Scoping Study for Daylight Metrics from Luminance Maps

Market Research Report

prepared by

HESCHONG MAHONE GROUP, INC.

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NORTHWEST ENERGY EFFICIENCY ALLIANCE
www.nwalliance.org
529 SW Third Avenue, Suite 600
Portland, Oregon 97204
telephone: 503.827.8416
fax: 503.827.8437

Sidelighting Photocontrols Field Study

Scoping Study for Daylight Metrics from Luminance Maps

Submitted to:

David Cohan
Northwest Energy Efficiency Alliance
529 SW Third Avenue, Suite 600
Portland, OR 97204

HMG Job 0418

Submitted by:

HESCHONG MAHONE GROUP, INC.
11626 Fair Oaks Blvd. #302
Fair Oaks, CA 95628
Phone:(916) 962-7001
Fax: (916) 962-0101
e-mail: info@h-m-g.com
website: www. h-m-g.com

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INTRODUCTION

This report investigates whether it's possible to use luminance maps of a space as the basis for calculating metrics that describe either the quality or quantity of daylight. The report covers both the suitability of the luminance maps as a way of recording data, and the suitability of the metrics as a means of describing daylight in a space.

At present there are only a few metrics of daylight that are used by designers and researchers. Most of these are based on illuminance and few have a good basis in research or usage. Luminance maps offer a richer source of data. Recent advantages in technology make luminance quick and convenient to measure and to record, opening the way to the development of new luminance-based metrics.

This report describes the results of two experiments. The first attempts to extract luminance metrics from an existing database of luminance maps of real spaces. This experiment offers insights into whether metrics can be extracted reliably, and how much the values of the metrics vary across different spaces. The second experiment looks in more detail at one test space, to investigate whether (and how) the value of the luminance metrics varies over time in that one space.

By comparing the results of the two experiments we are able to quantify how much each metric varies across spaces, compared to how much it varies over time in each given space. Due to the limited scale and comparatively small number of data points in this project, the results should not be taken to be conclusive, but are indicative of conditions in typical commercial buildings.

This report is organized into the following sections:

- An introduction explaining the technical background and the criteria for successful metrics
- An analysis of available luminance metrics
- A description of the methodology used in the experiments
- The findings of the experiments
- A discussion of the findings and experimental errors
- Conclusions about the suitability of the metrics, and recommendations for future development

1.1 Technical Background

A previous study, the *Sidelighting Photocontrols Field Study* (HMG 2005) identified several variables that predicted the performance and energy savings of photocontrol systems in sidelit spaces.

These variables were related to the window design, the interior design and layout, the type of control system and other factors, but the variables of interest to this study were the three illuminance-based metrics that predicted energy savings.

These illuminance-based metrics were intended by the research team to quantify, in different ways, the quality of daylight distribution in the space. This pilot study builds on the previous work by investigating whether alternative metrics based on *luminance* could, in the future, be used in a similar way.

Luminance versus Illuminance Measurements

Luminance and illuminance are different ways to quantify the distribution of light in a space. Luminance describes the amount of light *leaving* an object, whereas illuminance describes the amount of light *arriving* at an object. Luminance is the best approximation to what the human eye sees, but most lighting design and engineering calculations are based on illuminance because in the past this quantity was the easiest to measure.

However with the advent of relatively inexpensive digital cameras and specialized software one can now fairly easily create a luminance map of an entire view. The *luminance map* is a detailed record of thousands of point luminance values across a hemispherical field of view. This relatively low cost luminance mapping capability opens up a new field of measurement and analysis for researchers, and perhaps for designers as well.

In this pilot study, we examined a variety of luminance-based metrics that can be extracted from a luminance map, either mathematically or manually. These metrics were then analyzed to determine whether they could be successfully used by researchers and practitioners, and also whether they correlate with any of the existing, illuminance-based metrics used in the previous field study of sidelit spaces.

Luminance-based metrics using a digital camera and the luminance mapping software have several advantages over illuminance-based metrics:

- They can be easier to measure on site, since only one “luminance map” reading can record all the required data.
- Luminance maps contain much richer information – several million individual pixel values, as opposed to illuminance readings that typically include only a handful of manually measured points.
- Because luminance maps are analogous to the human field of view, metrics based on human vision (such as disability glare and discomfort glare) can be extracted from them.

Technology Required to Produce Luminance Maps

The luminance maps in this study were generated using a *Nikon 5000* digital camera with a fisheye lens and *Photolux* software from ENTPE. For technical background refer to online documentation[1], and to the research paper published by the software's authors (Coutelier and Dumortier 2003).

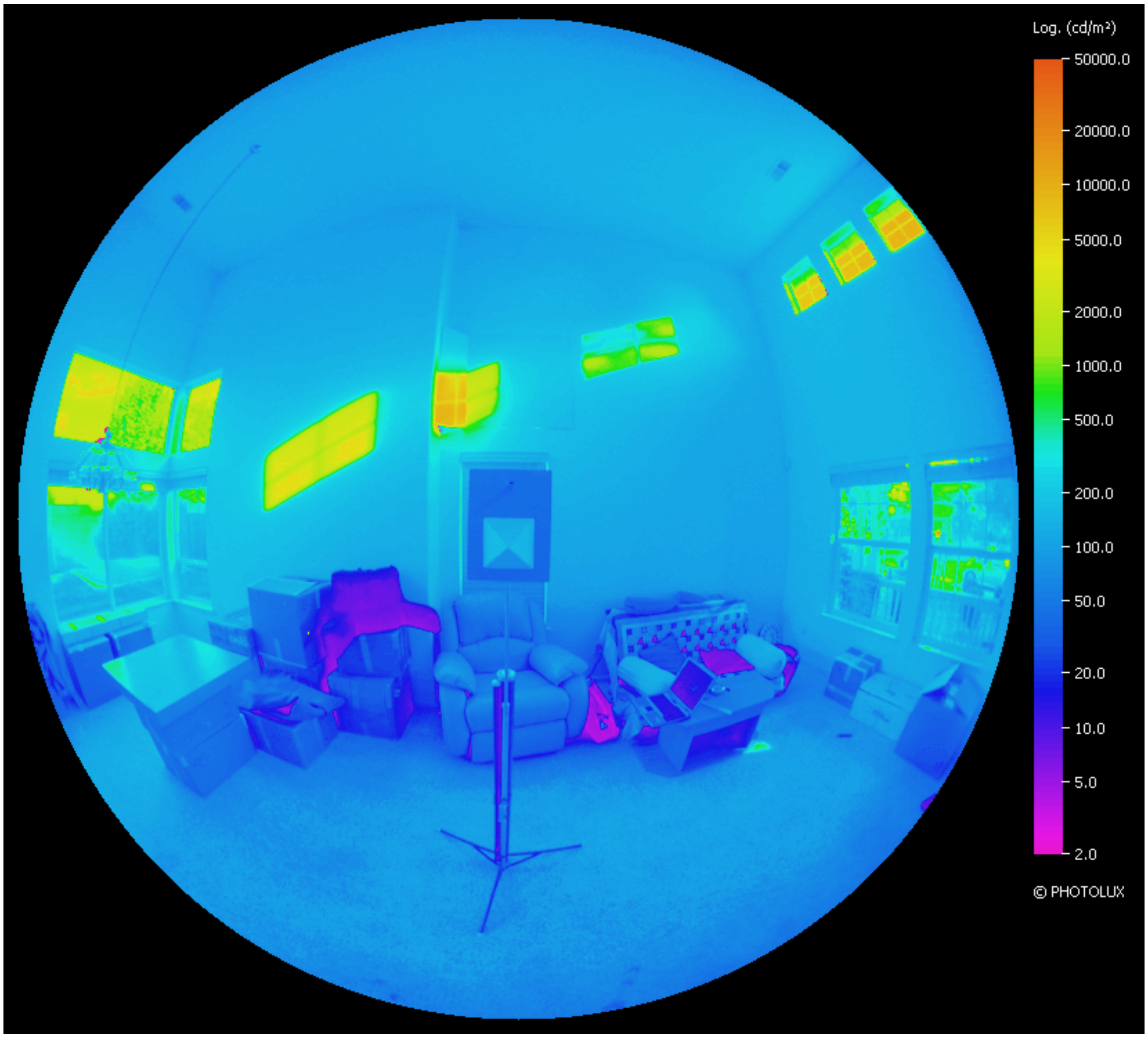

Figure 1 – An Example of a Luminance Map; the map records photopic luminance values for thousands of points across a hemispherical field of view

Integration of Luminance Maps with Lighting Software

The luminance-based measurements generated by Photolux can be analyzed with the open-source lighting calculation and rendering software *Radiance*. Radiance is used by some designers and many researchers because it is considered to use the most realistic lighting calculation algorithms and to produce the most photorealistic output. There are a number of utilities available for Radiance that will create luminance maps of a rendered scene, and perform various calculations based on the data.

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[1] Documentation can be found at www.entpe.fr-Dr-Lash-ImagesLum-photolux.PDF

1.2 Criteria for Successful Metrics

Successful metrics are usually (though not always) simple, and must be useful and meaningful to a wide variety of people: designers, researchers, and end-users at the very least. They must be convenient to use, and must fit into the building design and procurement process. The list below summarizes the desirables features of daylight metrics:

- Meaningful
  - Should describe the distribution of light in the space in a way that has a meaningful relationship to human comfort, human performance, or energy performance.
  - Should be based on currently accepted metrics, very similar to such, or provide a plausible alternative.
- Amenable to statistical analysis, i.e. the values should follow a normal distribution and not be not too clustered or discontinuous
- Easy to integrate into the architectural design process
  - Should be possible to calculate the metrics from computer models and/or physical models of the building, as well as on-site measurements
  - Should help to optimize daylighting design decisions and photocontrol design decisions
- Easy to measure on site
  - Minimal disruption to building occupants
  - Minimal equipment, cheap equipment
  - Fast
  - Simple and user-friendly, to avoid experimental error
- Stable and reliable
  - Metrics should capture the characteristics of the *space*, rather than the particular daylit condition at a given time of day, therefore:

    Not susceptible to changes in sky condition (either for *all* sky conditions, or for a specific range of conditions). So that a single measurement in time can be generalized to other times of the day and year.

    Variation with sun position and cloud cover should be less than the typical difference in values across spaces
  - Human error due to imprecise or subjective methodology should be less than the typical difference in values across spaces
- Simple and elegant

  - The metrics should be easily understood, and there should be an intuitive relationship between the metric and how people understand daylight in the space. (This is important in order to have an impact on design.)
  - The metrics should be as few in number and as simple as possible, yet still describe the variation of daylight in a space.
  - They should not be redundant with each other, i.e. no two metrics should measure the same quantity.

Ideally, a few metrics would capture all the important dimensions necessary to evaluate the success of a daylit space. Logically, these might include some description of:

- Intensity (average brightness of the space)
  - Relative to available daylight?
- Visual comfort (or discomfort), such as:
  - Uniformity across space?
  - Contrast ratios?
  - Glare ratios?
  - Interest?
- Stability in time (which applies to all of the above)

Our goal in developing a minimum set of metrics would be to identify at least one metric that captures useful information about each one of these dimensions.

2. ILLUMINANCE AND LUMINANCE METRICS

2.1 Luminance Metrics

Some metrics are simple to extract from luminance maps; others are more difficult. In this section we review three types of metrics:

- Those that are automatically generated by the Photolux software, and thus are very simple to extract, and highly repeatable.
- Those that can be manually derived from a luminance map, and thus are more time-consuming and may incur measurement error.
- Those that may be possible to extract in the future, with improved software

2.1.1 Luminance Metrics Automatically Generated by Photolux

Photolux automatically generates certain statistics about the image, as listed below and described in detail in Appendix B. These statistics are useful, but on their own they are not sufficient as metrics of daylight, mainly because they are not normalized to the average brightness of the space and would therefore vary significantly during the course of the day as daylight levels change.

- UGR (Unified Glare Rating)
- GI (Glare Index)
- CGI1 (CIE Glare Index #1)
- DGR (Discomfort Glare Ratio)
- Minimum luminance
- Maximum luminance
- Average luminance
- Standard deviation of the luminance
- Illuminance at the camera lens
- Number of saturated pixels in the image
- Number of under-exposed pixels in the image

2.1.2 Luminance Metrics Developed for Use in this Study

We developed several metrics for use in this study; these metrics were developed by taking into account the “criteria for successful metrics” described in section 1.2 and are mostly calculated using combinations of the automatically-generated Photolux metrics described above. A full description of each metric and how it was measured and calculated is given below. A graphical explanation of how each area of the space was defined is shown in Figure 2. The metrics developed for this study are also listed in Appendix B.

Normalized UGR (UGR_{ni} and UGR_{ne})

Unified Glare Rating (UGR) quantifies how much discomfort glare would be experienced by a person standing at a particular point in a space, facing in a particular direction, at a particular time. It is important to recognize that discomfort glare is a *threshold* metric, not a continuous metric, i.e. that glare only occurs above a certain threshold value (that may vary), and that at sub-threshold levels, a higher value of UGR should not be taken to mean that one space is more “glaring” than another – both spaces should be considered “non-glaring”.

Unfortunately the form of the equation for UGR means that it increases logarithmically as the space gets brighter (since brighter spaces are more glaring). This conflicted with our need for a metric that would be stable over a wide variety of daylight conditions.

We solved this problem by devising two metrics of “normalized UGR”, i.e., the UGR value calculated by Photolux scaled up or down to what it *would* have been if all the spaces had had the same level of daylight. UGR_{ni} (where the subtext stands for ‘normalized interior’) was normalized to an *interior luminance* of 50 cd/m^2 while UGR_{ne} (‘normalized exterior’) was normalized to an *outdoor illuminance* of 2000 fc.

We chose these values because they are typical for daylit spaces that give a reasonable sensitivity to the analysis. Our test space averaged 88 cd/m^2 and 2800 fc during the (sunny) test day in November.

We consider UGR_{ne} to be a more appropriate measurement of normalized glare, because there may be spaces in which 50cd/m^2 is either an unusually high or an unusually low value for the average interior luminance (because the space is either dimly or brightly daylit). This would lead us to either under- or over-estimate the typical value for UGR in that space. However, 2000fc is a typical value for external illuminance in *all* spaces, since approximately the same amount of external daylight is available in most US locations. Therefore, UGR_{ne} gives a UGR value that *is* typical for each space, and is a more representative way to compare typical UGR values across spaces. However, both UGR_{ne} and UGR_{ni} are considered in the following analysis.

Luminance variation

This is simply the standard deviation of the room luminance divided by the average of the room luminance. This is the only one of the luminance metrics that is generated in a completely automatic manner and subject to no interpretation by the experimenter.

Ceiling variation

This variable attempts to quantify how quickly the amount of daylight decreases across the ceiling; it is defined as the standard deviation of the ceiling luminance divided by the average value of the ceiling luminance. Photolux calculates these values automatically, after the user has defined the ceiling by hand in the Photolux software. Figure 2 shows an example of user-defined areas..

In some spaces the ceiling was not uniform across the space; some ceilings contained light fixtures, structural beams, set-back clerestory windows and other objects. The experimenter tried to define a representative slice of ceiling, usually spanning from the front of the space to the back, avoiding these objects. There were no spaces in which we judged it impossible to calculate the ceiling variation, and in order to capture the variety among real spaces, we retained even those spaces where it was difficult to measure.

Back wall brightness

This variable attempts to define how bright the back wall of the space is, relative to the rest of the space. It is defined as the average luminance of the back wall divided by the average luminance of the space. In some spaces, especially of course in open-plan offices, there is no back wall. Where possible, the experimenter used a proxy for the back wall such as a partition or a column. The experimenter excluded areas of the back wall that were not representative; for instance particularly dark pictures, bookshelves and other objects. There were 10 out of the 58 spaces in which the back wall was not visible and a partition was used as a proxy. There were two spaces in which sun spots on the back wall made the measurement difficult.

Window contrast

This is the average luminance of the window divided by the average luminance of the surfaces immediately adjacent to the window. This is the most subjective of the luminance metrics, since many windows have complex geometries including curtains, blinds, reveals, overhangs, bright sills, and objects that partially occlude the window; this is discussed in section 5.4.2.

The experimenter defined the window *only* as the area through which exterior objects not attached to the building were visible; this meant, for instance, that areas at the top of the window through which an overhang was visible were counted as “surround” rather than as window. Horizontal blinds that were lowered but “open” (slats horizontal), were counted as part of the window.

Directionality

For the new set of temporal measurements, we created a special, pyramid-shaped device named the ALDI, or Ambient Light Directionality Indicator (described in detail in section 3.2.2), which provided an integrated measurement of luminance intensities generated from four directions in the room: up, down, left and right. Using this device, we created a Directionality metric, which is the ratio of the luminances of the left-hand and right-hand faces of the ALDI pyramid. The experimenter measured the average luminance of each face by defining it as an area in Photolux. There is some degree of manual error in this process, but to minimize the error, the defined area was safely inside the pyramid face, and away from the base where additional shadowing was caused by the proximity of the gray base material. The ALDI was close enough to the camera to make each pyramid large enough in the field of view to allow accurate measurements.

Luminance Daylight Factor

This is the average luminance in the room divided by the unobstructed horizontal exterior *illuminance*, measured at the same time. This is a slight departure from the most usual method of measuring daylight factor, which is to measure the average horizontal *illuminance* in the room, and divide this by the exterior illuminance.

The main source of error in these measurements of daylight factor is incurred when taking the exterior illuminance measurements. There are two sources of error: first, when the sun is close to the horizon, a slight change in the tilt of the illuminance meter can cause a large variation in the measured illuminance; second, if the sky is partly cloudy the measured illuminance can change very quickly due to passing clouds.

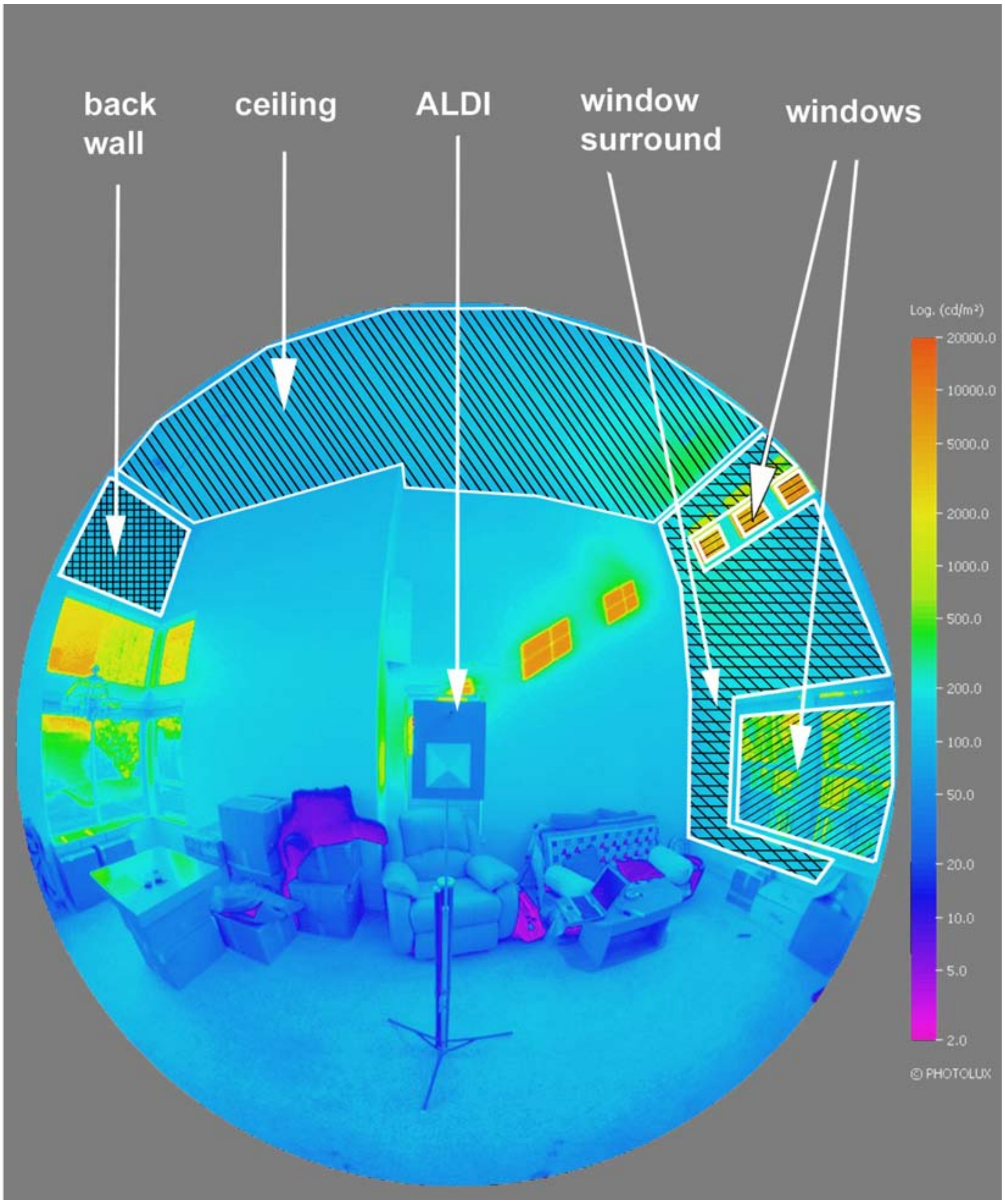

Figure 2 – Areas of the Survey Space used to Calculate Metrics

2.2 Illuminance Metrics Derived From Sidelighting Photocontrols Field Study

In the *Sidelighting Photocontrols Field Study*, six metrics were calculated from on-site illuminance readings, and three of these metrics emerged as being significant predictors of whether the photocontrol system in the space would be working. Therefore there is a good basis for thinking that luminance-based metrics will be good predictors of the same thing.

Therefore, in this study, we want to determine how much these *illuminance* metrics vary over time in the test space (i.e. whether they are stable), and also whether any of the new *luminance* metrics correlate with the illuminance metrics, since this would be an indication that they too might be useful predictors of the success of photocontrols.

Another reason for our interest in illuminance metrics is that they are the most common tools used by designers to describe the amount and distribution of daylight in a space.

2.2.1 Successful Illuminance Metrics from Previous Study

In the previous study, the direction of the effect of the illuminance metrics was the same in each case, and had a high level of statistical significance (see Figure 3). This suggests that spaces with more uniform daylighting are more likely to have functional photocontrol systems.

Using the same method as in the current study, horizontal illuminance readings were taken on a 3x3 grid at working plane height (2’6”), and vertical illuminance readings were taken in each of the four principal directions at seated head height (4’) at the center of the room.

Metric	**Explanation**	**Effect on likelihood of control systems being functional**
Horizontal diversity	Ratio of the maximum to the minimum horizontal illuminance measurement	negative, p<0.0163
Inverse of Drop-off Rate	A logarithmic approximation of the rate at which horizontal illuminance levels diminish from the front to the back of the room	negative, p<0.0008
Horizontal variation	The standard deviation of the 9 horizontal illuminance values, divided by their mean	negative, p<0.0020
Vertical diversity	Ratio of the maximum to the minimum vertical illuminance measurements	not significant
“Critical task” to average illuminance	Ratio of the “critical task” illuminance to the average working plane illuminance. The critical task was defined as the working surface closest to the edge of (but still within) the photocontrolled area.	not significant
“Critical task” to max illuminance	Ratio of the “critical task” illuminance to the single highest working plane illuminance measurement	not significant

Figure 3 – Illuminance Metrics Tested in Sidelighting Photocontrols Field Study

For the sake of convenience, the metrics above are quoted such that higher numerical values always imply higher levels of variation in illuminance levels.

Note that some of these metrics were also good predictors of how much *energy* was being saved by photocontrols (in addition to whether the systems are working, per above). Three of these variables (horizontal diversity, vertical diversity and horizontal variation) were negatively correlated with all measures of energy savings[1], although none of the correlations was found to be statistically significant. With a larger data set it is possible that these metrics might have also been found significant in predicting energy savings.

2.2.2 Independence of Illuminance Metrics

The six illuminance metrics from the previous study are interrelated. To some extent they all measure the variation in horizontal illuminance, although they measure it in slightly different ways.

If any of the metrics are very highly correlated with one another (i.e. not independent), there may be an opportunity to avoid duplication. The R^2 values in the graphs below show that the three metrics of horizontal illuminance are closely related, but that none of them can be dropped without losing a significant amount of richness in the data, i.e., because each metric varies somewhat independently of the others, it likely describes something interesting about the space, even if we don't yet know what that thing is.

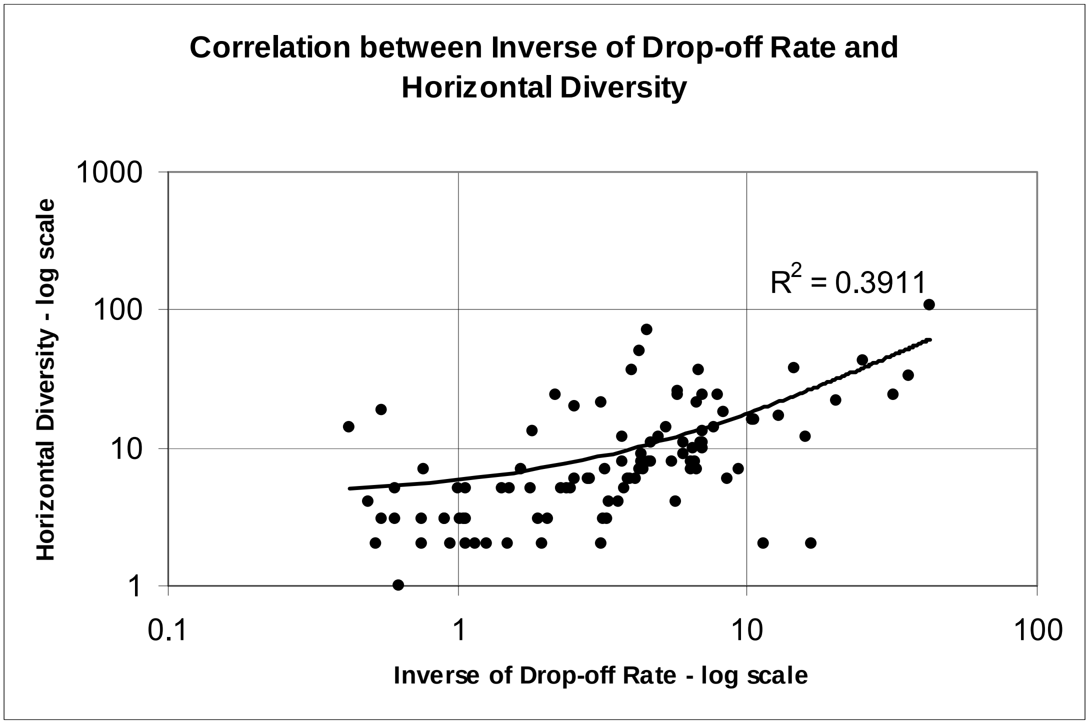

Figure 4 – Correlation between Inverse Drop-off Rate and Diversity, for Spaces from the Sidelighting Photocontrols Field Study

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[1] The amount of energy saved was calculated in four ways: as a percentage of ideal performance (realized savings ratio), in kWh/sf•yr, in full load hours equivalent, and peak demand savings in kW/sf.

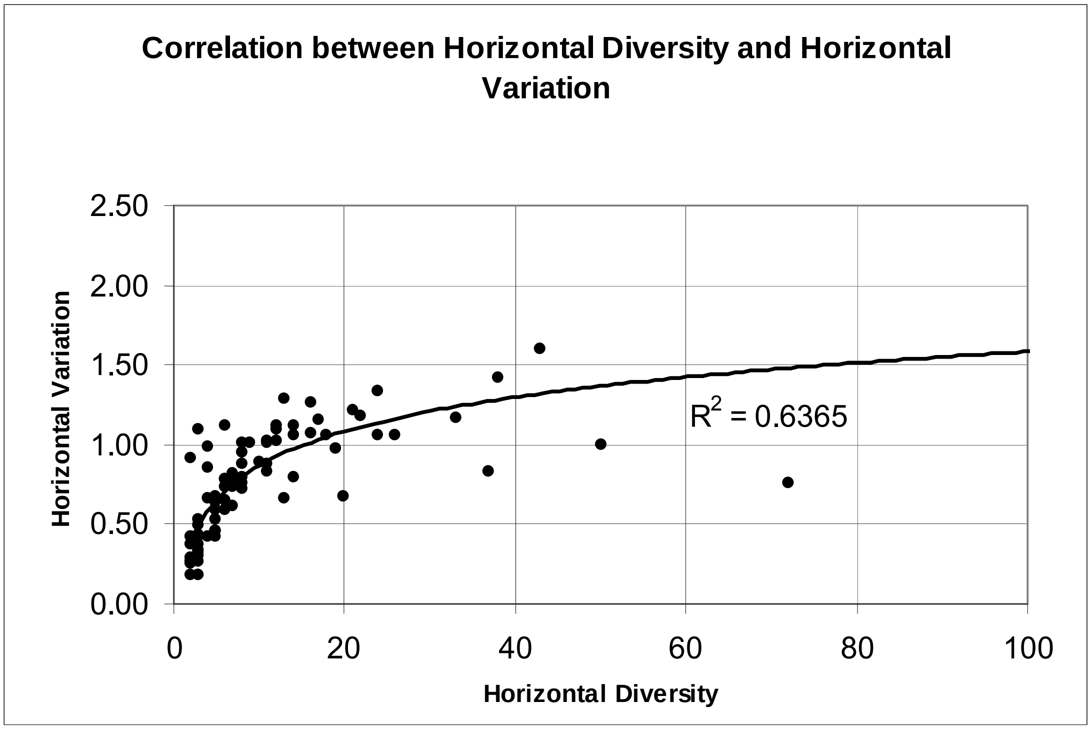

Figure 5 - Correlation between Diversity and Coefficient of Variation, for Spaces from the Sidelighting Photocontrols Field Study

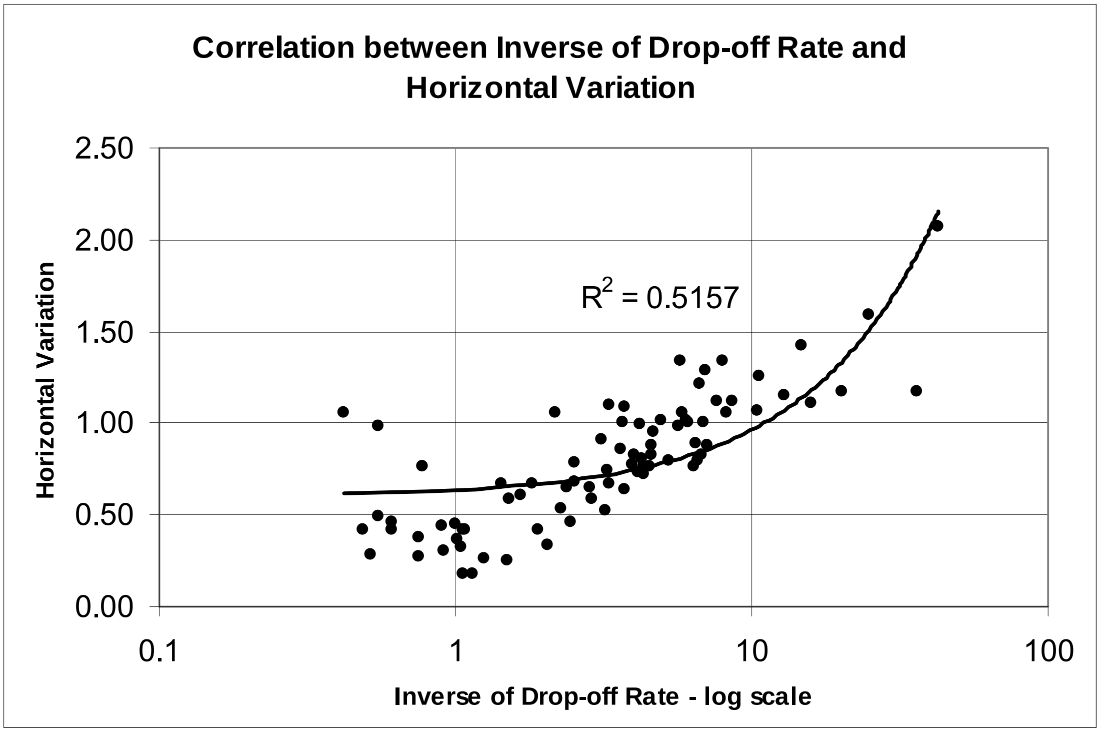

Figure 6 – Correlation between Inverse Drop-off Rate and Coefficient of Variation, for Spaces from the Sidelighting Photocontrols Field Study

3. METHODOLOGY

In this section we describe in detail the methodology used in the two experiments we conducted, one looking at variability across spaces and the other at temporal stability within a single space. The methodology includes the sampling frame, choice of test space(s), the experimental method and the method of analysis.

3.1 Variability across Spaces

This part of the study seeks to determine two things; first whether the luminance metrics can successfully be measured in a wide variety of sidelit spaces with different architectural features, and second how much each metric varies from one space to another.

HMG's study of photocontrols in sidelit spaces showed that illuminance-based metrics are good predictors of the success of photocontrol systems. It seems that the distribution of daylight in the space influences how comfortable occupants are with the visual conditions, and therefore how accepting they are when the photocontrol system dims or switches off their lights. Therefore there is a good basis for thinking that luminance-based metrics will be good predictors of the same thing.

We compared illuminance and luminance metrics for a sub-sample of the sites from the sidelighting study.

3.1.1 Sampling Frame

To get the greatest range of daylight distributions with a minimum number of analysis points, we analyzed a subsample of the 123 spaces in the sidelighting study.

First we considered the three space types: classrooms, open offices (not including private offices), and other . For each space type we ranked the spaces by the "rate of drop-off" (since this metric had the most predictive power), and selected five sample spaces as follows:

- The site with the lowest value
- The site with the highest value
- The site with the mean value
- The site with a value half-way between the mean and the highest
- The site with a value half-way between the mean and the lowest

This sampling scheme is slightly different from the common method of dividing the sample up by percentiles and taking, for instance, the sites at the 20th, 40th, 60th etc. percentiles. The method described above is the best choice when trying to maximize the statistical power of the analysis, while the alternative percentile approach is better when the intention is to make the subsample as representative as possible of the initial sample. Our intention in this analysis is to maximize statistical power.

Some spaces were excluded because the on-site photographs could not be analyzed; in two cases because the electric lights were switched on in the photographs, and in one case because the photographs were out of focus.

In addition to the spaces identified using the sample frame, another 14 spaces were included because their luminance data had already been processed as part of a previous study; this was additional “free” data.

The subsample of spaces shown in Figure 7 contains a mix of unilaterally and bilaterally lit spaces, i.e., spaces with windows on only one side versus spaces with windows one more than one side (opposite walls and/or adjacent walls). Note that there are no bilaterally-lit open offices (as expected), and that classrooms are mostly bilateral.

	Unilateral	Bilateral	**Total**
classroom	6	14	**20**
open office	22	0	**22**
other	8	6	**14**
Total	**36**	**20**	**56**

Figure 7 – Breakdown of unilaterally and bilaterally lit spaces in the subsample

3.2 Temporal Stability

One of the criteria for a successful metric is that it should be stable under changing sky conditions, or should change in a predictable way. To understand the temporal stability of our candidate metrics, we tested them in a single space under a range of solar conditions. Ideally, we would have tested the candidate metric under all possible sky conditions, but in the limited time available for this project we attempted to measure them under as wide a range of conditions as possible.

To test how much each metric varies, we selected a single space and recorded the metrics every hour during a single day. We chose to conduct the test on a day that was predicted to have mostly clear sky conditions, to achieve as much variety as possible.

3.2.1 Choice of Test Space

We selected a test space to which we had easy access, and that approximated the proportions and reflectances commonly found in the sidelighting field study. The test space was a large open living room, with little furniture or decorations installed.

One of the most extreme and therefore interesting daylight conditions is low-angle sunlight; so to ensure that low-angle sunlight would be admitted we chose a space that had windows on the east and west facades, and a mostly unobstructed view from those windows. As can be seen in Figure 8, low-angle sunlight entered the space in the morning (from around 9 to 11 a.m.)

Geometry of the Space

The space was approximately 25’ by 12’ with a 15’ ceiling. The walls were white, creating a space somewhat similar to some of the classrooms and private offices previously surveyed.

Windows and Blinds

The space is bilaterally daylit, with view windows on the east and west, and clerestory windows on the east. There was also a window to the north (just visible in the center of Figure 8) which was covered with opaque card during the experiment. The windows are conventional double-pane clear glass. The east view windows have an overhang extending approximately 4’, while the west windows and east clerestory have no overhang. All the view windows had roman-style shades that were retracted during the experiment.

To further increase the range of daylight conditions we ensured that the west-facing windows could be obstructed, so the space could be measured under both unilateral and bilateral conditions.

Figure 8 – Fisheye photo of test space. The windows at left face west, those at right face east. Note the ALDI mounted on a tripod 3' in front of the lens.

3.2.2 Test Methodology

The data collection methodology was based on the method used in the previous *Sidelighting Photocontrols Field Study*. In addition to the luminance map, the following measurements were taken:

- Horizontal illuminance measured on a 3x3 grid covering the entire space. Measurements were taken at working plane height – 2'6".
- Vertical illuminance measured at the center of the space in the four principal directions. Measurements were taken at seated eye height – 4 above the floor'
- Simultaneous outdoor horizontal illuminance, measured with an unobstructed view of the sky
- Transmittance of the windows, measured by taking illuminance values on the outdoor and indoor surfaces of the glass, with the illuminance meter facing out of the building.

Additionally, we used the ALDI to record the directionality of light at the center of the space. The ALDI was set up on a tripod at the same height as the camera lens, with the base of the ALDI 3' from the front of the lens.

Measurements were taken every hour on the hour from sunrise (8am) to sunset (5pm) on November 10th 2005 in Rocklin, CA. For the on-site survey we chose a day for which sunny skies were forecast, to maximize the variation in daylight conditions over the course of the day.

Ambient Light Directionality Indicator (ALDI)

One additional refinement was added to the method; a device known as the "ALDI" was created, to record illuminances from above and below, and from the left and right, as well as to record the directionality of the light. These illuminances cannot be calculated from the luminance map, since it records only half the visual scene (i.e. one hemisphere), and two luminance maps cannot be combined in the Photolux software.

These illuminances are a highly indicative of how daylight is admitted to the space; a comparison of two sides of the ALDI quickly shows whether the space is strongly lit from one side or evenly lit from both; a comparison of the top to the sides quickly shows whether the space is predominantly sidelit or toplit.

In the previous study, vertical illuminances were measured using a handheld illuminance meter; the ALDI method improves upon the previous study by providing a permanent record *within the image* of the directionality of the light.

The ALDI consists of a neutral-colored base to which a white square-based pyramid and a rectangular reflective post (gnomon) are attached (see Figure 9). The pyramid was constructed of white card stock - sanded to reduce specular reflections - with sides made from equilateral triangles.

The ALDI was mounted vertically on a stand, 3' in front of the camera, with the apex of the pyramid pointing directly toward the camera lens. In the luminance map software, it is simple to select each face of the pyramid in turn and calculate its average luminance.

The purpose of the reflective rectangular gnomon is to provide a visual record of the angle from which the light was coming from, indicated by the direction of the shadow(s) cast, and whether it was coming from a point source (which causes a specular reflection) or from a diffuse source.

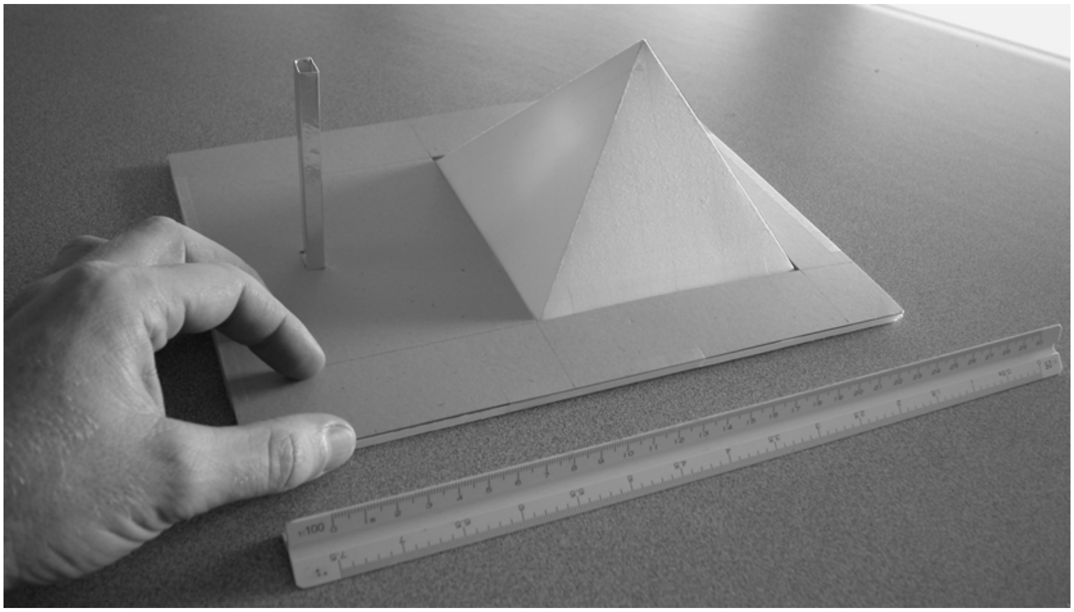

Figure 9 – Ambient Light Directionality Indicator (ALDI)

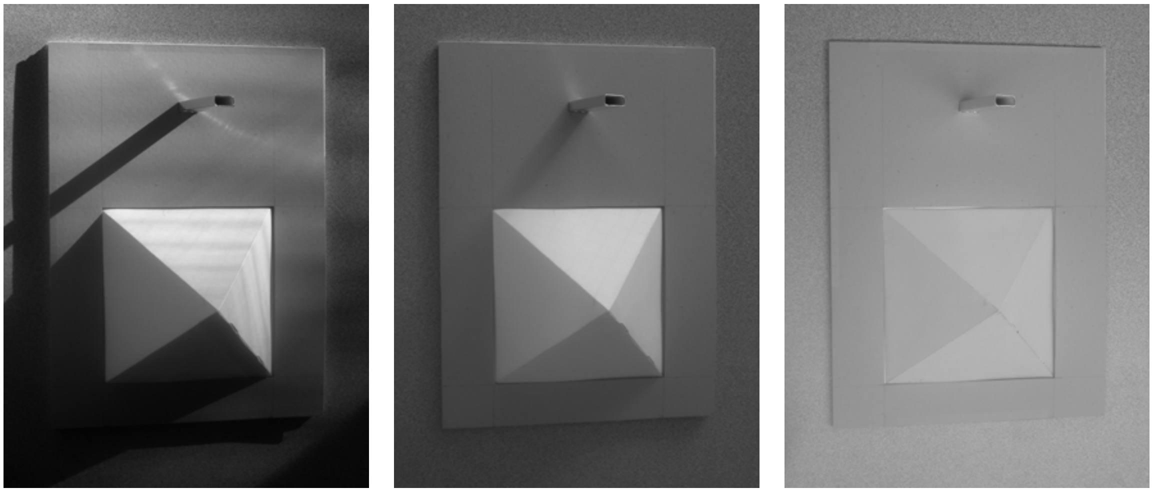

Figure 10 – ALDI under progressively more diffuse lighting (from left to right); note the shadow of the gnomon falling down to the left

4. FINDINGS

4.1 Variations across Spaces

In this section we present findings that describe how the luminance metrics vary from one space to another, whether they correlate with any of the *illuminance* metrics from the previous study, and whether they correlate with each other.

4.1.1 Correlations between Luminance Metrics and Illuminance Metrics

Figure 11 shows that several statistically significant links exist between the new luminance metrics and the illuminance metrics from the previous study. Eight out of the 28 possible combinations have significant relationships with $p<0.1$.

Ceiling variation and back wall brightness have the strongest correlations (2 correlations with $p<0.1$), but the other three metrics are close behind. It should be noted that ceiling variation and back wall brightness also had the highest degree of uncertainty and error in their measurements, which might be a factor in their strong (and sometimes unexpected) correlations with the illuminance metrics. We did not attempt to eliminate outliers and recalculate correlations because this process would also have been subjective.

There are three unexpected results – ceiling variation is inversely correlated with horizontal diversity, back wall brightness is unexpectedly *positively* correlated with horizontal diversity (i.e., more diversity leads the back wall to be brighter)., and UGR_{ne} is unexpectedly *negatively* correlated with vertical diversity.

	UGR_{ni}	UGR_{ne}	Room variation	Ceiling variation	Back wall brightness	Window contrast	Luminance daylight factor
Inverse of Drop-off Rate				**0.04**	**(0.09)**		
Vertical diversity		**(0.01)**				0.13	
Horizontal diversity	0.20		**0.07**	(0.15)	**0.001**		
Horizontal variation	**0.03**			**0.02**		**0.07**	(0.16)

Figure 11 – Table Showing Relationships between Luminance and Illuminance Metrics. Values shown are p-values, i.e. the probability that a relationship does not *exist. For values in parentheses the correlation is negative (but significant). Values in bold have $p<0.1$; p values greater than 0.2 are not significant and are not shown.*

Due to the comparatively small sample size, no single result should be taken as conclusive, but the overall picture is that the luminance metrics correlate with the illuminance metrics in a way that broadly matches expectations. It should also be noted that among the sixteen *non*-significant correlations, eleven of the relationships were in the expected direction, though, of course, not significant.

The relationships between the illuminance and luminance metrics remain significant even when broken down by building type. This is especially interesting because, often, relationships do not remain statistically significant when the number of data points is reduced.

4.1.2 Temporal Variation Compared with Variation across Spaces

The most relevant measure of the success of these metrics is whether the variation *across* spaces is greater than the variation *within* one space (over time). This allows the metric to effectively distinguish one space from another, irrespective of the time at which it was taken.

The coefficient of variation (COV) ratio in Figure 12 shows how great the variation across spaces is, compared with the variation within spaces; higher values are better. A COV of 1 means the variations are the same and therefore the metric is not useful.

The coefficient of variation is defined as the standard deviation of the metric divided by the mean of the metric.

$$Coefficient\ of\ variation = \frac{Standard\ deviation}{Mean}$$

For instance, there were 10 “normalized UGR” values recorded for the unilateral space during the on-site survey (10 hourly measurements from 8am until 5pm). These 10 UGR values had a standard deviation of 2.9 and a mean of 15.3, so their coefficient of variation was 0.19.

The test space (used for the measurements of temporal variation) is quite representative of the other spaces, i.e., the values of the metrics in the test space are in many cases close to the average of the rest of the spaces, as shown in the two leftmost columns of Figure 12.

Compared with the sample spaces, the test space has a slightly more uniform ceiling, significantly less drop-off from the front to the back of the space, lower diversity and lower variation.

	Average value of metric			**Coefficient of variation**		
	Over time (unilateral test space)	Over time (bilateral test space)	Across spaces	**Over time**	**Across spaces.**	**COV ratio**
Luminance metrics						
UGRni	15.32	11.34	15.75	**0.23**	**0.25**	**1.12**
UGRne	14.27	13.90	15.71	**0.25**	**0.39**	**1.60**
Room variation	4.76	3.06	4.07	**0.16**	**0.37**	**2.27**
Ceiling Variation	0.34	0.23	0.61	**0.44**	**0.53**	**1.20**
Back Wall Brightness	0.66	0.63	0.67	**0.23**	**0.63**	**2.69**
Window Contrast	14.30	6.75	14.09	**0.35**	**0.67**	**1.92**
Luminance daylight factor	0.02	0.06	0.06	**0.72**	**1.34**	**1.85**
Illuminance metrics						
Rate of drop-off	0.66	3.30	9.20	**0.27**	**1.35**	**5.00**
Vertical diversity	3.40	3.90	5.40	**0.15**	**0.88**	**5.87**
Horizontal Diversity	2.00	7.00	12.30	**0.30**	**0.92**	**3.07**
Horizontal Variation	0.23	0.87	1.00	**0.29**	**0.50**	**1.72**

Figure 12 – Comparison between Metrics in Test Space and Metrics in other Sample Spaces

4.1.3 Independence of Luminance Metrics

As with the *illuminance* metrics, it's important to know whether any of the luminance metrics are strongly correlated, because there may be an opportunity to simplify the analysis and avoid duplication by dropping one or the other.

As expected, there is a degree of correlation between the two measures of normalized UGR and room variation; this is because the measures of UGR are mathematically similar, and because room variation quantifies the proportion of high-luminance areas compared with the rest of the room, which is essentially the same quantity as UGR.

However, the negative correlation between ceiling variation and window contrast is unexpected, because rooms with smaller windows (and unilateral spaces) should score higher on both. This result may be related to the time of day; window contrast is higher when the sky is bright near the horizon (evening, morning) and for the same reason the ceiling variation is low at those times because the light is entering at a flat angle. Alternatively this correlation may simply be a consequence of the uncertainty and subjectivity of measurement of ceiling variation, as explained in section 5.4.2.

Correlations between Luminance Metrics	UGR_{ni}	UGR_{ne}	Room Variation	Ceiling Variation	Back Wall Brightness	Window Contrast	Luminance Daylight Factor
UGR_{ni}	1	0.51	0.57	0.14	-0.15	0.02	-0.10
UGR_{ne}		1	0.34	-0.06	-0.02	0.02	0.61
Room Variation			1	0.02	0.04	0.19	-0.12
Ceiling Variation				1	0.08	-0.48	-0.12
Back Wall Brightness					1	0.00	-0.09
Window Contrast						1	-0.02
Luminance Daylight Factor							1

Figure 13 – Correlations between Luminance Metrics. Values shown are Pearson correlation coefficients (R-values)

Note that there is a correlation between UGR_{ne} and luminance daylight factor; this is expected because spaces with higher daylight factors have higher interior light levels and therefore higher glare as explained in the section on normalized UGR above. This correlation does not exist for UGR_{ni} because UGR_{ni} directly controls for the interior light level.

4.2 Temporal Stability

In this section we present findings that describe the variation in the luminance metrics over the course of a single day in a test space. The test space was configured in two different ways – first, unilaterally daylit (windows on only one side), and then bilaterally daylit (windows on opposite sides).

The sky condition on the day of the test is a material part of the findings; in the morning there was a high layer of thin cloud from 8am until 12pm that produced somewhat overcast conditions, although direct sunlight was coming through the east window when each of the luminance maps was recorded. Patches of sunlight can be seen on the north wall of the space in the 8am, 9am, 10am and 11am luminance maps; by 12pm the sun had moved around to the south and was no longer shining through the east windows. By the late afternoon the sun had moved around to the west but was too low in the sky to shine through the west windows (which were actually oriented slightly north of west).

4.2.1 Judging the Stability of the Metrics

We judged the stability of the metrics in two ways; the first is the “coefficient of variation”, which is a measure of how much the metric varied through the course of the day in each space, relative to its mean value. The second way was to use a t-test to determine whether the metric was significantly different between the unilateral and the bilateral spaces; ideally, each metric would take distinctly different values in the unilateral and bilateral spaces.

Coefficient of Variation

A low coefficient of variation is desirable, since this means that the value of the metric is stable over a wide range of daylight conditions. As shown in Figure 14, the 10 actual UGR values fall reasonably well within the “bell curve” of an idealized normal distribution with the same mean and standard deviation. For comparison, a normal distribution with an even lower coefficient of variation (0.07 instead of 0.19) is shown, with a more pronounced peak.

The value of coefficient of variation is that a given COV represents the same *shape* of curve, irrespective of the actual values or their mean, so it is a useful way to compare different variables that might have different means.

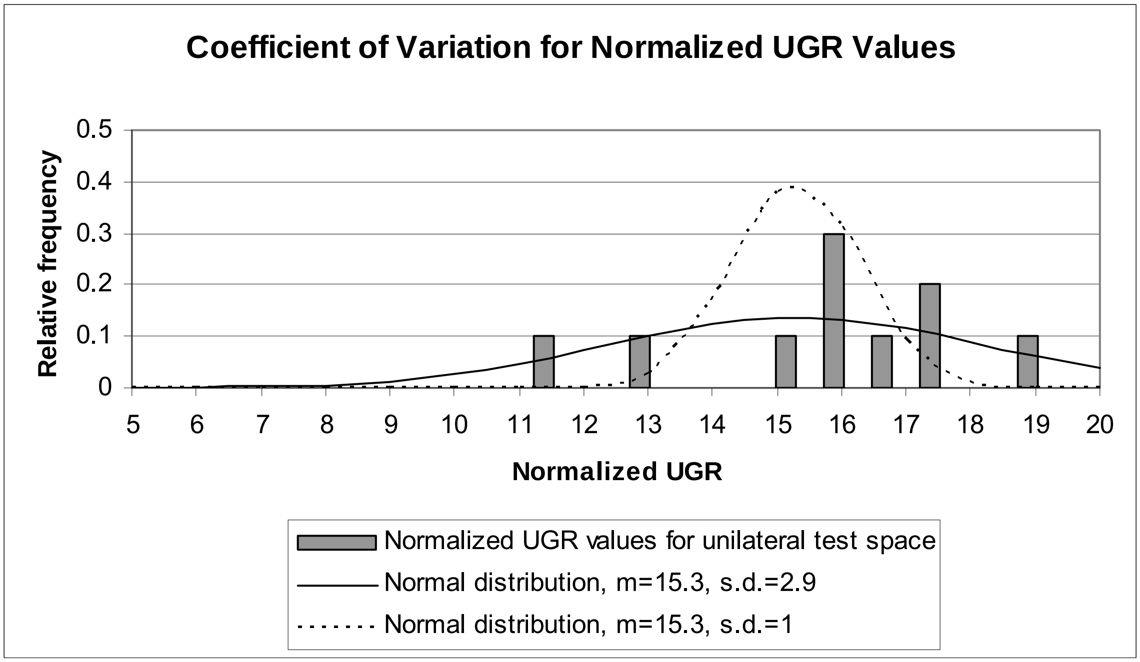

Figure 14 – Coefficient of Variation for Normalized UGR values

COV values for each metric considered are shown in Figure 15. There is no absolute value of COV that indicates that a variable is stable. The most important factor for this study is whether the COV value *within* the test space is lower than the COV of the same metric *across different* spaces. This is discussed in a later section.

T-test for Difference of Means

The t-test is a simple and commonly used way to tell whether two samples (i.e. two sets of data) could be drawn from the same population, or whether they are from different populations. The t-test uses the difference between the means, the standard deviation of each sample, and the number of data points to estimate the likelihood (p) that the samples are drawn from the same population.

As shown in Figure 15, for every metric except UGR_{ne} and back wall brightness, there is an extremely low probability that the samples were drawn from the same population. This means that five of the metrics successfully distinguish between the unilateral and bilateral spaces.

Note that although some metrics seem to perform better in either the unilateral or the bilateral space, on average they perform just as well in both. The average COV for unilateral spaces is 26.3, and for bilateral 26.7.

	Unilateral		**Bilateral**		**T-test for difference of means, p<0.1**
Metric	**Mean**	**Coefficient of variation**	**Mean**	**Coefficient of variation**	
UGR_{ni}	15.32	0.19	11.34	0.26	0.004
UGR_{ne}	14.27	0.22	13.90	0.27	not significant
Room Variation	4.76	0.18	3.06	0.15	0.00003
Ceiling Variation	0.34	0.50	0.23	0.39	0.051
Back wall Brightness	0.66	0.35	0.63	0.12	not significant
Window Contrast	14.3	0.40	6.75	0.30	0.001
Directionality	2.57	0.15	1.87	0.38	0.008
Luminance Daylight Factor	0.02	0.76	0.06	0.69	0.010

Figure 15 – Temporal stability of metrics in unilateral and bilateral conditions in the same space

4.2.2 UGR$_{ni}$

Figure 16 shows UGR$_{ni}$ plotted against the room average luminance. The graph shows logarithmic trendlines for the bilateral and unilateral space (the trendlines appear to be linear, because the x-axis is a logarithmic scale). The data points almost all lie close to these trendlines – R^2 correlation values are high at 0.82 and 0.80 respectively. There is one outlying data point for the unilateral space; we checked this outlier and the data was correct; it was not obvious from the luminance map why this particular point (the unilateral space at 10 a.m.) had an unexpectedly low UGR.

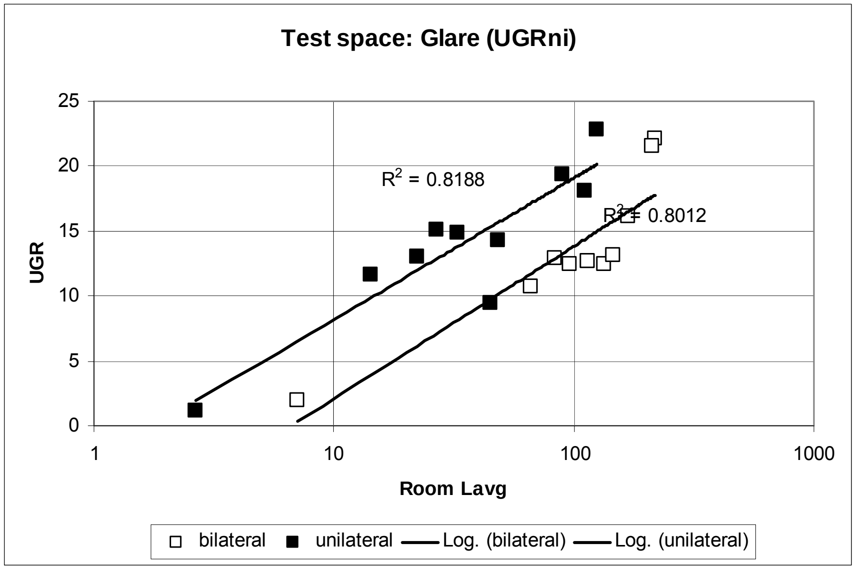

Figure 16 – UGR$_{ni}$: correlation with room average luminance

4.2.3 UGR$_{ne}$

Figure 17 shows UGR$_{ne}$ plotted against the exterior horizontal illuminance. The data points lie close to the trendlines, with moderate R^2 correlation values of 0.71 and 0.59. Note that there is no statistical difference between the two spaces – their lines of best fit are coincident. This means that the value for UGR$_{ne}$ was the same for the unilateral and bilateral spaces.

Both UGR graphs appear to have an outlier at the lower left; this is not an outlier but an absence of data points in the middle of the graph due to the measurements being taken on a sunny day with high exterior illuminances.

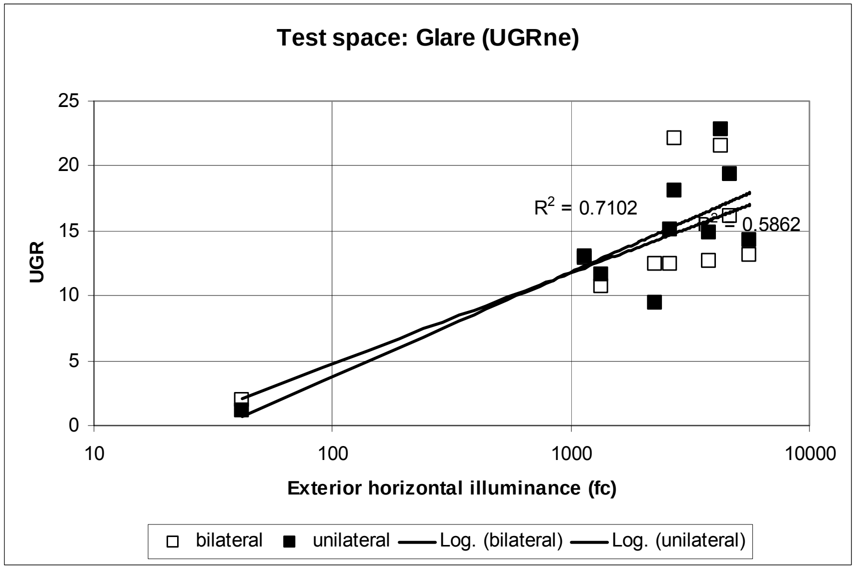

Figure 17 – UGR$_{ne}$: correlation with room average luminance

4.2.4 Room Variation

Room variation is the best-performing metric of the six metrics studied; it has the lowest average coefficient of variation and it's the best at distinguishing between the unilateral and bilateral spaces, although as shown in Figure 18 there are a few data points that lie closer to the *other* line-of-best-fit than to their own.

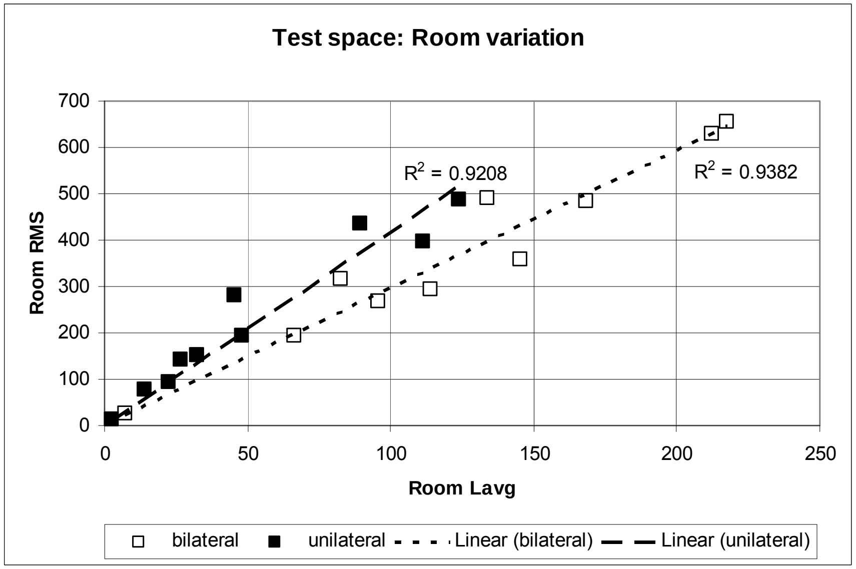

Figure 18 – Room Variation: correlation between room standard deviation and average room luminance

4.2.5 Ceiling Variation

Ceiling variation is a poor performer; it has high coefficients of variation and although it distinguishes successfully between the unilateral and bilateral space, the distinction is not as clear as with other metrics.

One possible reason for this poor performance is that the clerestory windows are close to the ceiling on the east side of the space, and this produces a hotspot of luminance that disrupts the gradation of luminance across the ceiling. If this is the source of the problem then the metric's usefulness may be limited because in many "real" spaces clerestories are likely to be close to the ceiling.

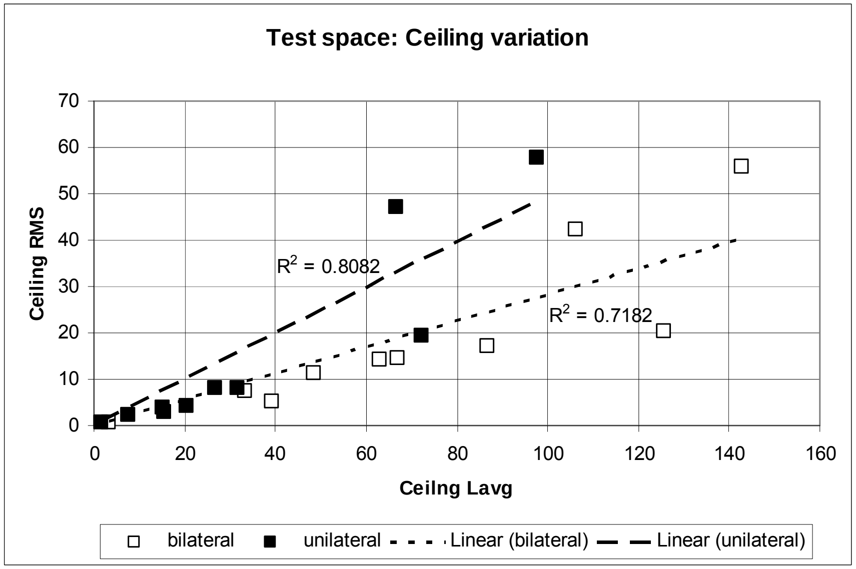

Figure 19 –Ceiling Variation: Correlation between ceiling standard deviation and ceiling average luminance

4.2.6 Back Wall Brightness

Back wall brightness is calculated by dividing the average luminance of the back wall by the average luminance of the whole space. This metric remains highly stable from one hour to the next; i.e., it has relatively low coefficients of variation.

Back wall brightness does not distinguish between the unilateral and bilateral spaces, i.e. the slopes of the two lines in Figure 20 are the same. However, this may simply mean that the unilateral and bilateral spaces actually had the *same* back wall brightness.

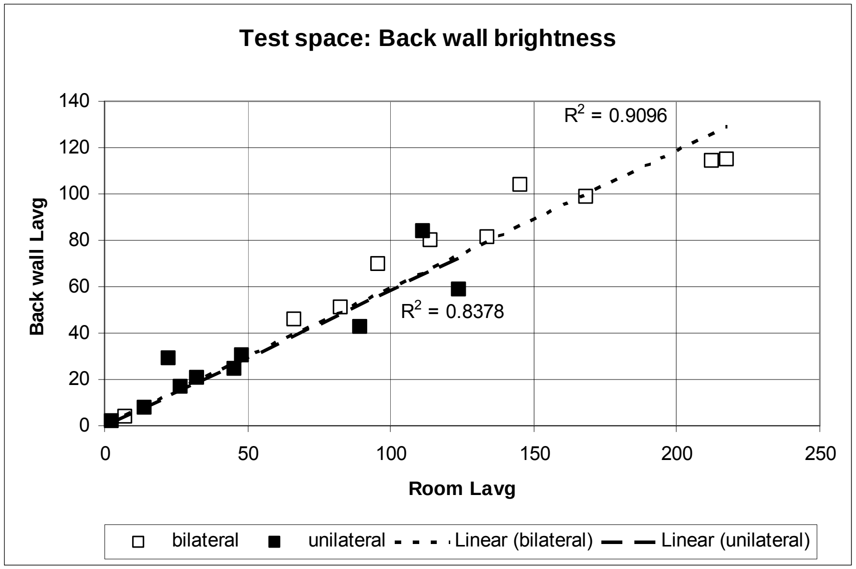

Figure 20 –Back wall brightness: Correlation between back wall average luminance and average room luminance

4.2.7 Window Contrast

Figure 21 shows an unusual relationship – several data points at the top end of the graph appear to curve away from the line of best fit. These outlier points appear to depart in a consistent way, i.e., they are not due to simple experimental error. This is discussed in section 5.4.2.

Because of the outliers, the coefficients of variation for this metric are quite high, but it distinguishes between the two types of space reasonably well.

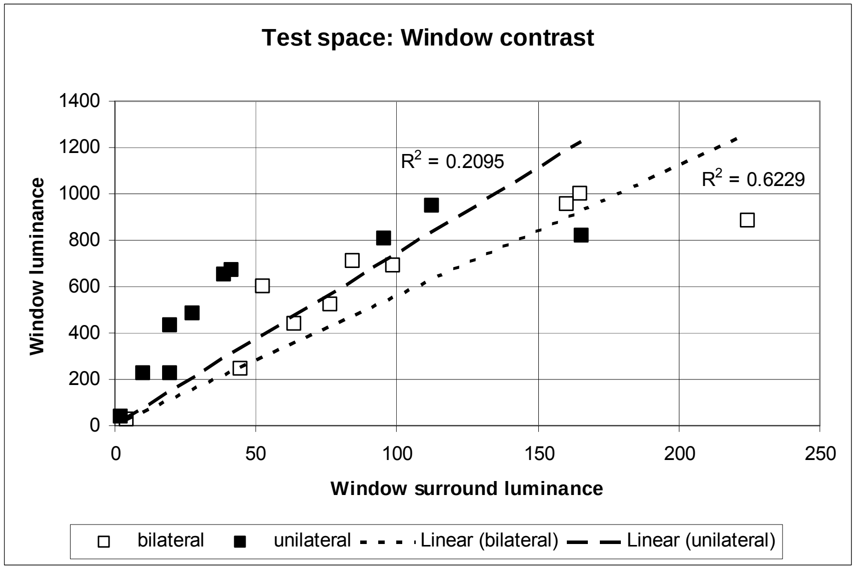

Figure 21 – Window Contrast: Correlation between window luminance and window surround luminance

4.2.8 Directionality

Directionality appears to be a usefully stable metric, comparable with the others. It has low coefficients of variation and distinguished well between the two spaces. It was significantly more stable in the unilateral space than in the bilateral space. Note that the measurement of directionality was the *maximum* divided by the *minimum* luminance of the left and right faces of the ALDI; the COV for bilateral spaces might have been even higher if directionality was defined more simply as left divided by right (or vice-versa).

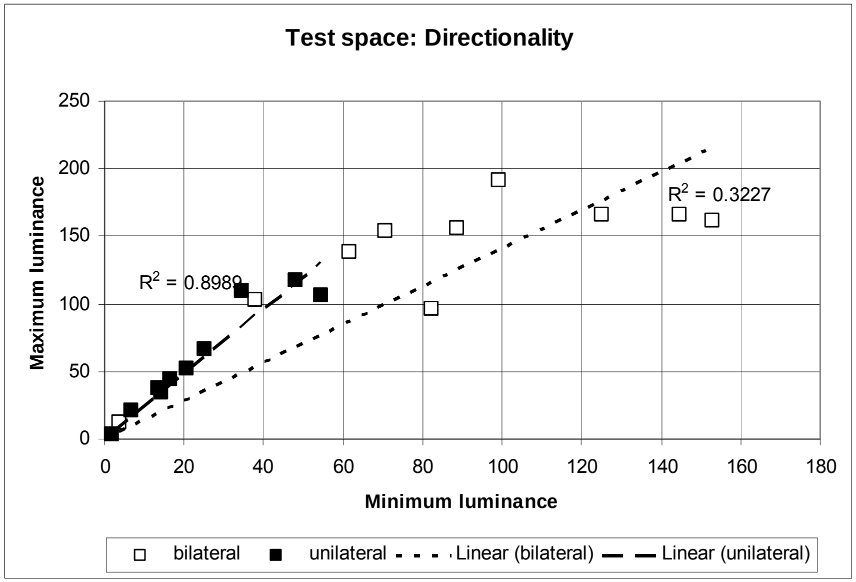

Figure 22 – Directionality: Correlation between maximum and minimum luminance of the left and right faces of the ALDI.

4.2.9 Luminance Daylight Factor

Luminance daylight factor was not stable over time in the test space. Figure 23 shows that although the metric distinguishes well between the two spaces, it varies a great deal around the line of best fit (poor R^2 correlation values of 0.33 and 0.35 respectively for the unilateral and bilateral spaces). This suggests that the metric would be unsuitable for characterizing a space from a single measurement, since the degree of variation is so high.

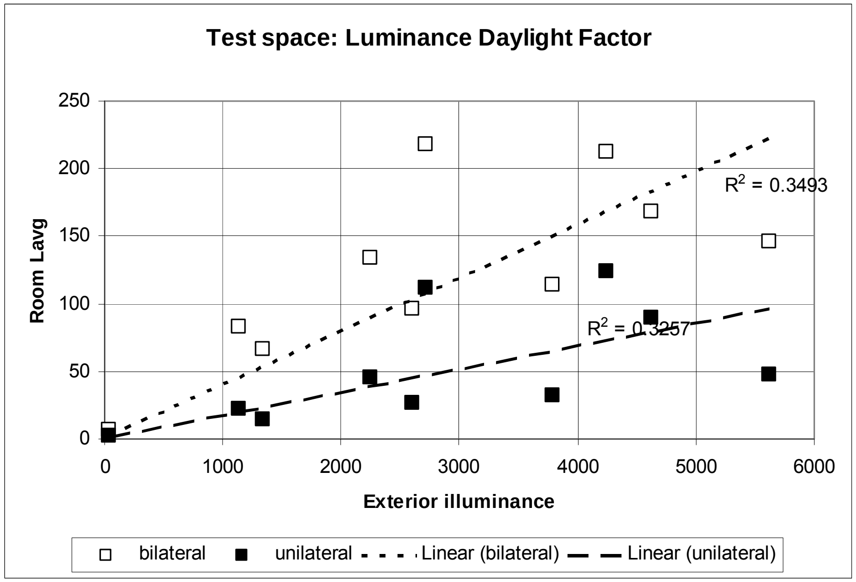

Figure 23 – Luminance daylight factor: Correlation between exterior illuminance and room average luminance

5. DISCUSSION

On the COV scale, none of the current luminance metrics score particularly high (see Figure 12). It is encouraging that they all have COV ratios greater than one (i.e. that the variation across spaces is greater than the variation within each space), but they fall in the range 1.0 to 2.5, which is not sufficiently high for a single measurement to be taken as a reliable characterization of a space.

The low values for "COV over time" in Figure 12 (typically 0.2-0.3) suggest that the experimental errors are small for all the metrics except luminance daylight factor. This suggests that those metrics could be effective once improved.

COV ratio could be improved either by reducing "COV over time" or by increasing "COV across spaces" (since COV ratio is simply the ratio of the two).

5.1 Reducing "COV over time"

To reduce "COV over time" it may be possible to incorporate one or more modifying variables into each metric to make it more stable over time. For instance, *solar elevation* might consistently affect the metric in some way, and this effect could be subtracted to make the metric more stable over time.

A more simple but less flexible way to achieve this same goal might be to restrict the time of day at which the metrics are measured (for instance, they might only be measured within one hour of noon), or to take several measurements in each space at "representative" times of day to create a more complete description of the better average. However, both these approaches would make it less convenient and more expensive to take field measurements, and more importantly might encourage distorted design practice by placing too much emphasis on the daylit condition of the space at a certain time of day rather than the whole day.

5.2 Increasing "COV across spaces"

To increase "COV across spaces", the metrics would have to distinguish more strongly between different spaces. While this is desirable from a mathematical point of view, it's important to remember that part of the function of a metric is to meaningfully describe the amount or quality of daylight, and a metric that makes artificial distinctions where none really existed would be counterproductive. For instance, the "rate of drop-off" metric varies greatly across spaces (from 0.42 to 136 in this sample) but there is probably no meaningful difference between a drop-off rate of 20 and one of 120, so the metric makes distinctions that may not actually exist. For this reason it may *not* be productive to deliberately modify the metrics to increase COV across spaces.

5.3 Comparison between Pairs of Luminance Maps

To record the whole visual scene in each space, two luminance maps are required, since each records only 180°. In this study we use luminance maps taken from the center of the space – one oriented 90° clockwise from the main window and the other oriented 90° counterclockwise.

In many spaces the view is similar in the two directions but in some spaces the view is very different. The difference in the value of the metrics when measured in the clockwise and counter-clockwise directions is shown in Figure 24.

If there were little difference between the values of the metrics in the two directions, it might be sufficient to take just one luminance map per space, but Figure 24 shows that the mean error between the two views for all metrics is 29%. This difference is almost as great as the "COV across spaces" shown in Figure 12, so taking only one luminance map would significantly affect the ability of the metrics to distinguish between one space and another.

Furthermore, although many of the differences between pairs in Figure 24 fall into the 5-20% category, a few exceed 70%. Note that this is greater than all but one of the "COV over time" values, so in some spaces this experimental error would be larger in magnitude than any other source of experimental error.

One of the limitations of this study was that we could not drill into the reasons for this difference between views, nor determine the best approach for addressing this variation within a space. This variation should eventually be addressed in revised data collection protocols, as discussed in the conclusions of this report.

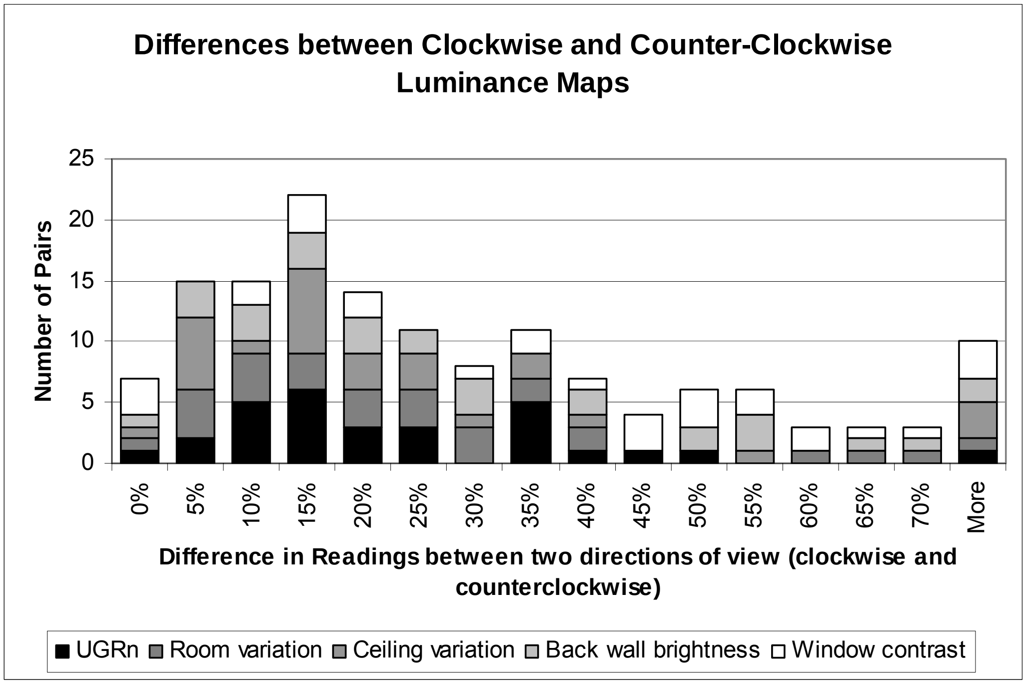

Figure 24 – Differences in each luminance metric between clockwise and counter-clockwise luminance maps.

5.4 Assessment of Experimental Error

5.4.1 Errors Due to Specularity of the ALDI

The geometric relationship between the camera, the sides of the ALDI and the windows makes it possible that specular reflections from the windows into the camera lens could be causing an error in the measurement of directionality.

We chose a pyramid with equilateral triangles so that the angle between the sides and the base is 54°. We did not want to have this angle equal to 45° because that would have maximized the chances of specular reflections of the windows entering the lens.

To minimize specular reflections, the sides of the ALDI were lightly sanded, but we expected that some degree of specularity would remain so we measured the magnitude of the error by comparing the ALDI values with on-site measurements of illuminance taken with a handheld illuminance meter.

For a perfectly matte (non-specular) surface, the illuminance on each side of the ALDI can be calculated using the equation below.

$$E = \frac{\pi \times L}{\rho}$$

Where: E = calculated Illuminance on that face of the pyramid

L = measured luminance on that face of the pyramid (measured from the luminance map)

ρ = Reflectance of that face of the pyramid

An analysis of the errors showed that the ALDI tends to overestimate illuminances by around 12% due to specular reflections. The left and right faces gave a 12% overestimate when there was a window to that side (the left face of the ALDI looked toward the west window that was sometimes occluded to make the space unilateral). Conversely the left face of the ALDI overestimated reflectance by only 3% when the window was occluded.

The “correct” reflectance was judged using the measurements from the lower and upper faces of the ALDI which, due to the geometry of the space, were not susceptible to specular reflections.

5.4.2 Errors due to Subjectivity of Metrics

Some of the metrics require the user to manually draw a line in the Photolux software to enclose a certain area, and this makes the measurement subject to human error.

This error is likely to be highest for the “window contrast” metric since it requires the experimenter to enclose areas that are often intricate, and to make judgments about what constitutes the window and what constitutes the surround.

Figure 21 shows several outlier points (for window contrast) with a consistent pattern. These outlier points in both spaces are the measurements taken between 9am and 11am, i.e., when direct sunlight was shining through the window and hitting the window frame. This suggests that particularly high luminances on the window frame (which is counted as part of the window surround) may be the cause of the outliers. This is supported by the fact that the 8am data point, when the sun was shining almost perpendicularly through the window and therefore only grazing the window frame, is not an outlier. The methodology for measuring window contrast could be changed so that the window frame is not counted as part of either the window or the surround, but excluded from both.

To produce an estimate of this error we measured the window luminance and window surround luminance twice using two experimenters. The average magnitude of the difference between their measurements was 16% for the window luminance and 7% for the surround luminance, suggesting that the combined error in the measurement of window contrast is of the order of 17%.

As stated in section 4.2.7, the window frame may be a significant source of error in taking this measurement because sunlight may be falling on it. A revised methodology excluding the frame from both the window and the surround measurement would likely result in lower experimental errors.

Ceiling variation also suffers from some measurement subjectivity, but to a lesser degree than window contrast since the edge of the ceiling is usually (though not always) easy to identify.

Back wall brightness suffers from a high degree of measurement subjectivity because, often, it is not clear what should be included in the back wall; furniture and doorways are two of the most obvious examples of areas that may or may not be included in the area defined as the back wall.

5.4.3 Errors due to the Geometry of the Space or other Physical Conditions

In 10 out of 58 cases the back wall brightness could not be measured because the back wall was not visible in the luminance map. In another two spaces there were sun spots on the back wall that made the measurement problematic.

To a lesser extent there were problems measuring the ceiling variation because of beams, roof monitors, sloped ceilings and other features, but it was always possible for the experimenter to find a representative slice of ceiling for the measurement.

6. CONCLUSIONS AND RECOMMENDATIONS

The main aim of this study was to investigate whether luminance-based metrics calculated from luminance maps of a space are a promising way to approach the problem of documenting daylight quality and quantity in an existing space.

The amount of data recorded in the luminance maps, and the flexibility and ease of extracting that data make the luminance maps a very promising tool, and suggest that it should be possible to define metrics that capture a wide range of the important characteristics of daylight inside spaces.

In this section we summarize the performance of each metric we investigated and make recommendations about which ones are most suitable for further consideration. Our recommendations are based on the “criteria for successful metrics” listed in section 1.2, and the COV ratio, discussed below. We grouped our candidates by the general qualities measured: Intensity, Visual Comfort and Temporal Stability.

Perhaps, like many research studies, this effort has raised many more questions that remain to be answered before a reliable, widely accepted set of metrics can be determined. However, we hope that this discussion will serve to help focus those efforts, and may help advance the work needed to create a new generation of daylight metrics.

6.1 COV Ratio

The primary criterion we considered in judging the success of each metric was the “COV ratio” (Figure 25). COV ratio is a measure of how well a single measurement of the metric at a given time in a given space characterizes *that* space in distinction to *other* spaces.

Luminance metric	COV ratio
UGR_{ni}	**1.12**
UGR_{ne}	**1.60**
Room variation	**2.27**
Ceiling Variation	**1.20**
Back Wall Brightness	**2.69**
Window Contrast	**1.92**
Luminance daylight factor	**1.85**

Figure 25 – COV Ratios of Luminance Metrics

A metric with a high COV ratio would have a low measurement error, small variations from one hour to the next within a given space, but large variations across different spaces that would allow a designer or researcher to make useful judgments about the nature of the daylight in those spaces.

Directionality is not included in Figure 25, since it was only tested in the temporal tests, and not across the spaces in the original field study, so no COV ratio could be generated.

6.2 Recommendations

We recommend that the best candidates for future development as daylight metrics are luminance daylight factor, room variation, directionality, and UGR_{ne} as discussed below.

We believe that all of these metrics satisfy the criterion from section 1.2 that they should be “meaningful”, and “easy to measure on site” with a digital camera. Also, all of them *could* be integrated into lighting design software in future. However, the metrics vary in the extent to which they fulfill the other criteria.

Intensity

The most promising metric of intensity is the “luminance daylight factor”, which compares the brightness of all interior surfaces to the amount of daylight available outside. This metric is a luminance-based version of daylight factor, but has advantages over the current illuminance-based daylight factor in that it assesses the whole visual field rather than a single point, and captures information on how well the overall design of the space transmits daylight throughout the space.

Luminance daylight factor has a fairly high COV ratio, but is also highly variable from one hour of the day to the next, which shows how susceptible any daylight factor is to changes in sun angle and changes between overcast and clear skies. We also had difficulty getting accurate exterior illuminance measurements, both at the correct time and under unobstructed sky conditions, adding to the error inherent in the metric for site measurements. If there were a way to normalize luminance daylight factor by sky condition and/or solar position, it might be more useful. The high degree of variability should be solved before this metric is used in any field studies.

Luminance daylight factor is a useful counterpart to the other metrics because it is the only one that is directly proportional to the amount of daylight entering the space. Furthermore, for this reason, it is highly independent of the other metrics and so fulfils the lack of redundancy requirement of the criteria in section 1.2.

Visual Comfort

Room variation is a very simple measurement to create from Photolux images. It is just the standard deviation of the brightness of all pixels in the field of view divided by the average brightness. It clearly distinguished between our unilateral and bilateral spaces, and proved to have the second highest COV ratio of the metrics, thus had substantially less variation within multiple time period measurements of a space than between spaces. It also has no measurement error due to subjectivity. It seems likely that it may be a useful proxy for uniformity and/or some other meaningful occupant assessment of daylight quality such as “visual variety” (Loe et al 1994).

The corresponding illuminance measurement from our field study is “horizontal variation” which was significant in predicting photocontrol system functionality.

Directionality is another promising metric. Measured with the use of the ALDI, it captures the ratio of vertical daylight illumination available from one side of the room versus the other. The corresponding illuminance measurement from our field study is “drop-off rate” which was significant in predicting photocontrol system functionality.

It was very successful in distinguishing unilateral from bilateral spaces, and was more stable over time within a space than between spaces. The use of the ALDI could easily be expanded to compare daylight available from other directions, such as from above versus from the sides, or the luminance of the visual field facing the camera versus that from behind the camera.

While the ALDI is another device that would need to be transported to and set up on site, it offers the advantage of standardizing all measurements across spaces, regardless of the unique design features of the space. An ALDI could also be programmed into lighting rendering software, or miniaturized for physical model studies.

As we tested it in this study, **Directionality**, created using the ALDI, is a more reliable substitute for other metrics of uniformity considered, such as ceiling variation, window contrast, or back wall brightness. Each of these three metrics, which we defined for use with the field study, is highly dependent upon the definition by the user, and can vary greatly in applicability across different space designs. **Ceiling Variation** is usually easy to define and provides a reliable description of daylight distribution across the space, but in some spaces is interrupted by shadowing elements like beams or bright spots caused by reflections from adjacent windows. In toplit spaces the skylight well would need to be excluded, adding more discretion in its definition. **Back wall brightness**, while stable in our studies and with a high COV, would be difficult to define in bilaterally lit spaces and might be meaningless in a top lit space. **Window Contrast** had the highest COV ratio of 1.9 in our study, but is also the most subjective and fussy and labor intensive to define. Nor would it be very meaningful in a skylit space,

UGR_{ne} and **UGR_{ni}** both have promise and problems as normalized metrics of glare in a daylit room. UGR_{ne} (normalized to exterior illuminance) has the higher COV of 1.56, but UGR_{ni} (normalized to average interior illuminance) does a better job of distinguishing between unilateral and bilateral spaces. Our measurements of UGR_{ne} across different spaces were compromised by inaccurate measurements of simultaneous outdoor illuminance, so the COV ratio would have to be further investigated using more spaces and more reliable exterior measurements. UGR_{ni} can be generated form a single set of Photolux images, while UGR_{ne} requires additional simultaneous measurements outside. Given these various pros and cons it is unclear to us at this time whether normalizing UGR for the average brightness in the space or the available daylight outside of the space would be more useful.

Temporal Stability

In this study we measured temporal stability versus spatial variation with the COV for these two sets of values for each metric, and then compared their ratio. Here the goal was to identify the metrics that did the best job of comparing different daylit spaces, independent of the sky conditions at the time of measurement.

Temporal stability would seem to be an important characteristic of a daylight design, but difficult to measure in the field at one point in time. Data loggers that can capture illuminance trends over time could be one solution. Comparing the range of values under a few key standardized conditions might be another. Other approaches might be to characterize the temporal stability of each metric, or to standardize the conditions under which the measurement is taken (as was done using the CIE sky for Daylight Factor). Temporal stability may also eventually be captured in an annual analysis of the energy performance of a space, as in Daylight Autonomy or Useful Daylight Index.

7. NEXT STEPS

7.1 Photo Data Collection Protocols

The digital camera images combined with the Photolux software provided a very easy and standardized method for collecting an enormous amount of data about the daylight characteristics of a space. We took two sets of eight photos, in opposite directions perpendicular to the primary windows in the space. The direction of the two sets of photos was determined by the need to record to rate of change from the front to the back of the space.

However, the difference in the value of the various metrics considered between these two sets of photos was considerable. Furthermore, for a toplit space, it may not be obvious in which direction to take these images at all. Thus, it would be useful to develop a protocol that could be universal for all daylit spaces. One possibility is to take one set of images facing the primary (or south) window direction. The ALDI could provide additional information about light form the opposite direction. Another possibility is to take the fish eye image looking up. The merits of these alternate view points should be considered more thoroughly.

Only **Room Variation** and **UGR_{ni}** can be derived solely from a set of Photolux images. Two other metrics, **UGR_{ne}** and **Luminance Daylight Factor**, require reliable measurements of exterior daylight illuminance, while the **Directionality** metric requires the use of the ALDI. Our preference would be to develop a set of metrics that require the least amount of equipment, data collection and analysis.

7.2 Luminance Metrics that could be Developed in Future

Luminance-based measurements make it possible to develop a much wider array of metrics than would be possible by using illuminance. We have briefly considered what luminance-based metrics could be developed in future, and these are listed below and described in detail in Appendix B. All of these metrics have a basis in existing visual science and lighting research, but have not yet been developed to the status of metrics. We have listed them because we think each one is a good candidate for further research into the way that daylight quality influences energy savings through the actions of occupants – for instance switching lights on or off, or adjusting or disabling photocontrols.

- Discomfort glare metric specific to daylight instead of electric light
- Disability glare
- Gloom
- Sparkle
- Complexity of the visual scene

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APPENDIX A

Calculation of Normalized UGR

The Photolux software calculates UGR for each space (i.e. for each luminance map) based on the luminance values in the field of view. This measured value of UGR (UGR_m) for each space is calculated as shown below:

$$UGR_m = 8\log_{10}\left[\left(\frac{0.25}{L_b}\right)\sum\left(\frac{L_s^2\omega}{p^2}\right)\right]$$

Where: L_s = Luminance of the source (window)

p = Guth position index

L_b = Background luminance, i.e., the average luminance of the field of view excluding the glare sources

"Normalizing" UGR means to scale all the luminances in the space up or down by the same amount. Using this method, the relative distribution of daylight in the space remains the same while the amount of daylight changes. Scaling up and down by a factor k implies that each luminance can be expressed as k times the original value. This gives the normalized UGR (UGR_n)

$$UGR_n = 8\log_{10}\left[\left(\frac{0.25}{kL_b}\right)\sum\left(\frac{k^2L_s^2\omega}{p^2}\right)\right],$$

Rearranging this equation gives:

$$UGR_n = 8\log_{10}[k] + 8\log_{10}\left[\left(\frac{0.25}{L_b}\right)\sum\left(\frac{L_s^2\omega}{p^2}\right)\right]$$

i.e.:

$$UGR_n = 8\log_{10}[k] + UGR_m$$

This equation means that as k varies, i.e. as the average luminance of the space increases and decreases, UGR can be expected to vary with the log of k.

In this analysis two different normalized UGR are used; one is normalized to an interior luminance of 50 cd/m^2 (UGR_{ni}) while the other is normalized to an outdoor *illuminance* of 2000 fc (UGR_{ne}). The scaling factor k must therefore be chosen such that kL_{avg}=50 for UGR_{ni} and such that kE_{ext}=2000 for UGR_{ne}.

Substituting these values for k into the equation above gives:

$$UGR_{ni} = UGR_m + 8\log_{10}\left[\frac{50}{L_{avg}}\right]$$

And:

$$UGR_{ne} = UGR_m + 8\log_{10}\left[\frac{2000}{E_{ext}}\right]$$

Calculating the Glare Threshold

To calculate UGR_m for each space, Photolux requires a “glare threshold” value that allows it to determine which pixels are part of the “source” and which are part of the “background”. Pixels with a luminance higher than the threshold are sources, those lower are background.

Depending on what value is chosen for the threshold, the calculated UGR will vary. Figure 26 shows how UGR varies as a function of the chosen glare threshold, for a sample of spaces. In Figure 26 the threshold is measured in terms of the number of standard deviations above or below the mean luminance value in the scene; for instance, a threshold of 1 would mean that the threshold was chosen to be the mean luminance of the scene plus one times the standard deviation of the luminances in the scene.

When the threshold is very low the UGR value is high because lots of pixels are counted as glare sources. The UGR value is fairly stable over a wide range of threshold values but then drops off sharply because it reaches a point where there are simply no pixels with such a high luminance, so there are no glare sources.

There is no objective way to determine the “correct” threshold for each space. But rather than making a subjective estimate for each space we wanted a more consistent and objective method to determine it. From Figure 26 it can be seen that the UGR values level out at slightly more than one standard deviation above the mean, so any value greater than one would be adequate. However, in some of the spaces it was not possible within the constraints of the software to calculate values much higher than two, so for convenience we chose two as the standard value, i.e. in each space the threshold was the mean luminance of the scene plus two times the standard deviation of the luminance.

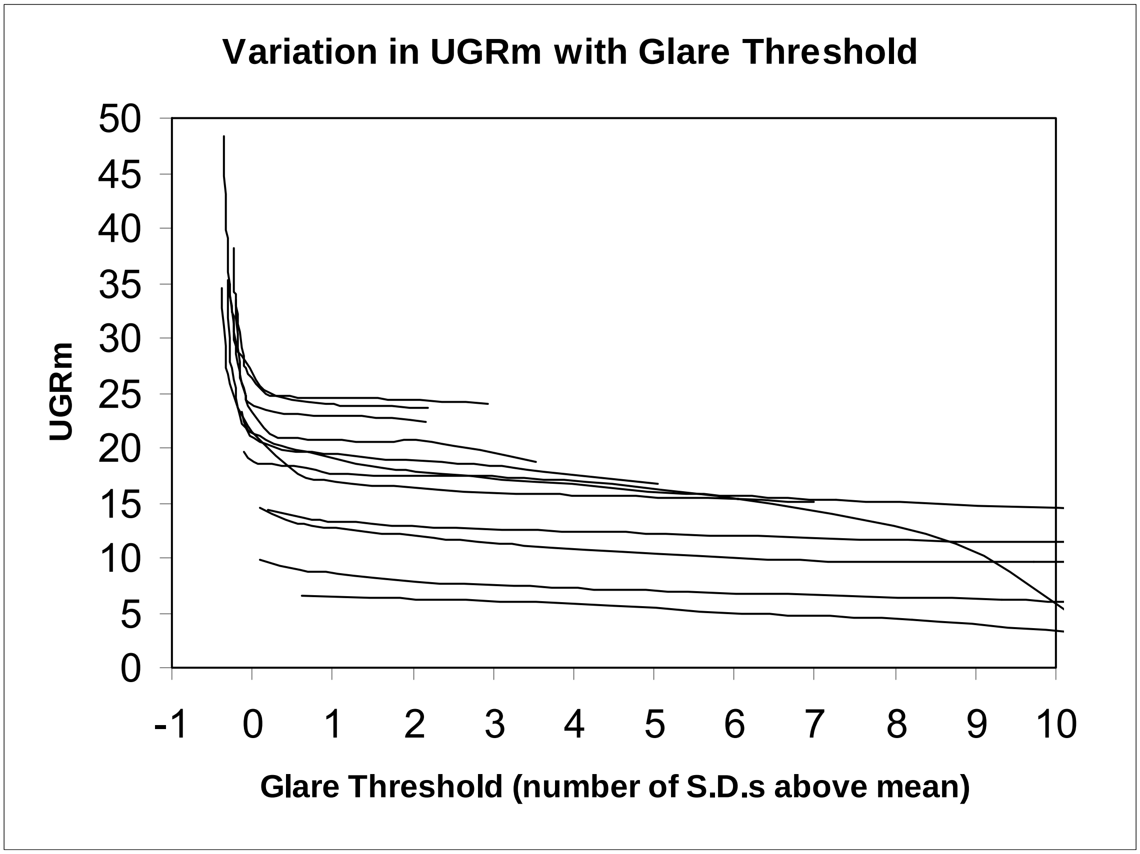

Figure 26 – Variation in UGR with glare threshold

APPENDIX B

Table of Luminance Metrics

This appendix shows tables of luminance metrics, as follows:

- Figure 27 - Metrics that are Automatically Generated by the Photolux Software
- Figure 28 - Metrics Developed for Use in this Study
- Figure 29 - Metrics that could be Developed in Future

Metric	What quantity does this measure? Where does it come from?	Why do we think this might be a useful metric?	What significant illuminance metric(s) might this relate to?	Selected for this study?	If no, why?
UGR (Unified Glare Rating)	Measures people's subjective appraisal of discomfort glare. Not specifically developed for daylight, only for luminaires with reasonably uniform luminances	Most commonly used glare index, supported by research studies. Often calculated in lighting software. May predict occupant satisfaction	None	Yes (see "normalized UGR" below)	
GI (Glare Index)	Discomfort glare	Glare index developed by Hopkinson, in UK,	None	No	Superceded by UGR
CGI1 (CIE Glare Index #1)	Discomfort glare	Original CIE glare index developed by Einhorn	None	No	Superceded by UGR
DGR (Discomfort Glare Ratio)	Discomfort glare	Part of the Guth *Visual Comfort Probability* system	None	No	Superceded by UGR
Minimum luminance	Minimum luminance of any pixel in the scene	Not useful on its own	None	No	Not useful on its own
Maximum luminance	Maximum luminance of any pixel in the scene	Not useful on its own	None	No	Not useful on its own
Average luminance	Average luminance of scene	Not useful on its own	None	No	Not useful on its own
Standard deviation of the luminance	Root mean square luminance of scene	Not useful on its own	None	No	Not useful on its own
Illuminance at the camera lens	Illuminance at camera lens	Not useful on its own	None	No	Not useful on its own
Number of saturated pixels in the image	number of saturated pixels	Not useful on its own	None	No	Not useful on its own
Number of under-exposed pixels in the image	number of under-exposed pixels	Not useful on its own	None	No	Not useful on its own

Figure 27 - Metrics that are Automatically Generated by the Photolux Software

Metric	**What quantity does this measure? Where does it come from?**	**Why do we think this might be a useful metric?**	**What significant illuminance metric(s) might this relate to?**
Normalized UGR (UGR_{ni} and UGR_{ne})	UGR increases logarithmically as the scene gets brighter; this metric makes UGR independent of brightness	As above	None
Luminance variation	Room standard deviation divided by room average luminance	Research has shown that occupants prefer interiors with a moderate degree of variation (Loe 1994). May correlate well with illuminance metrics	Inverse of drop-off rate, horizontal variety
Ceiling variation	Ceiling standard deviation divided by ceiling average luminance.	Proxy for uniformity of the working plane – a common measure of visual adequacy. The ceiling is also the most convenient surface to measure because it is usually uncluttered and visible from everywhere in the room. May correlate well with illuminance metrics.	Inverse of drop-off rate, horizontal variety
Back wall brightness	Back wall average luminance divided by whole space average luminance	Measure of how dark the back of the room is. May correlate well with illuminance metrics	Inverse of drop-off rate
Window contrast	Window average luminance divided by average luminance of the area surrounding the window	This is an alternative way to measure glare, and is specific to windows	None
Directionality	Ratio of how much light is coming from each direction along the primary axis of the room[3]. Calculated as the ratio of the luminance of the left and right faces of the ALDI	May be a good measure of general contrast, i.e. glare, depth of shadows. May correlate well with illuminance metrics	Inverse of drop-off rate, horizontal variety
Luminance-based Daylight Factor (LDF)	Average luminance of the interior divided by exterior illuminance	Research has closely linked daylight factor to occupant use of light switches (Hunt 1980), and to overall satisfaction with daylighting	Window transmittance metric (effective aperture)

Figure 28 - Metrics Developed for Use in this Study

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[3] We take the primary axis to be perpendicular to the windows

Metric	What quantity does this measure? Where does it come from?	Why do we think this might be a useful metric?	What significant illuminance metric(s) might this relate to?	How easy would it be to extract? (1=easiest, 3=hardest)	Error between experimenters (1=zero error, 3=significant error	Could it be measured for every space? (1=all, 2=almost all, 3=some)
Discomfort glare metric specific to daylight	Existing glare metrics are based only on subjective reports of discomfort. A more useful metric would be based on observed behavior	Would predict the likelihood of occupants closing blinds, switching on lights	None	unknown	unknown	unknown
Disability glare	Measures reductions in visibility caused by glare sources. Glare causes scatter of light in the lens and cornea, and lateral inhibition in the retina	May predict occupants' use of light switches and consequent energy use. behavior , as well as overall satisfaction with daylighting	None	1	1	1
Gloom	Measures subjective judgments of gloom. Gloom may be caused by an inability to discriminate colors	Same reasons as disability glare (above)	Effective aperture	unknown	unknown	unknown
Sparkle	Sparkle is "the good glare" caused by very small, bright light sources[1]. It has been defined mathematically in terms of the luminance and angular size of the source,[2]	Small, very bright highlights may counter gloom,	None	3 (Photolux has insufficient resolution)	1	1
Complexity of the visual scene	Number and sharpness of edges in the scene	May be a measure of naturalness; man-made scenes contain sharper edges than natural scenes	None	1	1	1

Figure 29 - Metrics that could be Developed in Future

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[1] Akashi, Y., Akashi, I., Tanabe, Y.,Mukai, K., 2000. *Sparkle Phenomena; Pilot Study*, Lighting Research and Technology, 32(1), pp.19-26

2 Myer, M., Boyce, P., Akashi, Y.2003. *Defining Sparkle*, Proceedings of the 2003 Annual Conference of the Illuminating Engineering Society of North America, pp.305-333