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A SIMULATION-BASED REVIEW OF THE UBIQUITOUS WINDOW-HEAD-HEIGHT TO DAYLIT ZONE DEPTH RULE-OF-THUMB

Christoph F. Reinhart
christoph.reinhart@nrc.ca
Institute for Research in Construction
National Research Council Canada
Ottawa K1A 0R6, Canada

ABSTRACT

This paper reviews the validity of the ubiquitous daylighting rule of thumb (DRT) that relates window-head-height to the depth of the daylit area adjacent to a facade. Different versions of the rule taken from prominent daylighting design guides and norms are presented. A formal link is established between the depth of the daylit zone and the simulated daylight autonomy distribution in a space. Based on this link daylit zone depths of rectangular sidelit spaces are simulated using Radiance for a variety of climates, facade orientations, facade geometries, and usage patterns. Simulation results largely support predictions made by DRT for standard design variants. At the same time they demonstrate the limitations of the rule and promote daylight simulations as a natural complement to the rule if more advanced daylighting systems are investigated.

INTRODUCTION

Different versions of the daylighting rule of thumb (DRT) which relates window-head-height to the depth of the daylit area adjacent to a facade are cited in daylighting design guidelines and norms for Canada (Enermodal 2002; Robertson K. 2005), Europe (Cofaigh *et al.* 1999), Germany (DIN V 18599 2005), North America (IESNA 2000), and the United States (US-DOE 2005; O'Connor *et al.* 1997). DRT constitutes one of the mantras of sustainable building design and often serves –as far as daylighting is concerned– as the sole quantitative justification for room proportions and the positioning of facade openings. Its strong appeal stems from its simplicity (no calculations required), its relevance for key design decisions (direct link between room proportions and the size of the daylit area), and the lack of competing design rules for daylighting.

Despite the rule's ubiquitous appearance in design guides, the author did not find any documented scientific evidence to support the rule. Table 1 presents different versions of DRT taken from prominent design guides. Figure 1 applies the different versions of DRT from Table 1 to a simple rectangular, sidelit room with a sill. Whenever a range is suggested in Table 1, the centre of the range is depicted in Figure 1. Both Figure 1 and Table 1 reveal a surprising lack of consensus as to what the exact content of the rule is. What are the commonalities and where lie the differences? All versions in Table 1 stipulate that the ratio between the depth of a sidelit daylit area and the window-head-height or ceiling height lies within a fixed range. Most versions choose the head height of the window with respect to the floor as the reference measure. All versions imply that the rule can be used for arbitrary facade orientations and throughout the climatic regions for which the guides and norms apply. Some versions mention that the ratio can be increased by the use of light redirecting facade elements such as a lightshelf.

Why is a rule that is so widely used so vaguely defined? One obvious explanation is that DRT is an empirical "rule of thumb" that covers a wider range of climate zones and building types, i.e. some degree of uncertainty is to be expected. Another explanation might be that the different versions of DRT in Table 1 differ in what the rule actually predicts: According to Table 1, DRT predicts a limiting depth of how far "significant", "adequate", "useful", or "balanced" daylight can penetrate into a building. Similar descriptions of the daylit area along with "sufficient", "well distributed", "acceptable", and "effective" were used by design professionals in a recent survey on the use of daylight simulations during building design (Reinhart & Fitz 2004). The survey confirmed DRT's significance for contemporary daylighting design with the majority of participants stating that they use a derivate of the rule during schematic design. In line with Figure 1, participants suggested a depth of the daylit area ranging from 1.5 to 2.5 times the window-head-height with a ratio of 2 being the most popular vote.

Summing up, DRT is an widely cited and frequently used design rule that predicts the depth of the daylit area in a building adjacent to a facade. To date no rigorous definition has been provided as to *what* the daylit area actually is, *how deep* it is with respect to window-head-height, and for which climatic

Table 1: Different versions of the daylighting rule of thumb

Daylighting Rule of Thumb (DRT)	**reference**
Daylighting within a building will only be significant within about twice the room height of a windowed facade.	A Green Vitruvius, p.72 (Cofaigh *et al.* 1999)
The maximum depth of the daylit area corresponds to 2.5 times the difference of the window-head-height and the height of the work plane.	DIN V 18599 part 4 (DIN V 18599 2005)
A standard window can produce useful illumination to a depth of about 1.5 times the height of the window. With lightshelves or other reflector systems this can be increased to 2.0 times or more.	US DOE – Building Toolbox → Design Construct & Renovate → Integrated Building Design → Passive Solar Design (US-DOE 2005)
Keep depth of rooms within 1.5-2.0 times window head height for adequate illumination levels and balanced distribution.	Tips for Daylighting, p. 3-1 (O'Connor *et al.* 1997)
Room depths of 1.5 times the room's window head height will allow sunlight to provide adequate illumination levels and provide for balanced light distribution.	Daylighting Guide for Canadian Commercial Buildings, p.23 (Enermodal 2002)
There is a direct relationship between the height of the -window head and the depth of daylight penetration. Typically adequate daylight will penetrate 1.5 times the height of the window head, although it may penetrate a distance of twice the height under direct sunshine.	Daylighting Guide for Buildings, p.4 (Robertson K. 2005)
To avoid large ranges of in daylight illuminances (greater than 25:1), the distance from the window wall to the inner wall should normally be limited to twice the window head height with clear glazings.	IESNA Lighting Handbook 8-24 (IESNA 2000)

regions, building types, facade orientations, and facade designs it applies.

This paper uses computer simulations to address some of these questions. The key hypothesis underlying this work is that the *depth of the daylit area in a sidelit space corresponds to the position of the half-value of the maximum daylight autonomy distribution in the space*. This hypothesis is explained and justified in the following sections. The objectives of this work are:

- to develop a formulation of the daylighting rule of thumb that is supported by scientific evidence, and
- to establish the boundary conditions under which the rule can be applied.

A secondary objective is to demonstrate that daylight simulations can serve as a natural extension to DRT, providing information for design decisions in situations where the rule is not valid any more.

ADVANCED DAYLIGHT SIMULATION TECHNIQUES

Over the past decade, daylighting simulation tools have become both increasingly sophisticated and easier to use. Validated simulation engines such as the Radiance raytracer (Ward & Shakespeare 1998) and flexible sky models (Perez *et al.* 1993) combined through a daylight coefficient approach (Tregenza & Waters 1983) allow users to reliably predict the annual amount of daylight in buildings

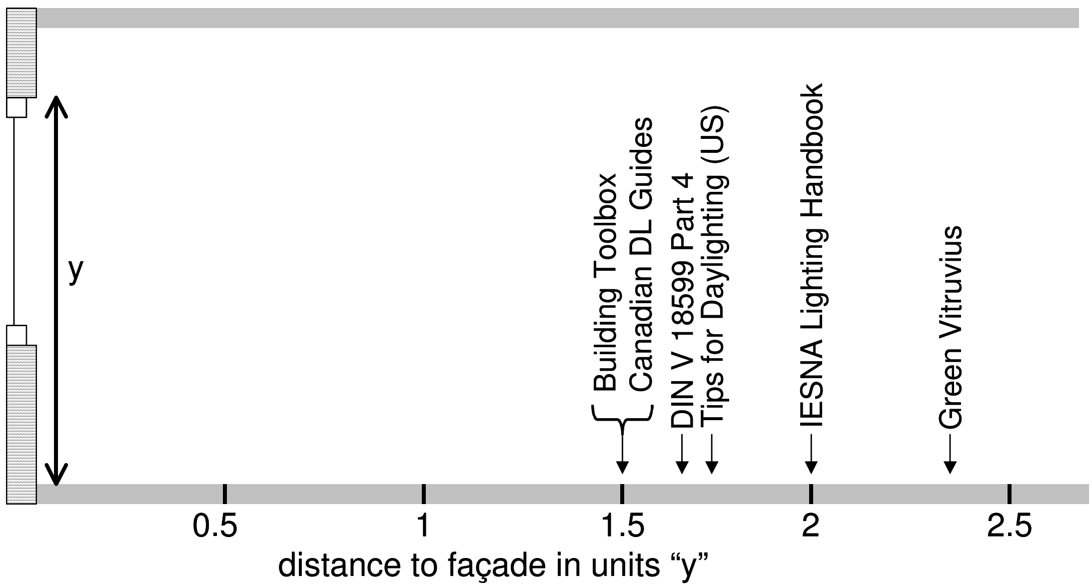

Figure 1: Predictions of the depth of the "daylit area" for different versions of the daylighting rule of thumb. The depth is expressed in units "y" with "y" corresponding to the window-head-height.

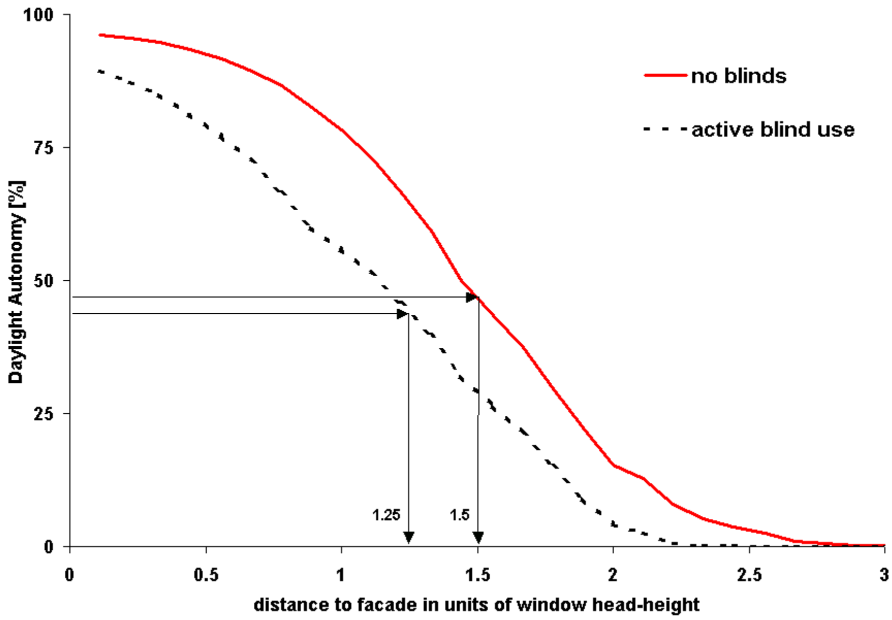

Figure 2: Daylight autonomy distributions for a rectangular room located in New York City facing South. The facade is fully glazed above work plane height and features a solar protective glazing with a visual transmittance of 35% . The minimum illuminance level in the office is 500lux and office hours are Monday to Friday from 8AM to 5 PM. Daylight autonomies are shown with and without the use of a generic venetian blind system.

with complex geometries (Mardaljevic 2000; Reinhart & Walkenhorst 2001). A new generation of user interfaces (Marsh 2005, IES 2005) is making these advanced, dynamic daylight simulation methods accessible to non-experts.

What are the performance indicators that can be predicted using dynamic daylight simulations, i.e. how can annual illuminance values in five-minute timesteps be converted into simple measures on which design decisions can be based? Of practical relevance are the times of the year when the work place is actually occupied. For those times the percentage can be calculated when a task-specific minimum illuminance is maintained by daylight alone. In simulation jargon, this quantity is also referred to as the "daylight autonomy" (e.g. Reinhart & Walkenhorst 2001).

LINKING THE DAYLIT AREA TO DAYLIGHT AUTONOMY

As elaborated above, the term daylit area remains vague. In this section, the descriptions of the daylit area from Table 1 are used to come up with a definition of the daylit area that can be modeled using computer simulations.

- "Adequate" and "sufficient": These terms allude to the quantity of daylight in a space, suggesting that a minimum level of daylight is maintained within the daylit area at certain times of the year. A customary way to express required lighting levels in a space is through task-specific, minimum illuminance levels on the work plane as recommended in various regulations and guidelines (e.g. IESNA 2005, CLC 1991). Daylight autonomy is an ideal candidate to predict the percentage of occupied times when a required illuminance level can be maintained by daylight alone. An example of a daylight autonomy distribution in an office facing South located in New York City is shown in Figure 2 (solid line).
- "Acceptable", "effective", and "useful" shift the focus to user satisfaction and glare prevention, emphasizing that direct daylight has to be controllable through the user at all times to maintain visual comfort. In order to avoid glare, the use of a shading device is mandatory for most spaces. Depending on the type of shading device considered, a different simulation approach has to be taken. For a *static* device (lightshelf, awnings) occupants' impact on the annual amount of daylight can be neglected. If a design solution features a movable device (venetian or roller blinds), occupants' use of the blinds has to be modeled as well using an occupant behavioral model such as Lightswitch (Reinhart 2004). Occupant use of venetian blinds have to be added to a daylight autonomy calculation if the usage of space requires glare free lighting conditions. As shown in Figure 2 (dotted line), considering the use of blinds reduces the daylight available in a

Table 2:Design Variables

Variable	**Range**					**#**
climates centers	Daytona Beach, FL	Los Angeles, CA	New York, NY	Vancouver, BC	Winnipeg, MB	**5**
facade orientation	North	South	West	East		**4**
$\tau_{visible}$ of windows [%]	35		75			**2**
balustrade	yes		no			**2**
sill	yes		no			**2**
occupancy	office		classroom			**2**
min illuminance [lux]	300		500			**2**

space for lighting. It should be stressed that *not* considering the use of a shading device can only be justified in exceptional cases, i.e. if an atrium, entrance foyer or comparable circulation area is considered.

- "Well distributed" and "balanced" refer to the evenness of daylighting levels throughout the space. If direct sunlight is controlled through the use of a shading device, there should not be any stark contrasts left within the daylit area. Yet, as can be seen in Figure 2, there is a distance from the facade in a sufficiently deep sidelit space at which daylight levels fall below the task-specific minimum illuminance level for most times of the year. As shown in Figure 2, the transition between daylit and non-daylit area is not necessarily step-like but can be gradual depending on the situation at hand. One possible approach is to declare the point in space at which the daylit autonomy reaches half of its maximum value the boundary of the daylight area. This boundary corresponds to the depth of the daylit zone. Using this definition for the two daylight autonomy distributions in Figure 2 yields daylit zone depths of 1.25 and 1.5 times the window-head-height depending on the presence of venetian blinds. It is important to note that picking the half value of the maximum daylight autonomy distribution to correspond to the boundary of the daylit zone (instead of, say, 25% or 75% from maximum mark) is a somewhat arbitrary choice. This choice has been made to unambiguously *define* the daylit zone depth as a measurable quantity. The choice will be further discussed below.

Summing up, the above analysis leads to the following definition of the depth of the daylit area within a space:

The "daylit area" within a space corresponds to the area in which a task-specific minimum illuminance level is maintained through daylight for a significant proportion of the year when the area is occupied. This proportion is also called "daylight autonomy" and can be calculated using computer simulations. Depending on the intended usage of the space, the use of a shading device has to be considered in the calculation of the daylight autonomy or not. The boundary/depth of the daylit area corresponds to points at which the daylight autonomy falls to half of its maximum value.

Note that this definition of the boundary of the daylit area is expandable from a one-dimensional daylighting analysis (building section) to a two-dimensional analysis (floor plan). The definition can further be applied to spaces lit through multiple facade openings and/or skylights. The definition constitutes a first attempt to link the concept of a daylit area to a measurable quantity. The definition is not meant to be static but should evolve over time as daylighting research progresses. Potential future modifications are:

- Luminance distributions within the field of view could one day join/replace minimum illuminance levels as a criteria for "adequate and sufficient daylight".
- The behavioral model that determines the manual use of a shading device might evolve as more field data will become available.

TESTING DRT

Simulation Description

In this section predictions of the daylighting rule of thumb from Table 1 are compared to calculations of the depth of the daylit area using the definition developed in the previous section. Calculations have been carried out for multiple design variants of a rectangular sidelit space placed in various climates and for varying facade orientations, facade

Table 3: Utilized Radiance Simulation Parameters

ambient bounces	**ambient division**	**ambient sampling**	**ambient accuracy**	**ambient resolution**	**direct threshold**	**direct sampling**
5	1000	20	0.1	300	0	0

geometries, and usage patterns (Table 2). All design variants had the same window-head-height.

Internal, purely diffuse reflectances of ceiling, walls, and floor were 80% 50% and 20%, respectively. The width of the space was 1.6 times the window-head-height. The space was located in five Canadian and US cities that were identified in a previous study to be the population-weighted climatic centers of five daylight regions in North America (Reinhart 2002). The regions were formed as the result of clustering climate data of 186 North American sites that represented 62.5% of the Canadian and 74% of the US-American population.

The facade was facing in either one of the four cardinal directions and featured a glazing of high or low visual transmittance (*see* Table 2). The facade was either fully glazed or had an opaque balustrade and/or a window sill. The height of the balustrade corresponded to the height of the work plane. The height of the window sill was 30% of the window-head-height. In the presence of a sill, the ceiling of the room was raised so that all design variants ended up having identical window-head-heights.

Occupancy was modeled for either a private office or a classroom. The former was modeled using a stochastic model for private offices with occupancy on weekdays from 8AM to 5PM with intermediate breaks (Reinhart 2004). For classrooms the static occupancy profile "Classroom, Secondary School, No After-School Activities" from the US Environmental Protection Agency program EFAST (http://www.epa.gov/iaq/schooldesign/saves.html) was used.

In the presence of a venetian blind system, it was assumed that occupants' work place would be located at half the window-head-height's distance from the facade. Generic venetian blinds were modeled assuming that –when lowered– the blinds would block all direct sunlight and transmit 25% of diffuse daylight (Vartiainen E. 2000). A simple yet realistic approach was used to model manual blind control: The blinds were opened when an occupant arrived in the space after an absence of at least 30 minutes. Blinds were fully lowered as soon as direct sunlight above 50Wm-2 hit the occupied work place. This algorithm is a modified version of an "active" user within the Lightswitch 2002 user behavior model, which was derived from field data collected in office buildings (Reinhart 2004). In the original approach the user only opened the blinds once in the morning upon arrival. This lead to a strong bias of the model against East facades (Reinhart 2002). This bias has been slightly mitigated through "allowing" users to open the blinds during the day. A so-called "passive" user who leaves the blinds in a closed position throughout the year was not considered. The reason for this choice was that the concept of "daylighting a space" is not really applicable for an occupant who constantly and consistently excludes most daylight from entering the building.

All calculations were carried out using the validated, Radiance-based Daysim simulation tool (www.daysim.com). Utilized Radiance simulation parameters are listed in Table 3. The combination of all design variables in Table 2 lead to 640 annual daylight simulations for the space with no blinds and the same number of simulations when blinds were considered.

Simulation Results

Given that all investigated design variants had the same window-head-height, DRT predicts the same range of daylit zone depths in all cases. Figure 3 shows the normalized frequency distribution of

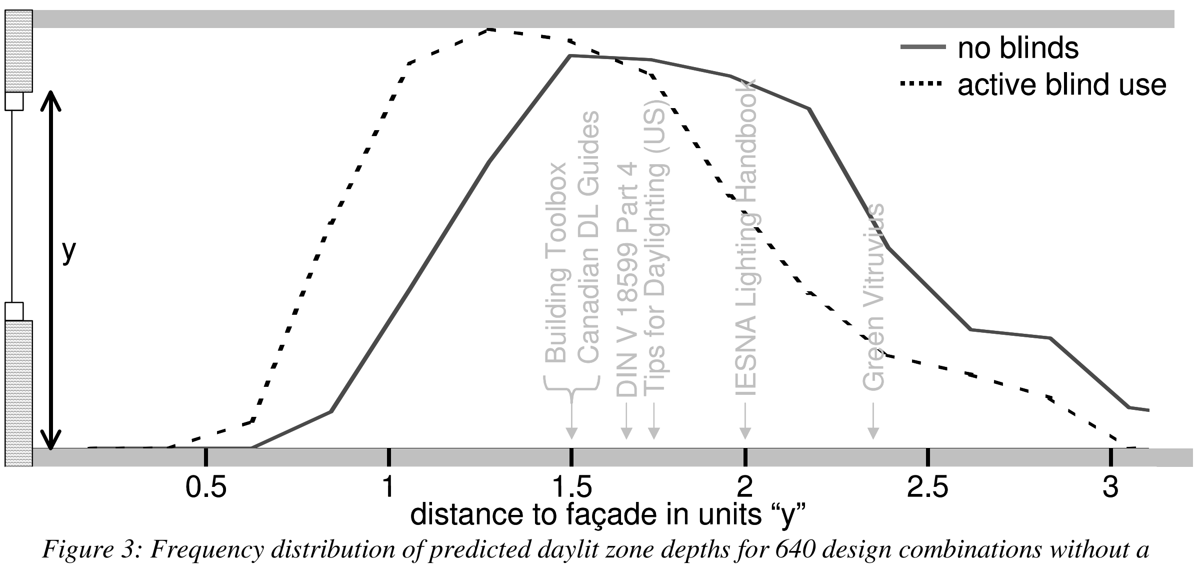

Figure 3: Frequency distribution of predicted daylit zone depths for 640 design combinations without a shading device (solid line) and with manually controlled generic venetian blinds (dotted line).

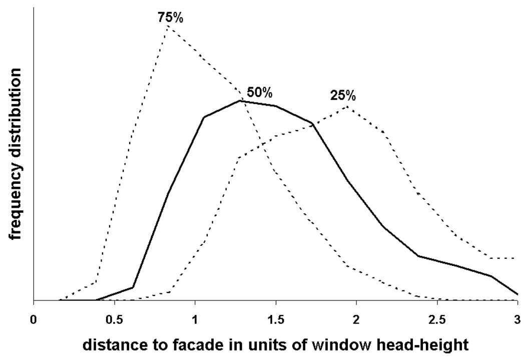

Figure 4: Frequency distributions of predicted daylit zone depths with blinds for varying "cut off" percentages of the maximum daylight autonomy in the space.

simulated daylit zone depths with (dotted line) and without (solid line) blind usage. Zone depths are expressed in units of window-head-height, and are based on the position of the half-value of the maximum daylight autonomy.

Figure 3 reveals that in the absence of blinds, predicted daylit zone depths range from as little as 0.5 to over 3.3 times the window-head-height. Over 85% of predicted zone depths fall into the ratio band of 1 to about 2.5. This range is comparable to the ranges predicted by most DRT versions from Table 1. The recommended value from the *Green Vitruvius* forms a bit of an outlier, the reason being that the guide uses ceiling-height instead of window–head-height as the reference measure.

Figure 3 further reveals that in the presence of blinds, overall daylit zone depths decrease, with 85% of all predictions now lying between 0.8 and 2. Since some type of shading device is necessary in most spaces, an upper boundary of 2 seems to be preferable to the optimistic 2.5 that can be achieved without blinds.

As mentioned above, the choice of defined daylit zone depth as the *half value* of the maximum daylight autonomy is somewhat arbitrary. Figure 4 shows how the results in Figure 3 (with blinds) would change if the daylit zone depth corresponded to 25% or 75% of the maximum daylight autonomy instead. Reducing the cut off level to 25% increases the average zone depth by about 0.5 the window-head-height. Increasing the level to 75% reduces the zone depth by roughly the same amount. This finding underlines, that the concept of the daylit zone boundary should be used a rough guidance not as an absolute divide of a space into daylit and non daylit areas.

For which design combinations does the daylit zone depth in Figure 3 lie outside of the 1 to 2 ratio band? Low values are generally a combination of a minimum illuminance of 500lux combined with a 35% transmittance glazing. On the flip side, high end ratios tend to be a combination of 300lux minimum illuminance and 75% glazing transmittance.

Figure 5 highlights the strong impact of both design variables on the daylit zone depth. The figure shows the frequency distribution in the presence of blinds for different minimum illuminance levels (Figure 5(a)) and glazing transmittances (Figure 5(b)). The binning size is 0.2 in units of window-head-height. Changing the glazing type from 35% to 75% transmittance shifts the peak of the frequency distribution by about 80% from a ratio of 1 to about 1.8. A massive effect. Similarly, reducing the minimum illuminance level from 500lux to 300lux increases the daylit zone depth from 1 to 1.5 times the window-head-height. Given that previous human factor studies suggested that office workers routinely work under and/or tolerate desktop illuminances below 300 lux (Reinhart & Voss 2003), this value might indeed be a better target level for daylighting design than the 500 lux for electric lighting that are conventionally used for offices (e.g. CLC 1991).

Figure 6 shows the frequency distributions for the four facade geometries investigated. The figure shows very similar frequency distributions independent of whether the facade had a sill or not, or whether the balustrade was glazed or not. The figure confirms the common notion that facade openings below the work plane height do not

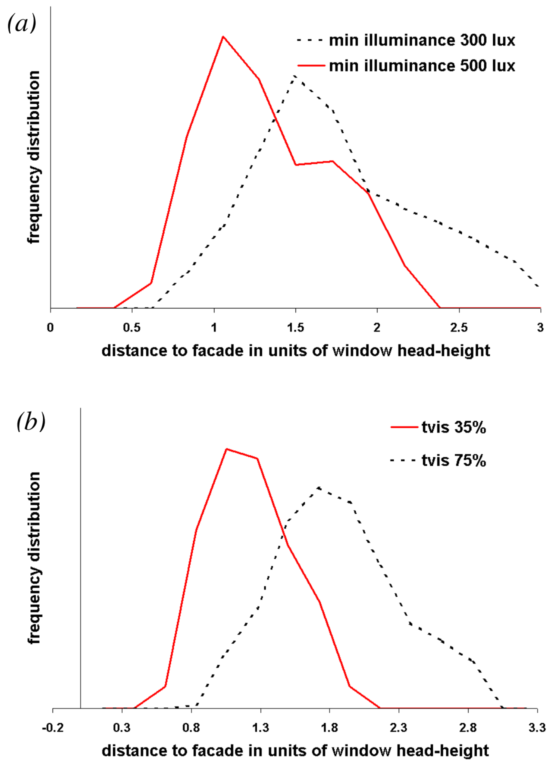

Figure 5: Frequency distributions of predicted daylit zone depths with blinds for varying (a) minimum illuminance levels and (b) glazing transmittances.

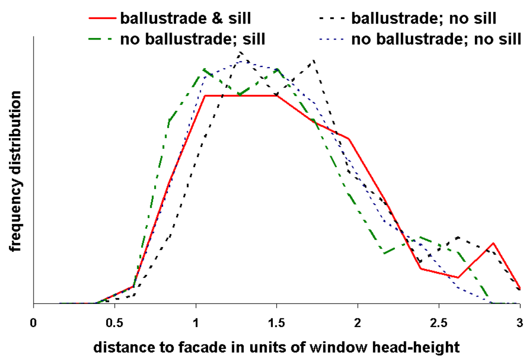

Figure 6: Frequency distributions of predicted daylit zone depths with blinds for varying facade geometries.

contribute to the amount of daylight in a space and that indeed window-head-height and not ceiling-height determine the size of the daylit zone depth.

Figure 7 shows frequency distributions of predicted daylit zone depths for the five climatic centers for North America (see Table 2). Again, the shape of the frequency distributions is similar even though there is a trend towards smaller daylit zone depths with increasing site latitude. The center of the frequency distributions shifts from roughly 1.6 for Daytona Beach to 1.25 for Vancouver.

Figure 8 presents frequency distributions for different facade orientations. The distributions for North, South and West are very similar. The distribution for facades facing East, on the other hand, lies significantly lower than the ones for the three other orientations. The reason for this is that the blind control model used in this study usually prompts the blinds in an East-facing space to be closed in the morning upon occupant arrival due to direct sunlight shining onto the facade. Once closed, the blinds remain lowered at least until lunch time. This “disadvantage” of East-facing facades is especially pronounced for classroom usage since occupancy mainly takes place in the morning.

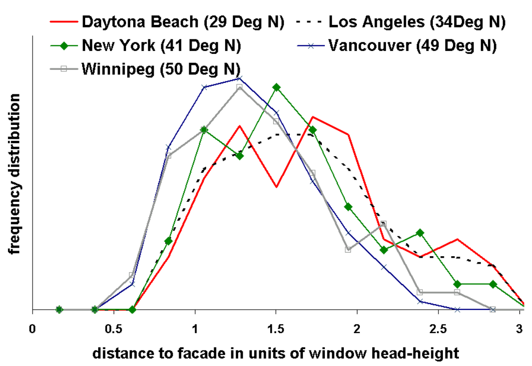

Figure 7: Frequency distributions of predicted daylit zone depths with blinds for varying climatic centers.

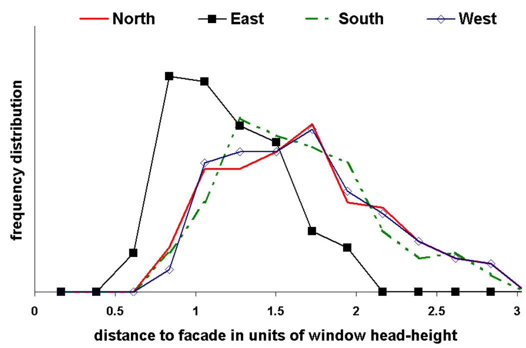

Figure 8: Frequency distributions of predicted daylit zone depths with blinds for varying facade orientations.

DISCUSSION AND CONCLUSION

The results from the previous section support the following version of the daylighting rule of thumb:

The daylit area in a building corresponds to the area in which target illuminances are routinely met through daylight during occupied hours. In a sidelit space with a standard window and venetian blinds, the depth of the daylit area usually lies between 1 and 2 times the size of the window-head-height. The exact number for a particular space is largely influenced by the glazing type and the target illuminance level in the space. In case a space does not require the use of a shading device, the ratio range can increase up to 2.5.

This DRT version is very close to most of the empirical versions presented in Table 1. This finding is relevant for both, the daylight simulation community as well as for the design community at large.

For the former group it suggests that the key hypothesis of this study, the link between the daylight simulation depth and the half-height of the daylight autonomy, leads to results which are consistent with conventional design wisdom. This result can be used to build trust within the wider design community.

For the design community at large these results may provide a fresh perspective of a long established rule, as the somewhat vague term “daylit zone“ has been linked to a measurable quantity. More importantly, this finding might convince some design practitioners that daylight simulations can provide meaningful design advice in situations in which the daylighting rule of thumb fails. E.g. DRT cannot predict how the size of the daylit zone changes due to a skylight, a lightshelf or a split blind system, or what impact obstructing buildings and/or internal partitions have.

In this spirit, daylighting rules of thumb and daylight simulations can work hand in hand together, the latter becoming a natural extension of the former when nonstandard designs are to be explored.

ACKNOWLEDGMENT

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