SDAR* Journal of Sustainable Design & Applied Research

Volume 7 | Issue 1 Article 4

2019

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Recommended Citation

Wasilewski, Stephen; Grobe, Lars Oliver; Wienold, Jan; and Andersen, Marilyne (2019) "A Critical Literature Review of Spatio-temporal Simulation Methods for Daylight Glare Assessment," *SDAR* Journal of Sustainable Design & Applied Research*: Vol. 7: Iss. 1, Article 4.
doi:https://doi.org/10.21427/87r7-kn41
Available at: https://arrow.tudublin.ie/sdar/vol7/iss1/4

A Critical Literature Review of Spatio-Temporal Simulation Methods for Daylight Glare Assessment

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Abstract

A well daylighted space can provide a highly satisfying visual environment. However, if that environment causes us visual discomfort, it can become such a nuisance that we, sometimes literally, turn our backs on this powerful connection to the outside world. Given this, there is enormous value in quantifying the occurrence of discomfort glare within buildings, and in glare models that may guide architects and engineers in design.

With the success of climate-based modeling techniques for daylight illuminance, there is now a focus on including discomfort glare metrics in spatio-temporal evaluations. This article conducts a literature review of research focused on spatio-temporal simulations for glare assessment. Studies are reviewed according to their objectives, metrics calculated, spatial scope, temporal scope and scene variety. The goal is to document the limitations of current simulation methods, the potential to generally apply these methods, and how well these methods incorporate empirical glare research.

This review finds that, due to computational constraints, there is an over-reliance on illuminance-based metrics for spatio-temporal glare assessment, even while user assessment research reinforces the importance of including contrast-based measures. To achieve an accurate zonal glare assessment, future research should focus on improving simulation efficiency and identifying ways to reduce the spatial, temporal and angular scope of the simulation, while maintaining high accuracy.

Nomenclature

E_h Horizontal illuminance (lux)
E_v Vertical illuminance (lux)
L_b Background luminance (cd/m^2)
L_s Source luminance (cd/m^2)
ω_s Source solid angle (steradians)

ASE	Annual Sunlight Exposure (IESNA, 2012)
CGI	CIE Glare Index (Einhorn, 1979)
DGI	Daylight Glare Index (Hopkinson, 1972)
DGP	Daylight Glare Probability (Wienold and Christoffersen, 2006)
DGPs	A simplified approximation of DGP based only on E_v (Wienold, 2007)
eDGPs	Daylight Glare Probability (Wienold, 2009)
UDI	Useful Daylight Illuminance (Nabil and Mardaljevic, 2005)
UDIe	Useful Daylight Illuminance Exceeded (Nabil and Mardaljevic, 2005)
UGP	Unified Glare Probability (Hirning *et al,* 2014)
UGR	Unified Glare Rating (International Commission on Illumination, 1995)

https://arrow.tudublin.ie/sdar/vol7/iss1/4
DOI: https://doi.org/10.21427/87r7-kn41

1. Introduction

1.1 Measuring glare from daylight in buildings

Discomfort glare from daylight is a multi-faceted phenomenon resulting from physical, psychological and physiological factors acting on building occupants. Unlike electric lighting, which operates in a fixed range of states and can be specifically designed and positioned to control the lighting distribution, daylight relies on the ever-changing sky and the complicated pathway between the sky and the occupants' eyes that interacts with much of the built environment. This combination of the many factors associated with glare, and the dynamic nature of daylight, make measuring and predicting discomfort glare from daylight exceptionally more difficult than either assessing glare from electric lighting or determining more basic photometric quantities, like illuminance, commonly used as an indicator of daylight performance.

In user assessments, metrics and quantities associated with visual comfort (E_v, DGP, luminance ratios) show a stronger relationship with user satisfaction than horizontal desktop illuminance values (Van Den Wymelenberg, 2014), but horizontal illuminance metrics prevail as the dominant metric for building standards. Examples include the IES Lighting Handbook (DiLaura and IESNA, 2011) and the IES Daylight Standard (IESNA, 2012). This is partially a legacy inherited from electric lighting and standards determined first by what electric lighting could deliver and then later by energy costs (Osterhaus, 1993).

The new European Standard EN 17037 (European Committee for Standardisation CEN, 2019) begins to address this, as it includes a glare evaluation using DGP alongside illuminance-based daylight metrics, but the standard is only a recommendation and is not yet required for any certification. However, it can be expected that national legislation as well as certifications will refer to the methods and thresholds and use them as a requirement in future. Perhaps the biggest factor for continued reliance on horizontal illuminance metrics is the efficiency with which they can be calculated, visualised and analysed zonally with a well-established, if arbitrary, acceptance criteria (Tregenza and Mardaljevic, 2018). In addition to being an important factor in determining indoor environmental quality, glare that is unaccounted for in the design stage leads to occupant intervention, such as lowering blinds etc, and has a direct impact on daylight availability and lighting energy use.

Without reliable and efficient methods for predicting glare throughout a building and over the course of a year, it is not possible to accurately assess the daylight performance of a building, in terms of either visual comfort or daylight availability. To this end, a number of published articles in the past decade have proposed, tested or reviewed simplified simulation methods as a path towards spatio-temporal glare (herein defined as assessing glare spatially throughout a building zone accounting for temporally changing sky conditions). This paper reviews these articles to determine what progress has been made, what areas of inquiry require more research, and how compatible these approaches are with current instantaneous user assessment glare research.

The need for a method to determine spatio-temporal glare metrics for building design is clear. A spatio-temporal approach enables the formulation of zonal metrics that are the standard for thermal comfort, electric lighting and, increasingly, for daylight availability (Atzeri *et al*, 2016). Active façade systems like venetian blinds and roller blinds are typically controlled zonally, and in open office areas there is not a one-to-one relationship between window and occupant because one person's glare can reduce another person's view and daylight illumination. For wide-ranging purposes from advanced façade control to compliance modeling and design optimisation, it is essential to have a metric from which a zonal determination can be made, even if a single metric cannot capture the natural variability of daylight across the space.

Increasingly, building regulations and standards are adopting visual comfort metrics for daylight visual comfort. These standards either rely on proxy measurements (like ASE) that do not account for material properties, prescriptive recommendations, or simulation requirements that rely on the practitioners to determine the pointof evaluation. The new European Standard (EN 17037) includes a performance path which includes an annual glare assessment from a worst-case point, but there is no criteria for determining that point and view direction (European Committee for Standardization CEN, 2019).

LEED daylighting requirements are built around daylight autonomy and glare is addressed implicitly in the annual sun exposure calculation (IESNA, 2012). This only indicates the presence of uncontrolled direct sun and does not assess glare through perforated, fabric, diffusing or otherwise redirecting materials. The WELL building standard also uses an ASE calculation buttressed by a number of prescriptive requirements to reduce the likelihood of glare (International WELL Building Institute, 2019). In the United Kingdom, public schools must meet standards according to Useful Daylight Illuminance (UDI) which uses an upper threshold (UDIe) as its discomfort glare metric (Education Funding Agency, 2014).

1.2 Relevant factors for glare assessment

While the methods and metrics for predicting glare are still widely questioned, there is a reasonable consensus on what the principal factors are that contribute to glare. The current understanding of these factors is well documented in a review article by Pierson *et al*, (2018). The factors related to discomfort glare can be divided into two broad categories – external (pertaining to the environment or an occupant's position therein) or internal (pertaining to the specific nature of the occupant). Daylight simulation will principally focus only on the external factors. Incorporating internal factors to a glare analysis could be achieved through a correction factor or other post-processing of the data, and it is unlikely that an internal factor would increase the simulation requirements beyond the identified external requirements. As established in the review by Pierson *et al*, (2018), the external factors most consistently linked to glare are the:

- Saturation effect;
- Contrast effect;
- Luminance of the glare source;
- Size of the glare source;
- Adaptation level;
- Position of the glare source.

Accurate simulation of glare conditions will thus require, at a minimum, the luminance distribution in all directions seen from a point, knowledge of the occupant view direction, and the adaptation of the eye (possibly related to both the light incident on the eye and

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the luminance of the object of focus). A good example of this level of detail is demonstrated in a paper by Amundadottir *et al*, (2017).

A recently-published validation study by Wienold *et al*, (2019) looked at the performance of established glare prediction metrics and found that for daylight-dominated workspaces, metrics that combine the contrast effect (which require the luminance distribution to calculate) and the saturation effect as input perform the best and are more robust across different lighting conditions. For the conditions included in the subject studies (typically window adjacent workspaces), DGP, which prioritises the saturation effect, performs the best.

There is still a question as to how to balance the two effects in deep floor plate buildings where there have not been the same number of user assessment studies. A field study of open plan buildings by Hirning *et al*, (2014) found that metrics (like UGR), which only measure contrast effects, perform the best, although Osterhaus (2005) demonstrates that UGR is inaccurate for large area glare sources such as nearby windows. Future research will need to resolve this transition from saturation-dominated environments to contrast-driven ones, but in any case, simulation methods will need to provide for both when used for glare assessments of building designs.

1.3 Simulation methods

When simulation (used to mean the physical simulation of light propagation into buildings) for glare assessment is extended to include multiple positions and times, sampling occurs across the dimensions of position (three degrees of freedom), view direction (two degrees of freedom), and sky condition (two degrees of freedom when represented spatially). While each of these dimensions require some level of detail to perform a zonal and climate-based spatio-temporal assessment, a high-resolution sampling across all seven of these dimensions requires a large, and typically infeasible, number of calculations. Instead, depending on the objectives of the reviewed papers, one or more of these dimensions are collapsed to a single value. Within the context of these objectives, this review is organised around each of these dimensions.

The angular resolution of the incident light is determined by either the simulation method employed or the requirements of the physical

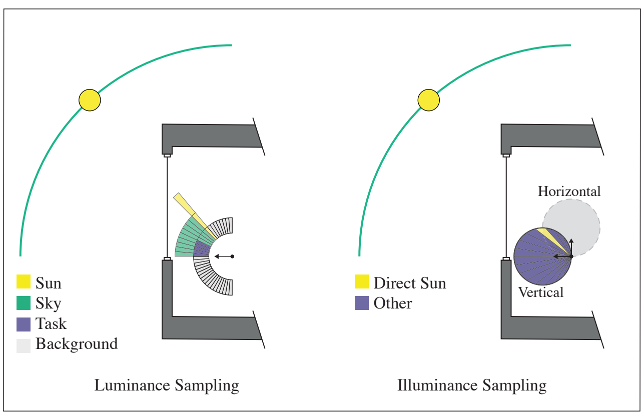

Figure 1. Simulation scope for luminance and illuminance-based simulations. Note that a single luminance image will contain the resolution squared number of samples, while the illuminance produces a single value. With a luminance image, sun, sky, task and background can all be extracted as separate statistics, whereas an illuminance value must be calculated separately for each source and ambient parameter.

quantities needed to calculate a desired metric. All of the reviewed articles use established or novel methods to efficiently perform the large number of simulations required. Figure 1 illustrates the scope of a single position and point-in-time illuminance or luminance-based simulation, and what discrete information can potentially be extracted from the output. Table 1 identifies which scope is needed to calculate the set of instantaneous metrics (measuring glare for a single time-step and point-in-time) included in at least one of the reviewed papers. Assuming a backwards ray-tracing algorithm, simulating a single pixel of a luminance map (representing some discrete ω_s) requires calculating the illuminance at every point a view ray intersects the scene. This means that each view ray (image pixel) can take as much time as calculating a single illuminance value.

Glare Metric or Quantity	Required Quantity	Required Simulation Scope*
DGI	L_s, L_b, ω_s	Luminance
DGP	L_s, E_v, ω_s	Luminance
eDGPs	L_s, E_v, ω_s	Luminance (direct view) + Illuminance
DGPs	E_v	Illuminance
UGR	L_s, L_b, ω_s	Luminance
E_v	-	Illuminance
E_h	-	Illuminance
$E_{h,dir}$	-	Illuminance (sun only)

Table 1. Single position and time glare metrics and their dependencies (*Luminance or Illuminance).

2. Literature review

2.1 Scope

The purpose of this review is to gather the breadth of simulation techniques employed and to summarise what the current state-of-the-art is in simulation for glare assessment across time and space. An extensive search yielded the set of peer-reviewed journal articles, conference papers and academic theses published between 2007 and 2019 shown in Table 2.

Publications for this literature review were initially found using Google Scholar. The search methods used were keyword searches, "cited by" searches, and checking the citations of found publications to conduct additional rounds of "cited by" searches. Keywords included common daylight glare indices and terms for annual simulation, glare and contrast. "Cited by" searches were performed both on publications identified for inclusion in the review set and publications used as general reference for this article. The journals of included studies were also searched for additional articles that otherwise were not found. This process was repeated iteratively over the course of writing this review, from April to September 2019. A publication was included in the review set if it met all of the following criteria:

- Is published in a peer-reviewed journal or conference proceedings, or is an accepted graduate level thesis from an accredited university;

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DOI: https://doi.org/10.21427/87r7-kn41

Study	Citiation	Study	Citiation
1.	Wienold (2007)	15.	Garcia-Hansen *et al.* (2017)
2.	Wienold (2009)	16.	Nezamdoost and Van Den Wymelenberg (2017)
3.	Jakubiec and Reinhart (2011)		
4.	Mardaljevic *et al.* (2012)	17.	Tsianaka (2018)
5.	Chan and Tzempelikos (2013)	18.	Jakubiec *et al.* (2018)
6.	Konstantzos *et al.* (2015)	19.	Jakubiec (2018)
7.	Torres and Verso (2015)	20.	Kong *et al.* (2018)
8.	McNeil and Burrell (2016)	21.	Bian (2018)
9.	Atzeri *et al.* (2016)	22.	Bian *et al.* (2018)
10.	Jakubiec and Reinhart (2016)	23.	Santos and Caldas (2018)
11.	Konstantzos and Tzempelikos (2017)	24.	Giovannini *et al.* (2018)
		24.	Giovannini *et al.* (2018)
12.	Jones and Reinhart (2017)	25.	Abravesh *et al.* (2019)
13.	Atzeri *et al.* (2017)	26.	Zomorodian and Tahsildoost (2019)
14.	Dutra de Vasconcellos (2017)	27.	Jones (2019)

Table 2. List of studies included in the literature review.

- Is written in, or has been translated into English;
- Includes a physically-based daylight simulation of an indoor environment evaluated across at least one spatio-temporal dimension. Spatio-temporal dimensions include:
    - (a) Multiple time-steps meant to represent a continuous time period;
    - (b) Multiple positions meant to represent a continuous distribution across a space or building;
    - (c) Multiple view directions meant to represent an adaptive position from a single position.
- Proposes, validates or compares simulation methods or glare metrics across the evaluated spatio-temporal dimension(s)

The last criteria is included to filter out studies that may calculate glare metrics to evaluate a particular space rather than evaluate the quality of the metric or method in some way. These studies are excluded because they often lack enough detail regarding the simulation method or metric reliability, and are primarily focused on objectives outside the focus of this review. There was no criteria for excluding articles that met the inclusion conditions. All studies that were identified by the search, and met the inclusion criteria, are included in this review.

2.2 Reviewed study objectives

The shared objectives of the publications in this review are organised into five different categories: metric comparison, new metric, metric validation, simulation validation and simulation method. Figure 2 shows the number of studies with each of these objectives. Note that, as defined, it is possible for a study to include multiple objectives, for example, a study proposing a new metric may also perform a metric validation.

The most common purpose of the research is to compare the validity of metrics (MC). Many of the studies are testing whether simpler illuminance-only based metrics provide a similar set of time-steps when there is glare. Of the 11 publications that included a metric comparison between an illuminance-only metric and a metric that requires some luminance information, all calculated DGP (either fully simulated or using the eDGPs method).

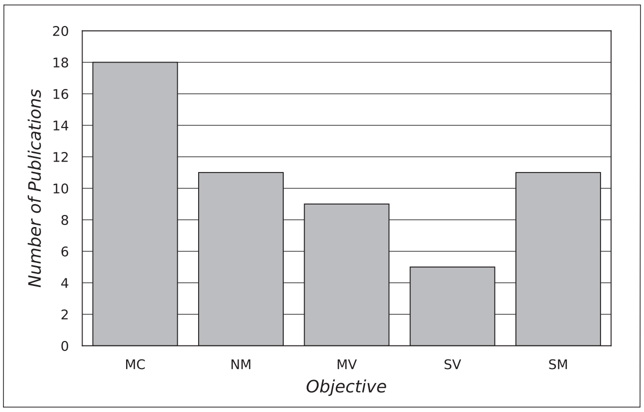

Figure 2. The frequency of objectives within the reviewed studies (MC: metric comparison, NM: new metric, MV: metric validation vs. human experiment, SV: simulation validation, SM: simulation method).

Eleven out of the 27 publications include a proposal for a new metric or group of metrics (NM). These proposals were either an accumulated metric to look at zonal or annual performance, or were proposed to simplify the simulation or setup (such as being direction agnostic) of the simulation.

Metric validation studies (MV) include a human survey component and offer helpful additional research into how duration impacts assessment of glare (Bian, 2018), or how a space is assessed over longer periods of time compared with the laboratory-based glare assessments used in the development of the principal glare metrics (Jakubiec and Reinhart, 2016; Nezamdoost and Van Den Wymelenberg, 2017; Jakubiec *et al*, 2018).

Publications with simulation validation (SV) include sensor data and/ or HDR image capture of physical spaces and compare results with a simulation model. For all of the included studies with this objective, it is secondary to another objective and pursued primarily for purposes of calibrating the simulation against the measured data.

Publications that explore simulation methods (SM) include a comparison or proposal of simulation approaches, typically focused on developing more efficient or faster methods for generating results. Of the 11 studies proposing new methods, six also propose a new metric associated with the method. When these two objectives are coupled, the metric and method are only applicable to the conditions covered by the variety contained in the analysis space. This review assesses a study's simulation methods based on its suitability for spatio-temporal glare assessment, which is not necessarily the study's principal objective. Three of the reviewed articles had multiple rounds of simulation pursuing differing objectives and used a different set of dimensions for each round. In the following sections, these rounds are included as a second line (denoted with a, b) for that study in all tables.

2.3 Discrete glare metrics

All of the approaches in this review, even if they include some annual or accumulated time-based metric, have at their root a discrete point-in-time calculation based on a single data point or image/luminance map. These calculations are either purely based on illuminance or include a luminance component, which requires angular distribution data of the incoming light, typically in the format of an HDR image generated from a lighting simulation. As shown in Figure 3, among the luminance-based metrics DGP or eDGPs was calculated in 20 out of the 27 publications. If the simplified DGPs, which is only based on vertical illuminance, is also included, 24 out of 27 publications include one of the three methods for calculating DGP. Vertical illuminance (E_v) was the most frequently-calculated illuminance metric. Horizontal illuminance (E_h) was typically included as part of a Useful Daylight Illuminance calculation (Nabil and Mardaljevic, 2005) examining the hours exceeded (UDIe). Overall, in the 27 publications there were 37 luminance and 44 illuminance metrics calculated to measure discomfort glare.

Many of the metric comparison studies were designed to test the validity of an illuminance-based metric against a more detailed luminance-based metric. Among the reviewed studies, eight (Wienold, 2007, 2009; Mardaljevic *et al*, 2012; Konstantzos *et al*, 2015; Torres and Verso, 2015; Jakubiec, 2018; Santos and Caldas, 2018; Giovannini *et al*, 2018) conclude that an illuminance-based metric is a suitable proxy for DGP in certain circumstances. All of these studies state that either the illuminance-based metric is not accurate if viewpoints are in direct sun, if the visible transmission of the fenestration is low, and/or if the transmission of the fenestration includes a scattering component. This is in line with findings from user assessment glare studies which have shown that illuminance-based metrics do not predict glare as well as metrics that include a contrast effect (Hirning *et al*, 2014; Pierson *et al*, 2018; Wienold *et al*, 2019).

2.4 Spatial resolution

Perhaps the most important dimension for assessing the glare potential of a space or building is the spatial dimension. An approach that uses a zonal calculation will enable the development of practical and useful glare metrics for comparing building performance. This is an important consideration for making design decisions, optimisation and establishing building standards. This development will also enable glare to be considered in parallel with other zonal building performance metrics. Table 3 shows the number and resolution of points, as well as number of view directions, calculated for each study.

Except for Bian *et al*, (2018), all of the publications included with a metric validation objective looked at user survey data across a large number of locations within a building/buildings. These studies have a

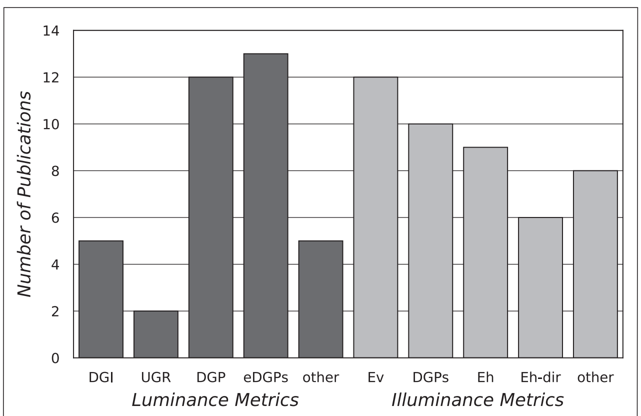

Figure 3. The frequency of metric use within the reviewed studies.

Study	Author (year)	Total points simulated	Approx. resolution (m²/point)	View Directions
1.	Wienold (2007)	1	1	1
2.	Wienold (2009)	1	1	1
3a.	Jakubiec and Reinhart (2011)	10	0.5	120
3b.	Jakubiec and Reinhart (2011)	5	0.5	31
4.	Mardaljevic *et al*. (2012)	16	0.3	4
5.	Chan and Tzempelikos (2013)	1	1	1
6.	Konstantzos *et al*. (2015)	1	25	1
7a.	Torres and Verso (2015)	9	1	8
7b.	Torres and Verso (2015)	1	9	8
8.	McNeil and Burrell (2016)	1	1	3
9.	Atzeri *et al*. (2016)	9	1	1
10.	Jakubiec and Reinhart (2016)	500	1	1
11.	Konstantzos and Tzempelikos (2017)	3	1	1
12.	Jones and Reinhart (2017)	9	1	1
13.	Atzeri *et al*. (2017)	1	1	1
14.	Dutra de Vasconcellos (2017)	432	0.37	1
15.	Garcia-Hansen *et al*. (2017)	40	1	1
16.	Nezamdoost and Van Den Wymelenberg (2017)	Unknown	0.37	0
17.	Tsianaka (2018)	12	Variable	10
18.	Jakubiec *et al*. (2018)	543	1	1
19.	Jakubiec (2018)	4	1	2
20.	Kong *et al*. (2018)	14	1	1
21.	Bian (2018)	3	0.25	19
22.	Bian *et al*. (2018)	2	1	1
23a	Santos and Caldas (2018)	1	1	1
23b	Santos and Caldas (2018)	6	13.4	8
24.	Giovannini *et al*. (2018)	9	1	1
25.	Abravesh *et al*. (2019)	1	1	5
26.	Zomorodian and Tahsildoost (2019)	Unknown	0.66	Unknown
27.	Jones (2019)	819	0.5	8

Table 3. The spatial resolution as described within each study. An "unknown" indicates the value could not be determined from reading the paper. An 'a' or 'b' attached to the study number indicates that the article conducted independent rounds of simulation with different scopes..

user level resolution (shown as 1 m^2) and for luminance-based metrics are only calculated at the point of occupancy (instead of across a representative grid). Illuminance metrics are typically calculated as continuous fields of points with a 0.37 m^2 resolution (2'x2') which is the grid size required by LEED version 4.0 and is the current best practice and recommended resolution for calculating sDA according to the IES LM83-12 standard. Two out of the six of these metric validation publications include eDGPs calculations. The remaining four only evaluate illuminance-based metrics.

The most recent study included in the survey, Jones (2019), outlines a new simulation method for efficiently calculating annual glare metrics across a large number of points. This is the only study that produces luminance-based metrics for a large field of points. In order

https://arrow.tudublin.ie/sdar/vol7/iss1/4
DOI: https://doi.org/10.21427/87r7-kn41

to achieve this efficiency, the method involves calculating the DGP value for a point and time directly from matrices of the illuminance at each point and the luminance of each sky-patch as seen from each point. As noted by Jones (2019), this method has a very limited scope and is only valid for direct views to the sky and cannot account for glare sources resulting from reflection or non-specular transmission.

The rest of the publications use either generic shoebox models for the simulations or are recreations of single office/laboratory test bays. The total points simulated ranges from one to ten, with a number of setups using a 3m x 3m grid of nine points at eye-level to capture a room. For the most part, the studies that place points at desks only make conclusions about the glare at that particular desk, but in two articles (Konstantzos *et al*, 2015; Torres and Verso, 2015), methods are employed to determine a single point that is representative of the entire space (25m^2 and 9m^2) respectively. Tsianaka (2018) proposes a variable resolution grid with higher density areas corresponding to areas with more glare, but without a formal methodology for determining this density.

A final recurring theme within the spatial dimension is the impact that view direction may have on glare. Jakubiec and Reinhart (2011) propose an adaptive zone for assessing glare that introduces a freedom of movement both laterally and in the view direction for a seated occupant. They base the glare evaluation on the position and direction with the lowest glare risk. Their calculation includes five points per location spaced 0.25 meters apart, and they simulate view directions in three-degree increments. Bian (2018) proposes a similar method with three points spaced 0.25 meters apart and capture-view directions every five degrees. Torres and Verso (2015), propose a glare metric based on a cylindrical illuminance calculation based on a 45° view direction resolution. Unlike Jakubiec and Bian, this calculation effectively captures the worst-case direction (most glare) instead of the best case (least glare). Van Den Wymelenberg (2014) proposed that this worst-case could actually be a better predictor of glare.

It should be noted that DGP, which all of these studies use as their base metric, is based on the capture of a fixed view direction HDR image, so correlations of the scale with user assessments for now are only valid for a fixed simulation direction. Recent and ongoing research into gaze direction (Sarey Khanie, 2015) could eventually impact how glare metrics are formulated, but for now the research into the impact adaptive positioning has on glare perception is inconclusive (Pierson *et al*, 2018).

2.5 Temporal resolution

Daylight is a dynamic and ever-changing condition, but one that follows cycles and patterns leading to a range of lighting conditions within a space. Static approaches, such as calculating daylight factors or looking at typical sky conditions, offer value in that they can be interpreted by an expert to reveal how the space will perform over time. Increasing the temporal resolution of a simulation effectively reduces the level of interpretation needed to understand the daylight in a space. Climate-based daylight modeling offers the best proxy for the actual conditions in a building and can, when not obscured by complicated metrics, offer the clearest picture to a lay-person into how a building will perform.

Sometimes, such as when comparing dynamic shading options or control strategies, a temporal analysis is the only way to capture the difference between systems. For daylight availability metrics, the annual calculations are typically expressed as either mean values, percentiles, or as time-based statistics based on achieving a threshold (effectively a percentile). For glare metrics, a percentile-based approach is likely necessary, as relative luminance levels would not make much sense when averaged across time, which means that some accumulation of time-steps will need to be calculated independently, as is currently done in the EN 17037 Standard. Table 4 shows, for each study, the number and resolution of time-steps at the scale of the hour, day and year.

Among the publications reviewed, there were three broad strategies employed for choosing a time-series. First, the metric validation studies used the survey period to match the observed data. The pure

Study	Author (year)	Days/year	Steps/day	Steps/hour	Total steps
1.	Wienold (2007)	365	10	1	3650
2.	Wienold (2009)	365	11.9	1	1434
3a.	Jakubiec and Reinhart (2011)	3	48	4	144
3b.	Jakubiec and Reinhart (2011)	365	12	1	4380
4.	Mardaljevic *et al*. (2012)	365	32	4	11680
5.	Chan and Tzempelikos (2013)	365	10	1	3650
6.	Konstantzos *et al*. (2015)	365	10	1	3650
7a.	Torres and Verso (2015)	54	1	1	54
7b.	Torres and Verso (2015)	365	12.6	1	4586
8.	McNeil and Burrell (2016)	365	12	1	4380
9.	Atzeri *et al*. (2016)	365	10	1	3650
10.	Jakubiec and Reinhart (2016)	80	100	10	8000
11.	Konstantzos and Tzempelikos (2017)	365	10	1	3650
12.	Jones and Reinhart (2017)	365	10	1	3650
13.	Atzeri *et al*. (2017)	4	70	12	280
14.	Dutra de Vasconcellos (2017)	365	10	1	3650
15.	Garcia-Hansen et al. (2017)	1	1	1	1
16.	Nezamdoost and Van Den Wymelenberg (2017)	365	10	1	365
17.	Tsianaka (2018)	3	7	1	19
18.	Jakubiec *et al*. (2018)	365	10	1	3650
19.	Jakubiec (2018)	365	36	4	3514
20.	Kong *et al*. (2018)	365	10	1	3650
21.	Bian (2018)	3	40	4	120
22.	Bian *et al*. (2018)	59	85	10	5015
23a	Santos and Caldas (2018)	365	Unknown	1	Unknown
23b	Santos and Caldas (2018)	365	Unknown	1	Unknown
24.	Giovannini *et al*. (2018)	365	12.6	1	4602
25	Abravesh *et al*. (2019)	365	10	1	3650
26.	Zomorodian and Tahsildoost (2019)	365	10	1	3650
27.	Jones (2019)	365	9.6	1	3508

Table 4. The temporal resolution as described within each study. An "unknown" indicates the value could not be determined from reading the paper. An 'a' or 'b' attached to the study number indicates that the article conducted independent rounds of simulation with different scopes.

simulation exercises used either a full annual set of times, usually at an hourly time-step, or focused on a few typical days (solstice and equinox) using a finer time-step (5-15 minutes) to capture a smoother set of sun positions across individual days. Jakubiec (2018) used a full annual evaluation at 15-minute intervals, but limited the total number of simulations by isolating times when the sun was both on the façade and the typical weather file showed sunny conditions. The high proportion of studies employing an hourly time-step for either all daylight hours in the year or typical working hours is likely due to the typically-available format of weather files, conventions in energy modelling, and/or the implementation of eDGPs and annual illuminance calculation in commonly-used software like Diva for Rhino.

2.6 Scene variety

Depending on the objectives of the study, the need for including multiple geometries, climates, orientations and façade systems will vary, but when evaluating the suitability of a glare metric for wider adoption, a greater variety of scenes will more likely lead to more robust conclusions. Table 5 quantifies four types of scene variety included in the studies. Locations include different building sites, climates or building orientations. The number of geometries indicate the variety in building massing or room volume. Variety in materials count the unique set of non-transmitting surface properties. Each façade has a different transmitting material, shading system, or active shade positioning. This review did not include access to the full details of each study, other than those published (as shown in Table 5).

Therefore, it is not possible to comment on the level of variety of scenes included in each study, nor on the accuracy and general applicability of a particular study's approximations. A higher total number of points, times and façades would suggest higher variety, but if the variation is small, the types of observed glare events (low or high-angle direct sun, directly transmitted or diffusely scatter light, etc) could remain quite small. Rather than attempting a forensic analysis of each study, the discussion section below contains a simple thought exercise working through the setup of a simulation for glare assessment to demonstrate the necessary caution needed to suggest a general strategy for spatio-temporal glare assessment.

Study	Author (year)	Locations	Geometries	Materials	Façades	Total
1.	Wienold (2007)	1	1	1	57	57
2.	Wienold (2009)	1	2	1	3	6
3a.	Jakubiec and Reinhart (2011)	1	2	1	2	3
3b.	Jakubiec and Reinhart (2011)	1	1	1	2	2
4.	Mardaljevic *et al.* (2012)	32	2	1	1	64
5.	Chan and Tzempelikos (2013)	2	1	2	3	12
6.	Konstantzos *et al.* (2015)	1	1	2	2	4
7a.	Torres and Verso (2015)	1	5	1	1	5
7b.	Torres and Verso (2015)	2	1	1	1	2
8.	McNeil and Burrell (2016)	1	1	1	1	1
9.	Atzeri *et al.* (2016)	2	1	2	2	5
10.	Jakubiec and Reinhart (2016)	1	1	1	1	1
11.	Konstantzos and Tzempelikos (2017)	2	1	1	4	1
12.	Jones and Reinhart (2017)	2	2	2	2	16
13.	Atzeri *et al.* (2017)	1	1	1	1	1
14.	Dutra de Vasconcellos (2017)	1	1	1	1	1
15.	Garcia-Hansen et al. (2017)	3	1	1	1	3
16.	Nezamdoost and Van Den Wymelenberg (2017)	22	1	1	1	22
17.	Tsianaka (2018)	1	1	1	4	4
18.	Jakubiec *et al.* (2018)	10	10	10	10	10
19.	Jakubiec (2018)	8	5	1	3	360
20.	Kong *et al.* (2018)	1	1	1	2	2
21.	Bian (2018)	1	1	1	3	3
22.	Bian *et al.* (2018)	1	1	1	1	1
23a	Santos and Caldas (2018)	2	1	1	1	1
23b	Santos and Caldas (2018)	3	1	1	1	1
24.	Giovannini *et al.* (2018)	2	1	14	6	38
25	Abravesh *et al.* (2019)	3	1	1	3	9
26.	Zomorodian and Tahsildoost (2019)	1	4	1	1	4
27.	Jones (2019)	1	1	1	2	2

Table 5. The scene variety in each study. Note that the total is not always the product of all combinations. An 'a' or 'b' attached to the study number indicates that the article conducted independent rounds of simulation with different scopes.

3. Discussion

While the objectives of the reviewed research varied, common to nearly all of the simulations conducted was an identified need to reduce the total number of calculations needed to generate a result. The most common reduction, and a frequent objective, was to reduce the simulation time by only calculating an illuminance value for a point rather than a full view. Studies that simulated luminance maps of a full view typically did so only for a subset of points or times, and often used the eDGPs method where a direct-only luminance map is supplemented by point-based calculations. Jones (2019) proposes what is effectively a compromise between these approaches, where more angular information is maintained than in an illuminance calculation, but less than what is typically calculated for full luminance maps. Among the directional, spatial and temporal dimensions, studies typically only consider methods for reducing one of these dimensions. Few of these reductions were based on a sensitivity analysis relating glare detection to grid size or time-step, although a number of studies provided some intuitive methods for reducing the number of calculations while maintaining resolution where or when necessary. These include:

- Checking for incident sun and clear weather conditions before running more detailed simulations (Jakubiec, 2018);
- Running a faster E_v calculation to find likely glare locations before running a full view-based simulation (Santos and Caldas, 2018);
- Proposing a variable grid based on higher glare incidence (Tsianaka, 2018);
- Using cylindrical illuminance to calculate all view directions from a point at once (Torres and Verso, 2015);
- Calculating DGP directly from a contribution matrix between sky-patch and view-point (Jones, 2019).

Santos and Caldas (2018) propose using E_v as a heuristic to do an initial search for important glare points and directions before doing more detailed glare assessments. While this idea sounds promising, this heuristic is likely not applicable towards a zonal glare assessment. According to their results, E_v is a decent predictor for locating disturbing glare events, but is poor at identifying perceptible/borderline glare events. The heuristic approach is used to identify a worst-case time and spatial location to study with a full luminance map simulation, but a useful spatio-temporal glare metric should include both extent and duration quantities. For this purpose, the high E_v results suggest that these times and locations may not need further study as they have already been identified as having glare conditions.

Given this, if the goal is a spatial glare assessment, identifying the boundary conditions for a more detailed study is likely more important than following up on extreme events. While this and some of the other studies have unanswered questions as to their applicability or accuracy, the idea behind all of them is sound. Glare incidence at any single point inside a building will occur for only a minority of the hours in a year, therefore a majority of point-time combinations do not need to be calculated. It should be possible to eliminate a large number of these null-glare event point-times without reducing the resolution or accuracy of the overall calculation. Based on the surveyed literature and drawing from studies conducted for daylight availability, it is possible to outline a starting point for an accurate simulation resolution.

3.1 Metrics and scene variety

Any conclusions made from a metric comparison will only be valid for the range of glare conditions observed in the simulation. A simple thought exercise working through an increasing variety of common daylighting scenarios in buildings demonstrates that simplified metrics will not only introduce additional variance in the calculation (which may be acceptable), but will systematically miscalculate certain daylight conditions:

- Consider a simple room with a single glazed façade and a sky condition with direct sun entering the room. Assume an evaluation of glare metrics that only considers view directions facing the window and view positions near the window. Horizontal illuminance (E_h) will show a strong correlation with the occurrence of glare because any point in direct sunlight will have a high illuminance and a high probability of glare;
- Now suppose the glare evaluation also includes view directions facing away from the window. The probability of glare for these positions will be much lower, as the sun is not in the direct field of view, but E_h does not change. When this data is included the strength of the correlation will be greatly reduced;
- In this case, it would be preferable to measure the vertical illuminance (E_v) at the eye as this will account for the change in view direction. Given this scene, where there is direct sun in parts of the room and the observers either face the window or face away from the window, E_v should be strongly correlated with glare. It will be high for observers in and facing the sun and low for everyone else;;
- To further improve the variety in the glare metric evaluation, assume the data also includes an additional façade type that greatly reduces the light transmission of the window without scattering, such as an electrochromic glass or dark shade fabric with an open weave. Under these conditions, the E_v will drop significantly but subjective assessments will still report glare (Konstantzos and Tzempelikos, 2017). Intuitively, this makes sense, as 1% or 3% of the brightness of the sun is still incredibly bright and beyond what is typically comfortable in an indoor environment. Because E_v does not capture the distribution of luminance in the field of view, it does not distinguish between this incredibly bright point source and a benign even field of comfortable luminance;
- With this level of variety, it is now apparent that a glare metric will also need some measure of contrast, even if in most conditions E_v remains a strong predictor of glare. In studies which include this range of conditions, DGP has been found to be the most accurate and robust (Wienold *et al*, 2019);
- Finally, consider that the evaluation is extended to include viewpoints farther from the window. In these cases glare occurrence is much more likely to be caused by contrast rather than saturation, and DGP may under-predict the likelihood of glare because of the strength of the vertical illuminance term (Hirning *et al*, 2014). In these cases, which require more user assessment research to properly quantify (Wienold *et al*, 2019), simplified simulation methods (including eDGPs) may not be valid as they cannot accurately calculate contrast-based metrics like UGP, which Hirning *et al*, (2014) propose as a preferred metric for this scenario.

Unfortunately, the most typically-studied conditions for spatio-temporal glare often do not include scene variety beyond Step 3 outlined above. A useful simulation for glare assessment must be suitable for lower illuminance scenarios as in many typical open-office spaces there is more floor area away from a window than adjacent to it. In their article, Hirning *et al*, (2014) presented a survey of employees working in open-office buildings. They found that the existing glare metrics under-predicted glare in these conditions and that the metrics based entirely on luminance distribution and contrast effects (DGI, UGR and CGI) performed the best.

They propose a modified version of UGR, dubbed UGP for unified glare probability, as the simplest to calculate and best performing metric for the low vertical illuminance conditions that occurred throughout the survey data. As glare analysis extends to full building calculations, it will be important for the method to account for the more complex contrast calculations alongside the relatively simple conditions of high vertical illuminance and/or direct sun in the field of view.

3.2 Temporal resolution

A temporal component is needed in order to account for the full range of incident sun angles and local climate conditions, to capture the impact of dynamic shading devices, to quantify glare duration, and to weight the metric with both an intensity of glare occurrence as well as total times with glare in a space. Occupant survey research has shown a link between the duration of a glare event with the subjective assessment of glare (Bian, 2018). To account for glare duration it will be necessary to have a sub-hourly analysis.

Except for very large whole building simulations, the temporal dimension of a spatio-temporal analysis typically has the largest magnitude. Fortunately, a number of straightforward approaches exist to reduce the magnitude of time-steps. Some, like only running the simulations for daylight hours or working hours, are trivial. Others, like calculating a grid of sun positions and then looking up the closest value for each time-step, are more subtle, but have been well developed and documented (Reinhart and Walkenhorst, 2001). Both of these approaches are well incorporated into existing simulation methods. Jakubiec (2018) has proposed the most novel approach for reducing the number of time-steps needed by including additional pre-checks to ensure that the sun is incident on a relevant façade. In their study, glare was calculated at 15-minute increments, which when combined with this initial filter, resulted in fewer total simulations than a typical annual-hourly calculation.

In order to extend glare simulation to include both a sub-hourly time-step and a large spatial dimension (which could also include multiple view directions), it would be beneficial to investigate additional methods for further reducing the number of time-steps calculated. While the grid of sun positions reduces the calculation overhead substantially for hourly simulations, the resolution required in order to capture sub-hourly time-steps undermines this efficiency. The change in sun position from one hour to the next is far greater than the change from day to day, but none of the reviewed studies investigates approaches that could balance these increments. More flexibility in the filtering and estimation of sun positions needed to calculate annual performance could lead to methods that are both more accurate (with a finer time-step) and more efficient (fewer total calculations).

3.3 Spatial resolution

Compared with a zonal metric, where the area of interest can be well defined by the building plan, relying on the modeler to select the analysis point requires expert knowledge of the likely glare conditions in the space. This makes the standardisation of performance impossible to validate. Existing illuminance standards have established methods for defining point grids representative of building zones. The LM-83-12 specification for spatial daylight autonomy requires a two-foot grid throughout the occupied area. A sensitivity analysis showed that results of annual calculations were fairly close for a range of grid spacings less than one meter (Brembilla *et al,* 2015). Based on their results, the authors recommend a grid spacing of less than one meter. While a similar sensitivity analysis has not been published for glare calculations, given the typical dimensions found in most office spaces, it is reasonable to assume that a grid much larger than one meter will miss important variation within a space.

Only two studies (Jakubiec and Reinhart, 2016 and Jones, 2019) calculated a luminance metric for more than 12 points, and both studies used methods that only calculate luminance values for the glare sources and not the background. To calculate a high density of points across a large space or building using brute force is not practical without access to powerful computing clusters. Two of the reviewed studies (Santos and Caldas, 2018 and Tsianaka, 2018) propose methods for reducing the density of points where glare is unlikely to occur. Tsianaka hypothesises that such a method exists, and Santos and Caldas (2018) use E_v as a heuristic to identify worst-case glare. This heuristic may not be suitable for calculating generalised spatial metrics, as E_v categorically misses some glare events, such as low illuminance conditions with very bright small sources.

Other heuristics or importance sampling methods that vary the positional density of simulations or the resolution of those simulations have not been thoroughly researched. Especially when combined with novel temporal sampling, a variable spatial density could be a powerful tool for making spatio-temporal glare simulation and assessment practical and efficient without reducing accuracy.

4. Conclusion

The development of climate-based daylight modelling techniques and the adoption of these calculations in commonly-used software packages (DIVA, Ladybug, OpenStudio) has made it simple and efficient to calculate annual illuminance for a grid of points. Compared to this, calculating DGP with full luminance images is impractical. This review has found that commonly-used approximations to simplify glare calculation will generate results that are expected to be inconsistent with the findings of user assessment glare research. While there have not been a large number of published articles looking specifically at spatial and temporal glare analysis, a number of common themes have emerged from those that do exist:

- The focus of the simulation methodology is typically on efficiency of the calculation, leading to a simplification of calculated metrics;
- The most commonly-used method for annual glare analysis is eDGPs. Since this method uses DGP as a glare metric it might underestimate the glare for viewpoints deep in a space and low vertical illuminance values. While eDGPs maintains the accuracy of the DGP, it can only be used to calculate DGP and cannot be used for glare metrics that require a background luminance term. Although it is far more efficient than a full ambient simulation, it is still not fast enough to practically calculate glare across a large number of positions and times;
- Well spatialised studies (more than a few typical points) typically reduce the calculation to simple illuminance calculations.
- Proposed methods for increasing efficiency tend to focus on a single dimension, either spatial, temporal or angular (collapsing luminance data into illuminance or a reduced angular resolution).

Based on the requirements of current best practice glare evaluation and the current limitations of computation, extending simulations for glare assessment to a spatial-temporal analysis will require the development of new simulation techniques to efficiently produce high accuracy luminance maps for a large number of points and times across a space. A number of methods for consolidating glare metrics into annual performance exist (Wienold, 2009, Jakubiec and Reinhart, 2011; Atzeri *et al*, 2016; Jakubiec *et al*, 2018) and could be easily adapted to a high-resolution temporal glare evaluation.

Resolving the difference between human subject glare research, which indicates that a high degree of angular and temporal resolution is necessary, and current simulation capabilities, which cannot produce this resolution in reasonable timeframes, should be a priority for future research. While the existing research included in this review outlines a wide range of possible methods for spatio-

https://arrow.tudublin.ie/sdar/vol7/iss1/4
DOI: https://doi.org/10.21427/87r7-kn41

temporal glare simulation, none of the proposed methods offer a path towards a method that is both generally applicable and efficient. One reason for this could be that current approaches are built on top of simulation methods used for illuminance-based calculations. Many of the shortcuts and approximations that have enabled the wide acceptance of climate-based daylight modeling are not valid for accurately evaluating discomfort glare.

Future research should consider the problem from a wider lens, interrogating the required level of detail needed across time, position and view direction. Across all of these dimensions the focus should be on the specific objectives and requirements of a high-accuracy glare evaluation.

Acknowledgements

This research was supported by the Swiss National Science Foundation as part of the ongoing research project "Light fields in climate-based daylight modeling for spatio-temporal glare assessment" (SNSF #179067). We thank Stephen Wittkopf, the project's principal investigator, for accompanying the work with his constructive and critical feed-back, and our colleague Roland Schregle for contributing his expertise in daylight simulation techniques.

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