plan of the 2nd floor studio space of the Carpenter center.
Another climate-based metric called **useful daylight illuminance** (UDI) was introduced by Mardaljevic and Nabil in 2005 [5]. UDI largely resembles DA but defines lower and upper illuminance thresholds of 100 lux and 2000 lux for daylight to be “useful”. Due to the two levels, each point in a space has three UDI values: the percentage of the occupied time when the illuminance at the point is below 100 lux, above 2000 lux or in between. In a later paper Mardaljevic, Heschong and Lee further subdivided the 100–2000 lux “useful” UDI bin into a “supplementary” (100–500 lux) and an “autonomous” (500–2000 lux) range [7]. In the simulations below, it is assumed that the daylit area corresponds to the “useful” 100–2000 lux range.

The present study takes a step back from these theoretical approaches toward defining daylight availability and instead explores how architectural students, following their own intuition, divide a given sidelit space into a “daylit” and a “non-daylit” area. As described above, traditionally, the use of upward facing illuminance measurements has served to make such a distinction. But, to the authors’ knowledge, the only documented study in which a group of individuals was asked to intuitively locate the boundary of the daylit area within real spaces is a technical paper published in 1931 [12]. In that study a jury of experts and a group of building occupants evaluated 20 rooms in the UK’s then new government building, Whitehall. The jury located the daylit area boundary at around 0.2 percent of the sky factor (around 10 lux target illuminance). While a recent analysis [13] of the composition of that jury raised concerns regarding the objectivity of these results, which indeed seem very low, the authors still find the basic study approach solid and therefore asked 60 architectural students to draw the boundary of the daylight area in a north facing sidelit space. Afterward a series of daylight availability metrics were calculated for the space and the resulting daylit area boundaries were compared to the student assessments.

Several arguments exist as to why one is actually unlikely to find good agreement between the illuminance based daylighting metrics mentioned above and occupant assessments. First, work plane illuminances, the amount of variable light falling on real or virtual surfaces, may be considerably different than what we see, namely light that is emitted off a surface toward our eyes (luminance). Second, the human eye is weak at detecting absolute illuminance levels, meaning that even if a test subject wanted to determine the “300 lux boundary” within a space, he or she could not determine this line without an

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**Table 1**

<table>
<thead>
<tr>
<th>Description</th>
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<td>Void glass carpenter glazing 0 0 5 0.2 0.2 0 2 0 0</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Sample assignment result with cross point and cross point illuminance (38 lux) and distance to façade (11.7 m).

**Fig. 4.** Radiance model of the Carpenter center.
illuminance meter. Third, given that sky conditions, and hence interior lighting levels, are constantly changing, it is unlikely that occupants can mentally average the location of the 300lux boundary over time, especially for a space in which they have not spent a lot of time. Finally, the perception of where the boundary between the daylight and the non-daylit area lies is likely to have a strong subjective element, so that different individuals will likely make very different assessments. Despite this series of arguments why current daylight availability metrics and occupant assessments might not correspond, the authors conducted this experiment because the underlying promise of daylight availability metrics is that they do in fact predict the daylit area in spaces. Designers frequently use either of the above outlined daylight availability metrics to determine where the daylit area lies and what percentage of a space is daylit. This paper thus puts this promise to a first, direct test in a single space.

At this point it is already important to mention that — beyond a validation of the metrics — introducing students to the concept of a “daylit area” helps them to better understand the role of daylight in architectural space as well as to “calibrate” their own assessment of daylit spaces against current and emerging daylight availability metrics.

3. Methodology

3.1. Student assignments

During spring 2011 the first author taught two semester-long graduate-level classes to architectural students, a required introductory class on Environmental Technologies in Buildings (6205) and an elective class on Daylighting Buildings (6332). Enrollments for the classes were 45 and 15 students, respectively. There was no student overlap between the two classes. Course 6205 was concerned with basic phenomena of heat flow, lighting and acoustics whereas the primary focus of Course 6332 was the study of natural and electric lighting in an architectural context. At the very beginning of 6332 and at the beginning of the lighting module in 6205 students were given the following 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 2nd floor Studio in the Carpenter Center into a daylit and

**Table 2**

<table>
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<tr>
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<th>Ambient division</th>
<th>Ambient sampling</th>
<th>Ambient accuracy</th>
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**Fig. 5.** Individual and mean daylit boundary for courses 6205 (a) and 6332 (b).
Please visit the studio 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.

The Carpenter Center, which houses Harvard University’s Department of Visual and Environmental Studies (VES), was designed by Le Corbusier and completed in 1962 (Fig. 1). As the study required that the test space would have both daylit and non-daylit areas, the studio was chosen for its generous room depth of 19.5 m from the window plane to the back wall with no obstructions except for a few columns. A north facing space was chosen for the study to minimize the potential for direct sun during testing and to thus avoid having to consider venetian blinds. The ceiling height throughout the space was 12 feet (3.66 m). During their visit, the students were given Tabloid-sized copies of the floor plan (Fig. 2) and initially asked to draw the boundary of the daylit area. The students were then asked to measure illuminance levels at desk height along the center gridline of the space at intervals correlating to the 7 feet (2.12 m) floor grid. The grid was also provided on the plan (dashed lines in Fig. 2) to aid students in observing their location in space. Note that for consistency, this grid was also used for the digital analysis (see below). Fig. 3 shows a sample assignment result. The point at which the daylit boundary line crossed the center gridline is in the following referred to as the “cross point”. Each cross point has an associated illuminance level (based on the students’ illuminance meter readings) and distance to the North façade as shown in Fig. 3. The cross point illuminance

![Image](https://example.com/image.png)  
**Fig. 6.** Mean boundary lines for 6205, 6332 and total mean boundary line encompassing 164 m².

![Image](https://example.com/image.png)  
**Fig. 7.** a and b: Distribution of cross point illuminances for 6205 and 6332.

and distance to the façade in Fig. 3 were added later by the authors to explain the concept.

As a side note, the significance of using the Carpenter Center for this exercise is not lost on the authors, as Le Corbusier’s climatic analysis largely relied on intuition in the design and application of forms for daylight modification to create an “espace ineffable.” In the Carpenter Center, only the size of the bris soleil was calculated [14]. As this research seeks to help quantify intuition, it seems appropriate that the test would occur in a space that was also largely designed based on intuition.

3.2. Simulations

For the simulation-based analysis of various daylight availability metrics, a detailed digital model of the Carpenter Center and a massing model of surrounding buildings was generated in Rhinoceros [15] based on university owned floor plans and sections as well as building visits (Fig. 4). Using the DIVA for Rhino plug-in, the model was exported into the validated Radiance/Daysim daylight simulation programs [16–18]. Daylight factor, interior illuminance distributions on solstice days at 9 am and 3 pm and daylight autonomy distributions according to the IESNA RP were calculated in Radiance/Daysim for the 2nd floor studio using a grid resolution of 0.5 m. For the solstice calculations the standard clear CIE sky with a sun was used via the gensky Radiance program.

Material definitions were set by assessing materials in the actual space using a CISBE Surface and Reflectance Chart [19]. Direct normal visual transmittances of the glazings were estimated through metering light levels on both sides of the glass (Table 1). The Radiance simulations parameters used are listed in Table 2.

4. Results

4.1. Assignment results

15 students enrolled in GSD course 6332 completed their assignments on February 14, 2011, a mostly sunny day. On April 4, 2011, a mostly overcast day, 45 students enrolled in GSD course 6205, repeated the experiment. All participants were asked to make their recordings between 11 am and 2 pm on the given day. Submitted assignments were then digitized and the daylit area boundaries were traced and compiled using the Adobe Creative Suite software [20]. After importing all vectors into Rhinoceros, a Grasshopper script was used to assess where all lines intersected the Carpenter floor grid [21]. Fig. 5 shows the resulting daylight boundaries. Most boundary lines have the form of an arch that is furthest away perpendicular to the center of the North facing glazing. On the other hand, a substantial degree of discrepancy exists between the exact location of the boundary lines. The size of
the daylit area formed by the façade and the boundary line varies between 100 m² and 248 m².

In order to determine the “mean daylit boundary” for all student submissions, the following procedure was employed at each vertical gridline intersection (Fig. 3): The projected distances between the North façade and each boundary line were determined. The mean daylit boundary position was then defined as the arithmetic mean of all of these distances. The resulting mean daylit boundaries for both courses are shown in bold in Fig. 5(a) and (b). Fig. 6 shows the mean daylight boundary for both courses as well as for all samples taken together. The three lines lie surprisingly close together with daylight areas ranging from 161 m² for 6205 to 169 m² for 6332, resulting in an overall mean of 164 m².

This is actually somewhat surprising given that the two student groups evaluated the space under very different sky conditions. Figs. 7 and 8 show the distributions of the cross point illuminances and the distances to the North façade as defined in Fig. 3 for 6205 and 6332, separately. Fig. 7 shows that the illuminances for the cross points were higher for 6332 than for 6205 students due to different prevalent sky conditions for both groups. Fig. 8 reveals that the chosen distances to the North façade were more similar for both groups. The average cross point illuminance and distance to the north façade for all students was 144 lux at 9.2 m as denoted by the X in Fig. 8. The mean daylit boundary for all assignments (Fig. 6) will be used in the comparison to daylight availability metrics below.

4.2. Comparison to daylight availability metrics

According to the above cited window-head-height rule of thumb for a space without venetian blinds, the daylit area extends about 2–2.5 times the window-head-height into the space. The rule was originally derived for a straight façade [2]. In order to apply it to the strongly bent North window in the Carpenter Center, the different distance lines were simply drawn as parallel offsets to the glazing. Fig. 9 accordingly compares the mean daylit boundary line form Fig. 6 with the rule of thumb predictions for various multiples from the façade. It is interesting to see that — except for the region close to the left window edge — the mean daylight boundary lies within or very close to the range predicted by the zone suggesting that the rule of thumb is consistent with the user evaluations. Near the left edge of the North glazing, the assessments and the rule of thumb show opposing trends with the mean daylight boundary

Fig. 10. Comparison of the mean daylit boundary with the 2% daylight factor line.

Fig. 11. Comparison of the mean daylit boundary with the 269 lux lines under clear sky conditions on September 21st at 9 am and 3 pm.
moving toward the façade. This suggests that the rule of thumb cannot be simply applied to curved glazings as suggested above. Fig. 10 shows a comparison of the mean daylit boundary line with the 2% daylight factor line. There is good agreement between the two lines near the left edge of the glazing. But, near the grid centerline, the daylight factor line lines 28% closer to the façade than the mean daylit area boundary meaning that the former substantially underestimates the size of the daylit area throughout the space (122 m² opposed to 163 m²). This result is somewhat disappointing for the daylight factor, given that the investigated space is north facing and thus barely ever subject to direct sunlight.

Fig. 11 compares the mean daylit boundary line with the 250lux lines under clear sky conditions on September 21st at 9 am and 3 pm (LEED 3.0 daylighting credit). While the 9 am LEED line marks an area that is only 7% smaller than the mean daylight area, the 3 pm area is 32% larger.

Fig. 12 shows a comparison of the mean daylit boundary with daylight autonomy predictions for target levels of 150lux, 300lux and 500lux. In accordance with the IESNA RP, the minimum daylight autonomy level is 50%. The figure shows that the currently proposed climate-based daylighting metric is in good agreement with the subjectively assessed mean daylit area. In fact, the 300lux predicted daylit area of 152 m² is only 7% smaller than the mean daylit area proposed by the student evaluations.

Fig. 13 shows a comparison of the mean daylit boundary with UDI predictions for a minimum target level of 50% to mark the boundary of the daylit area. The resulting UDI based daylit area of 239 m² is 46% larger than the daylit area based on the student assessment. Apart from extending deeper into the space than other metrics, a fundamental difference is that the UDI based daylit area excludes areas right near the North window. Table 3 summarizes the results for all investigated daylight availability metrics.

5. Discussion

What can the reader learn from these results? First, for the investigated space the IESNA daylight autonomy metric and the window-head-height rule of thumb both correlate well with the 60 student assessments. This result is encouraging for the IESNA Daylighting Metrics Committee. The close agreement between the rule of thumb and the daylight autonomy calculation are not surprising given that the rule was previously validated based on daylight autonomy simulations [2]. For the daylight factor, the results were substantially smaller than the assessments whereas
the LEED 3.0 clear sky criterion yielded very different daylit areas for 9 am and 3 pm. Given that according to LEED a space has to meet a certain daylit area for both times of day, this result is hard to interpret and may point to a certain inconsistency in how the credit is phrased. The daylit area according to the UDI was substantially larger than for student assessments.

With a sample size of only one space, it has yet to be determined whether these results are of a more general nature. This caveat notwithstanding, the results for the different daylight availability metrics show that all metrics, except for UDI, mark a daylit area that according to the LEED 3.0 clear sky criterion yielded very different daylit areas for 9 am and 3 pm. Given that according to LEED a space has to meet a certain daylit area for both times of day, this result is hard to interpret and may point to a certain inconsistency in how the credit is phrased. The daylit area according to the UDI was substantially larger than for student assessments.

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