A concept for predicting occupants' long-term visual comfort within daylit spaces

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Abstract

A new concept of long term visual comfort is introduced to describe the long-term visual impression of space occupants. This concept, in contrast to instantaneous assessment of visual comfort, aims to describe an overall rating of visual quality. A paired study consisting of occupant surveys and detailed 6-minute timestep comfort simulations was performed for the studio spaces of Gund Hall (Cambridge, MA, USA), which is occupied by over 500 students. Occupants reported four primary ways of experiencing visual discomfort: discomfort glare, insufficient monitor contrast, direct visibility of the sun and direct sunlight on the workplane. Survey results were located spatially and in terms of orientation within Gund Hall, and the simulation model was calibrated based on furniture layout, measured material reflectances and local measured weather data. The results of the study illustrate that it is possible to use current simulation-based visual comfort predictions to predict occupants' long-term visual comfort assessments in a complex daylit space. Between 53.7% and 70.1% percent of polled occupants' evaluations were correctly identified. Through a spatial and temporal presentation of the simulation data, this new methodology can be used as feedback during the process of designing daylit spaces, avoiding visual discomfort and increasing satisfaction with the built environment.

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Introduction

Visual comfort, the absence of discomfort such as glare, insufficient visual contrast or the presence of visible direct sunlight, is one of the ‘holy grails’ of daylighting research. Researchers have laboured for over 80 years with the goal of being able to predict visual discomfort, and ultimately, to avoid it altogether. However, the current practice of building performance analysis has yet to embrace visual comfort prediction. The most common design recommendation is to ‘avoid direct sunlight’ even though most other fields of building analysis have approached increasingly detailed energetic, daylighting and thermal comfort evaluations of buildings.

One reason for this lack of action in the application of visual comfort prediction in practice comes from research inadequacies. Most visual comfort research today focuses on the comfort of an individual at a single instant. While the capacity exists to calculate discomfort glare for every hour of an entire year [Wienold 2009], there is no guideline for how often and how much discomfort is acceptable. Thus, in a world of annual building performance simulations, the application of visual comfort metrics to design analysis is limited. A second reason is that recent studies have found poor agreement between laboratory-derived measures and the experience of occupants in real spaces. The application of these metrics to less controlled daylit interiors or separate laboratory validation studies are only now emerging, and there is little consensus between different studies in varied space types and climates [Painter, Fan, and Mardaljevic 2009; Hirning et al. 2013; Jakubiec and Reinhart 2013; Hirning, Isoardi, and Cowling 2014; Konis 2014; Van Den Wymelenberg and Inanici 2014]. A third reason is that new standards such as IES-LM-83 suggest potentially unreasonable glare control measures, never allowing more than 2% of floor area to have direct sunlight [IESNA 2012]. While IES-LM-83 is codified as a theoretical control strategy in a conceptual building analysis and is not designed for application to real buildings, it perhaps ignores the benefits of direct sunlight some distance from occupants: plentiful natural light, visual interest and contrast.

In response, this paper analyses long-term visual comfort as a concept to refer to overall visual acceptance by space occupants in contrast to instantaneous visual comfort which is a discrete measure of sensation. The authors argue that such an analysis is necessary in order to assure that designed spaces will be accepted by occupants as a comfortable and productive place to live or work while still accepting some amount of direct sunlight and temporary or minor visual discomfort. In other words, it is possible to experience some instantaneous visual discomfort but still find a space comfortable overall. This paper therefore illustrates the prediction of long-term visual comfort for occupants of a single existing building through annual simulation-based visual discomfort analysis and detailed occupant surveys. This is the first long-term field study of visual comfort in a daylit space which is not a laboratory.

A comprehensive visual comfort analysis is presented of over 500 occupants at the Harvard University Graduate School of Design Gund Hall studio spaces, well-known for visual comfort problems. First, an online visual comfort survey was administered to the students of Gund Hall. Several causes of visual discomfort were reported: discomfort glare, insufficient monitor contrast, direct visibility of the sun and direct sunlight on the workplane. Following, the occupant assessments are compared against detailed simulations and visual comfort predictions of the workspaces using a six-minute time interval for the duration of the semester. Finally, predicted visual comfort results are computed and displayed using architectural plans and temporal falsecolor graphics. Therefore the analysis methodology provides helpful spatial and time-of-occurrence information to avoid future visual discomfort problems during the design of a building.

Discomfort Metrics

There are several possible causes of discomfort in daylit spaces noted in this study: discomfort glare, reduced monitor contrast ratios from reflected daylight, visibility of the sun with the naked eye, and the presence of direct sunlight on the workplane which are defined below. Discomfort due to electric lighting is not considered.

Discomfort Glare

Discomfort glare is physical discomfort caused by extreme brightness, contrast or both. Contrast is defined as the weighted ratio of the size, location and brightness of glaring light sources in a field of vision when compared to the average visible luminance. In this analysis, the Daylight Glare Probability (DGP) [Wienold and Christoffersen 2006] metric is utilized to represent discomfort glare because it accounts for contrast and brightness whereas other glare metrics only account for contrast. Jakubiec and Reinhart [Jakubiec and Reinhart 2012] showed that DGP is the most robust of existing discomfort glare metrics and the least likely to give false positives based on a theoretical simulation study of several types of daylit spaces and solar positions without subjective evaluations. Van Den Wymelenberg [2014] also found that two of the most prominent discomfort glare metrics, DGP and DGI, were not typically successful at predicting subjective occupant responses; however, it is noted that note that DGP consistently performs better than DGI in perimeter office spaces [2010; 2014]. However, Van Den Wymelenberg also notes that DGP should not be used as a standalone metric when evaluating discomfort. Multiple studies have found [Fan, Painter, and Mardaljevic 2009; Hirning et al. 2013] that in dim situations neither DGP nor DGI are able to resolve occupant-reported subjective visual discomfort, at least at the typical evaluation points of 0.4 or 22 respectively, identifying thresholds at which disturbing glare is experienced. Later, Hirning and colleagues concluded that DGI and other similar discomfort glare measures such as UGR and CGI are the most correlated with subjective discomfort in open floorplans where vertical eye illuminance is relatively low compared to the conditions under which DGP was derived [Hirning, Isoardi, and Cowling 2014]. Konis found that simple contrast ratios predicted discomfort best in ‘core’ zones of buildings further than 6m from the façade [Konis 2014].

Together these results suggest the potential that occupants in interior spaces close to the building façade may experience visual discomfort dominated by total brightness and vertical eye illuminance, making DGP a relatively well-performing metric. At the same time, in less-bright areas where contrast discomfort would dominate, measures that rely entirely on contrast such as DGI and UGR seem to perform better. Overall, the consensus from existing research is that DGP responds less to contrast-based discomfort glare but appears to correlate more strongly than other comfort metrics in brightly lit spaces.

The specific expression of DGP is described in (1) below,

$$DGP = 5.87 \times 10^{-5} E_v + 0.0918 \times \log_{10}\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right) + 0.16 \qquad (1)$$

where E_v is vertical illuminance measured at the eye, L_s is the brightness of a glare source with a contrast ratio three or greater relative to the visible luminous environment, ω_s is the size in solid angle of the glare source and P is the Guth position index which relates the position of the glare source in the field of view to human eye sensitivity. DGP evaluates in a range between zero and one, representing the percentage of people who would feel uncomfortable under a specific luminous environment. For example, a glare probability of 0.45 means an estimated 45% of people would feel discomfort in such a lighting situation. In discomfort glare calculations using DGP, evaluations greater than 0.35 are typically classified as perceptible, those greater than 0.45 as disturbing and those greater than 0.45 as intolerable.

Monitor Contrast

When light reflects from a monitor screen, the observable contrast between pixels is lowered. For specular (shiny) LCD screens, this problem is exasperated by veiling glare, when bright light sources are reflected in the monitor. The observable contrast ratio between bright (high state) and dark (low state) pixels can be calculated based on the amount of light reflected from a monitor as shown in (2),

$$CR = \frac{L_H + L_r}{L_L + L_r} \qquad (2)$$

where L_H is the high state luminance, L_L is the low state luminance and L_r is the amount of reflected light. According to ISO standard 9241-3:1992 [[ISO] International Standards Organization 1992], contrast ratios above three are necessary to preserve readability. Later standards [ISO 2008] suggest contrast ratios as high as four are necessary for a low state luminance of 10 cd/m^2.

Direct Sunlight

Direct sunlight falling on the workplane or the eye directly is likely to cause discomfort. IES standard LM-83-12 states that horizontal illuminance from direct solar exposure over 1000 lux, as derived by running a simulation accounting for the direct solar beam alone, is a good indicator for visual discomfort [IESNA 2012]. Experience also shows that viewing the sun directly is uncomfortable. While the illuminance contribution of direct sunlight in spaces is not entirely easy to measure, it is simple to simulate for the purposes of this study.

Methodology

Subjective Visual Comfort Survey

A survey was conducted of the students seated in the studio spaces of the Harvard University Graduate School of Design's Gund Hall at the end of the Spring 2011 academic term accounting for the time from January 24 until April 15. The survey was administered digitally, and participants were solicited to complete the survey via email and on their own time. Students were asked to identify their desk using a numbered seating plan of the school or the corresponding label affixed to their desk and to describe in detail their long-term visual impression of the space. They rated their comfort during the semester for three specific periods of the day: morning, from 8:00–12:00; midday, from 12:00–14:00; and afternoon, from 14:00–18:00. For each of these intervals, students sorted their visual comfort into one of four categories: imperceptible, perceptible, disturbing or intolerable. Students were also given the opportunity to describe the cause or causes of their discomfort and what actions they took in response. The relevant questions and answer choices (in *italics*) are presented below.

1. Indicate the typical degree of discomfort glare you experienced at your desk during this semester.

   Three time periods: Mornings (8:00 – 12:00), Midday (12:00 – 14:00), and Afternoon (14:00 – 18:00)

   Imperceptible / Perceptible / Disturbing / Intolerable

2. If you are experiencing glare, what is its cause? (Choose all that apply.)

   I am not experiencing glare / Direct view of the sun / Electric lighting conditions /

   Reflections from the monitor (veiling glare) / Excessive brightness or contrast /

   Other (free response)

3. If you experienced visual discomfort over the course of the semester, which strategies did you employ to increase your comfort? (Choose all that apply.)

   *Nothing. Discomfort was **not** experienced /*

   Nothing. Discomfort was experienced /

   Moved to another position in front of the desk /

   Built a shading device not originally a part of the workspace /

   Temporarily rotated my chair to avoid bright light or contrast /

   Temporarily moved to a completely different location in the building /

   Other. Describe the actions you took to avoid discomfort. (free response)

A separate question asked respondents to indicate the cause of discomfort, if it existed. Responses indicating ‘electric lighting conditions’ are removed from the survey data as electric lighting is not considered in this study.

Visual Comfort Simulations

A calibrated daylight simulation model was constructed of Gund Hall using the Radiance simulation engine. Radiance is a physically-based backward raytracer, developed at Lawrence Berkeley National Laboratory (Ward 1994). It is a reasonable choice for representing the visual, luminous environment as it includes a series of material modifiers that allows the definition of custom materials based on optical measurements and has been validated by numerous studies [Mardaljevic 1995; Reinhart and Walkenhorst 2001; Ochoa and Capeluto 2006]. The model is geometrically accurate including urban context and the glazing of nearby buildings. The material models within the simulation account for measured visible window transmissivity [Voit, White, and Bummele 2007] and measured diffuse reflectance values for opaque surfaces in the space, described in Table 1. The ceiling was modelled using a standard 80% reflectance, as it was inaccessible for measurement purposes. Electric lighting is supplied by louvered fluorescent fixtures, which are illuminated for most hours of the day; however, discomfort from electric lighting is not considered in this study.

TABLE 1 Measured material properties.

Surface Description	Transmissivity
Clerestory glazing	0.142
North and south glazing	0.185
Dining hall glazing	0.948
	Reflectance
Concrete walls and floors	0.243
Desk surfaces	0.541
Desk backs	0.776
Floor	0.070
Mullions	0.100
(Painted) Cinder block walls	0.759
Handrails	0.048
Ceiling	0.800

The studio space of Gund Hall, portrayed in Fig. 1 as a rendering of the simulation model, provides desks for over 500 students of architecture and urban design. It is a five story tiered space with plentiful daylight, which comes from east-facing clerestory windows and large floor-to-ceiling glazing at the north and south ends of the space. Student desks are either directly underneath the clerestory windows or sheltered by the level above. Figure 2 portrays the surrounding context of Gund Hall, notably the CGIS building to the east, which has highly reflective solar control glazing.

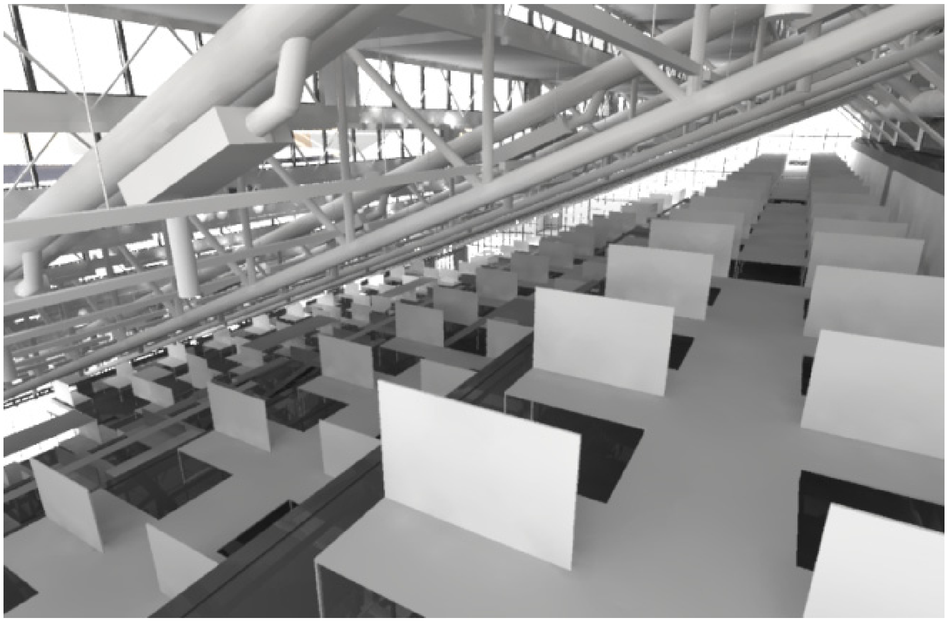


Fig. 1 A rendered image of the simulation model looking South from the fourth level corner.

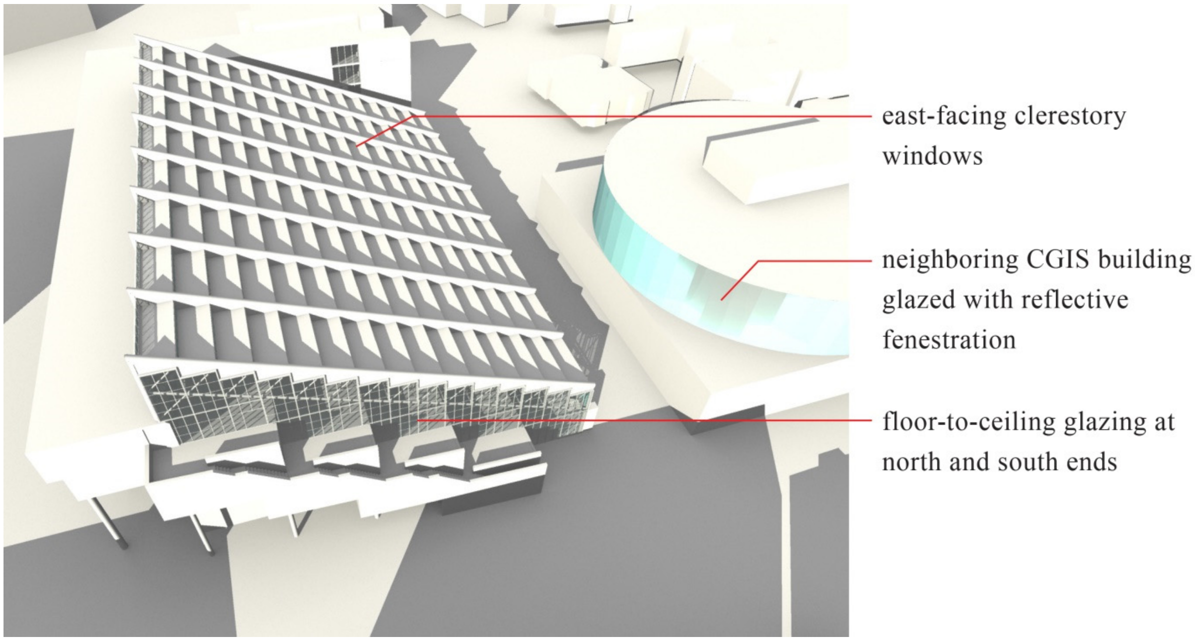


Fig. 2 Exterior rendering of Gund Hall from the south showing key context.

In accordance with the noted discomfort metrics, each survey respondent's work area was the subject of discomfort glare, monitor contrast and direct sunlight (visible with the eye and incident on the workplane) simulations. Because of the many small clerestory windows relative to the size of the space, the presence of visual discomfort is highly transient in Gund Hall for those not seated near the large North or South windows. Therefore, all of the discomfort predictions performed in this study were simulated using a six-minute time interval from January 24 until April 15, the start of the semester until the time when the survey was administered.

DGP predictions were made using the enhanced simplified DGP (eDGPs) method [Wienold 2009]. The eDGPs method uses the standard DGP equation from (1) to evaluate visual discomfort, however, vertical eye illuminance (E_v) is calculated in a simplified way, and contrast is determined based on rendered images of direct sunlight using a 0 'ambient bounce' calculation compared to the calculated Ev values. These two steps are done in order to save computational resources. Ordinarily, the eDGPs method uses Daysim [Reinhart and Walkenhorst 2001] to calculate the vertical eye illuminance term. However, in the case of this study, vertical eye illuminance was calculated using standard Radiance tools (gendaylit and rtrace) in order to avoid direct solar interpolation errors from Daysim's direct daylight coefficient methodology that may be exacerbated in deep spaces with small window openings. Wienold [2009] found a RMSE of 1.3% using this method without any shading devices such as blinds or roller shades when compared to a DGP calculation using fully rendered luminance images including the ambient calculation. By contrast, using Daysim to calculate the E_v term resulted in a RMSE of 5.5% due to the aforementioned direct interpolation errors. Calculations using rtrace or Daysim are likely to miss contributions of direct specular reflections of the sun to vertical eye illuminance. The 0 ambient bounce renderings do record the luminance of such reflections. One way to overcome this limitation would be to employ the Radiance 'mirror' material, which was not done in this paper. The difference in results due to this calculation limitation is likely to be minimal in most cases.

One potential concern is that the quantity of vertical eye illuminance is affected by electric lighting conditions inside the space; however, luminaires were not included in the simulation model. This has an impact on two parts of the DGP equation, the 'brightness' term, a linear function of E_v, and the contrast term. Even a very high contribution of electric light to vertical eye illuminance, such as 300lx, would only increase the DGP evaluation by 0.01761. At the same time, this theoretical 300lx value would also decrease the contrast term. In both cases the size and luminance of daylight glare sources would be equal as the eDGPs method chooses 8000 cd/m^2 as a constant luminance threshold for the identification of glare sources. In the case of Gund Hall, an open plan space, the contribution of electric light to vertical eye illuminace is likely to be less than 300lx as there are few vertical surfaces to reflect light towards the eye.

Monitor contrast ratios were predicted based on vertical illuminance calculations on a presumed monitor screen location. In this study, monitor reflectance was standardized based on the average measurement of three monitor screens (a Dell U2412Mb LCD monitor, a Lenovo Thinkpad T520 laptop LCD screen, and a Lenovo desktop LCD monitor) at 5.4 % diffuse reflectance. L_H and L_L from (2) are fixed at realistic assumptions of 80 and 10 cd/m^2 respectively [Moghbell 2012], yielding a default contrast ratio of eight without the presence of reflected light. Specular reflections from monitors were not considered. Direct sunlight greater than 1000 lx was predicted using a 0 ambient bounce calculation in Radiance such that diffuse and reflected light is not considered in the calculation of illuminance from direct sunlight.

Weather data was acquired from a local urban weather station approximately one kilometre (0.62 mi) away from the site for the period of the study [Keneli.org 2012]. Measured global horizontal solar irradiation was converted into direct and diffuse components using the Reindl method [Reindl, Beckman, and Duffie 1990] and used as input information to the Perez all weather sky model [Perez, Seals, and Michalsky 1993] for the purposes of the lighting simulations performed in this study.

Results

Survey Results

The survey received 194 responses of which 90 were complete, but only 67 respondents did not experience discomfort caused by electric lighting and also identified their desk space properly. Those 67 respondents are studied henceforth unless otherwise noted.

While between 47.7 and 67.7% of studied responses were from visually comfortable individuals and over three-fifths of the space occupants did not reply to the survey in any form, there is still a high level of discomfort observable in the space. Forty of the 500 desks in the space had custom shading devices built by students, suggesting a real visual comfort problem in certain areas of Gund Hall. The survey results also illustrate relatively high levels of discomfort; however, since this was an optional survey, students more attuned to visual discomfort may have been self-selecting. This is represented in Fig. 3, which details the occupant-reported long-term comfort for each of the three time intervals, the response to Question 1, using a histogram. The severity of response is represented by colours: green (🟩) indicates comfort, and red (🟥) indicates intolerable discomfort, a standard maintained throughout this manuscript. As the building's clerestories face east, the morning hours yield the most discomfort with 52.3% of occupants indicating perceptible discomfort or worse. During midday, fewer users report discomfort (36.9%), but the intensity of reported intolerable discomfort is the highest with 9.2% of respondents indicating such. This is likely due to direct sunlight entering through the full glazing of the southern façade. In the afternoon, discomfort is further reduced as the sun moves to the west of the building where there are no windows opening onto the studio space.

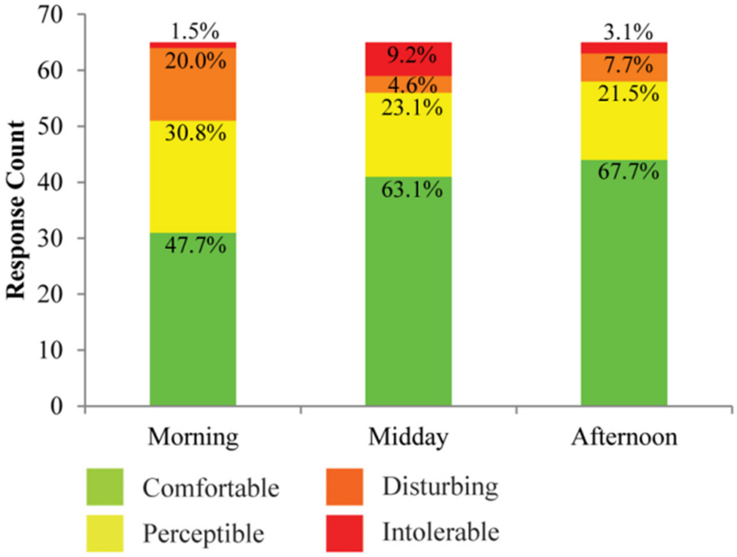


Fig. 3 Histogram of occupant-reported long-term comfort (Question 1) by time of day.

Question number 2, which asked about the causes of visual discomfort, found the following for all 90 complete survey responses,

- 28.8% (26) did not experience any discomfort.
- 30.0% (27) had a direct view of the sun.
- 17.8% (16) were made uncomfortable from the electric lighting.
- 27.8% (25) could not see their computer monitor due to reflections.
- 14.4% (13) experienced extreme brightness or contrast (discomfort glare).
- 13.3% (12) reported other.

where students could pick multiple responses. The experiences of the occupants illustrated by the Question 2 responses clearly show that the choice to test for multiple visual discomfort metrics is a reasonable one. The responses to Question 3 regarding responses to experiencing discomfort are reported in the discussion section.

Predicting Long-Term Occupant Evaluations

With a complete set of discomfort glare, monitor contrast and direct sunlight (visible and workplane incident) simulation results for each desk location in Gund Hall, it is possible to analyse the intensity and frequency of discomfort from multiple disparate causes. A logical question to ask is, how much discomfort glare, reduction of monitor contrast or direct sunlight must be experienced in order for an occupant to deem the space uncomfortable?

A strong correlation was found between the percentages of occupied hours above certain visual comfort thresholds with reported visual comfort. Any instant with a DGP value above 0.4, classified during a moment in time as 'disturbing' [Wienold 2009], predicted monitor contrast ratio below four [International Standards Organization 2008] or with direct sunlight on the eye or desk greater than 1000 lx is considered uncomfortable for this purpose. Students in Gund Hall tended to be more sensitive to discomfort glare and direct sunlight than contrast ratio in their evaluations of the space. It was found that on average occupants experiencing discomfort glare ($DGP \geq 0.4$, disturbing) for more than 3.5% of occupied hours would evaluate the space as 'intolerable.' On average direct sunlight (vertical eye illuminance or illuminance on the workplane ≥ 1000 lx) needed to be experienced for 5.25% of occupied hours to evaluate the space as 'intolerable.' Finally, predicted low monitor contrast ($CR < 4$) needed to be experienced 24% of the time, on average, to account for an 'intolerable' evaluation. In this model, multiple types of discomfort contribute to the overall evaluation of visual comfort by accounting for partial contributions from multiple analysis types and a linear scale from imperceptible (0% of occupied hours) to intolerable. For example, if discomfort glare is experienced for 1.7% of occupied time and direct sunlight is experienced for 3%, the model prediction is still 'intolerable.'

It is important to note that this result is specific to the students, space and culture of Gund Hall. For example, in an office space with fixed computer monitors and adjustable window blinds, occupants might be more sensitive to contrast ratio and less sensitive to discomfort glare or direct sunlight. The model described above can be represented by way of (3),

$$VS = 28.6 * \%hrsDGP_{0.40} + 19.05 * \%hrsDirectSun_{1000} + 4.2 * \%hrsCR_{4} \qquad (3)$$

where the equation evaluates such that,

- imperceptible < 0.5,
- 0.5 ≤ perceptible < 0.75,
- 0.75 ≤ disturbing < 1.0,
- and 1.0 ≤ intolerable.

Spatial Display of Results

Predictions using the simulation results and (3) are compared to the survey responses gathered from occupants in Fig. 4. Results are overlaid on a plan of the Gund Hall studio spaces showing all terraced levels simultaneously. Shaded areas indicate desks that are covered by the floor above or shaded by a custom, student-built shading device. A small rectangle is located at each desk, representing the model-predicted visual comfort. These rectangles are colour coded from imperceptible green (🟩) to intolerable red (🟥). Contained within squares where students who responded to the survey are seated, a small circle is placed representing occupant-reported visual comfort, and colour coded in the same way (🟢, 🔴). The goal of this exercise was to compare model predictions (squares, ■) to occupant-reported comfort (circles, ●). Perfectly matched predictions will appear as one solid colour with a thin line separating the two; however, over and under-predictions will be apparent by the colour difference between the interior circle and the enclosing square.

During the morning (Fig. 4a), the southern and eastern side of the building and clerestory windows are exposed to direct sunlight, causing discomfort predictions deep inside the space. Midday (Fig. 4b), from 12:00 to 14:00, is when the altitude of the sun is at its peak and its azimuth is to the south of Gund Hall. Thus, predicted discomfort is primarily localized to the southern side of the space. In the afternoon (Fig. 4c), predicted discomfort is primarily concentrated near the south façade and on the east side of the building. This is because of reflections from the glazing of the neighbouring building (Fig. 2) and afternoon sun penetrating from west to east across the southern end of the studio space.

Spatial agreement between the survey results and comfort predictions are overall high. The morning visual comfort predictions (Fig. 4a) illustrate discomfort throughout the space with the notable exception of desks that are shaded. The occupant reported results seem to corroborate this analysis. Midday discomfort (Fig. 4b) is localized to the south and east sides of the building. This result is also close to the occupant survey's results. During the afternoon, many occupants report comfort near the southern glazing although the model predictions indicate the opposite due to the presence of direct sunlight. Potential reasons for this discrepancy are discussed in the following section.

Ability to Predict Long-term Occupant Visual Comfort

Table 2 documents the predictive ability of the model for each time interval when compared to the survey results. Exact matching to actual occupant evaluations ranges from 53.7% in the morning to 70.1% for the midday period during the semester. This may seem low; however, the percentage of matching within one comfort threshold is relatively high, from 77.6% to 88.1%. This suggests that simulation results are capable of predicting long-term occupant visual comfort trends within a space.

TABLE 2 Discomfort predicted by long-term visual comfort model.

Matching Criteria	Morning	Midday	Afternoon
Exact match	53.7%	70.1%	64.2%
Identified polled comfort as discomfort	14.9 %	4.5 %	7.5 %
Identified polled discomfort as comfort	11.9 %	9.0 %	9.0 %
Over-prediction	22.4%	4.5%	9.0%
Under-prediction	23.9%	25.4%	26.9%

Discussion

What does the ability for simulation to predict long-term occupant visual comfort in spaces mean for architecture, the building simulation community and design? One impact is that designers may probe a space for the potential appearance of discomfort resulting from several causes. The process proposed in this paper can hence be used to assess designs of daylit spaces for maximum comfort without the use of operable shading devices. When discomfort is identified, it is possible to discover and address the causes by location, typology (discomfort glare, monitor contrast or direct sunlight) and time of occurrence. For typological and time-based analysis of visual comfort see the following section and Fig. 5. This same methodology can also be applied to interior furniture and seating layouts. Space layout has a large impact on visual comfort, as visual discomfort is dependent on the viewing direction. Building simulationists currently have a large role to play in this analytical design process, as there is not an established method to determine view position and direction. There is also no fully automated method to produce and evaluate such metrics.

The comfort maps shown in Fig. 4, which compare model predictions to reported visual comfort, show a reasonable degree of spatial agreement. When coupled with the analysis methodology presented herein, these spatial visual comfort maps allow designers to improve the visual quality of designed spaces through fenestration, orientation and interior design choices. The accuracy of predicted occupant responses presented in Table 2 shows that there is a good correlation between model predictions and occupant-reported visual comfort. Some further details regarding visual comfort observed in these results are examined in the following section.

(a) Predicted morning long-term visual comfort from 8:00 – 12:00.

(b) Predicted midday long-term visual comfort from 12:00 – 14:00.

(c) Predicted afternoon long-term visual comfort from 14:00 – 18:00.

Fig. 4 *Predicted semester-long visual comfort categorized by time and compared to actual response.*

Using Multiple Visual Comfort Criterion

Occupant behaviour models for dynamic shading devices such as Lightswitch [Reinhart 2004], DGP-based shading control in Daysim [Reinhart and Walkenhorst 2001], the Adaptive Zone [Jakubiec and Reinhart 2012] and IES standard LM-83-12 [IESNA 2012] utilize predictions of visual comfort. However, until now, they have all looked at visual comfort through a narrow lens. Lightswitch lowers a shade when greater than 50 W/m^2 of direct normal irradiation falls on the workplane. DGP-based shading control implemented in Daysim closes the blinds when a DGP value of at least 0.40 is observed. The Adaptive Zone proposes a modification of the Daysim DGP control method, but occupants have the ability to adapt by looking in directions where the least discomfort is experienced. IES-LM-83 suggests that window shades should be lowered when greater than 2% of the space receives direct sunlight greater than 1000lx. However, visual discomfort may occur, for example, when a monitor screen is not legible without any contribution from direct sunlight, so the methods enumerated in this paragraph may not always be reliable.

The results in predicting long-term visual comfort allow important reflection on the assumptions made by the aforementioned models. Foremost, the use of a single metric for determining comfort is challenged. Results at each of the more than 500 workspaces in this study were tallied separately for each time interval and for each type of predicted discomfort that occurs more often than 1% of occupied time. During the morning interval, only 28.6% of workspaces with predicted discomfort at some point originated from a solitary type of discomfort analysis. During the midday interval when the sun is higher, this percentage increases to 47.4%. Finally, during the afternoon period only 37.5% of desks with predicted discomfort are affected by a single type of discomfort. This suggests that predicting visual discomfort with a single metric is inadequate, because in reality several causes may be responsible for what occupants label visual discomfort. It is reasonable to conclude that occupant behaviour models and comfort prediction methods analysing only direct sunlight or discomfort glare may miss some periods of discomfort.

That single-metric models do not adequately quantify discomfort in daylit spaces is further reinforced by Fig. 5, which compares hourly discomfort metrics using temporal maps for two desks labelled ‘1’ and ‘2’ in the plans of Fig. 4. Discomfort glare probability, monitor contrast ratio, direct visible sunlight, and direct sunlight on the desk are displayed graphically with the horizontal axis indicating the day within the survey period and the vertical axis indicating time of day in six minute intervals. The colour scale for each metric is calibrated such that dark red (■) indicates a threshold at which discomfort would be predicted by the plotted metric. In these examples, all four causes of discomfort are observed. In example 2 it is predicted that reflections from the monitor are uncomfortable before noon and discomfort glare occurs after noon. Thus, in a single example two discomfort causes are observed. Visible direct sunlight and direct sunlight on the desk have morning and afternoon periods of discomfort for both examples. These periods of direct sunlight are not entirely correlated with monitor contrast ratio or discomfort glare in example 1 and 2 respectively. Overall, the students at both example desks experience discomfort, especially during morning and midday periods but from disparate causes. In this case at least, occupant comfort models that consider multiple sources of discomfort are necessary. An analysis looking at only a single discomfort measure would necessarily miss other problems, which should also be addressed.

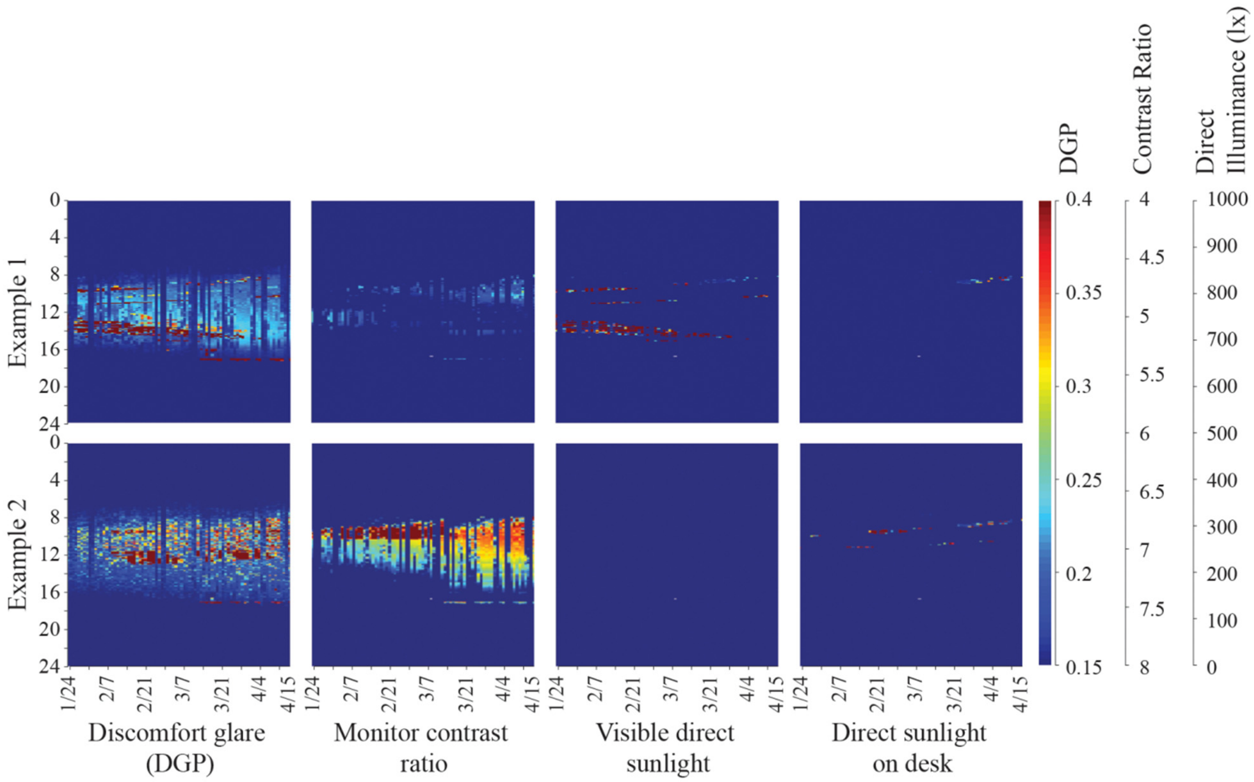


Fig. 5 *Comparison of predicted discomfort for two desks.*

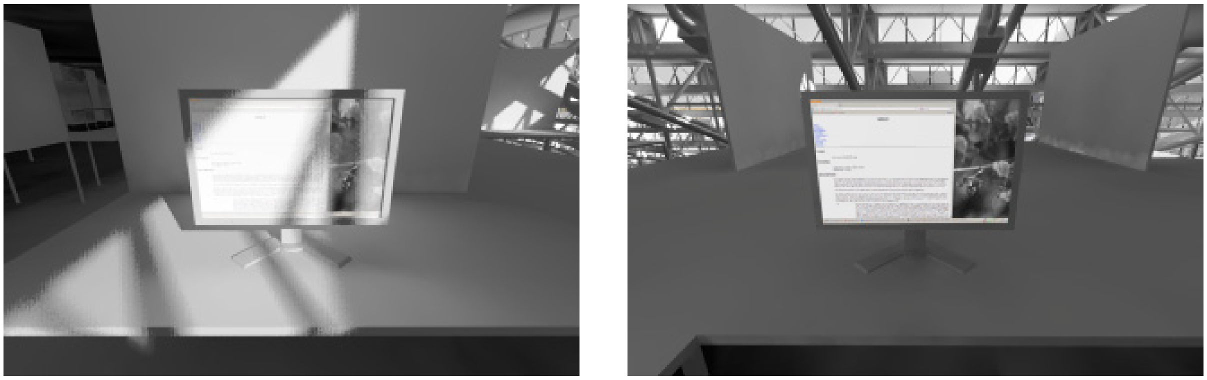
Values that might be associated with the closing of blinds are colored dark red (🟥).

Occupant Variability

Occupants are highly variable in their assessments under similar conditions. For example, the student labelled '3' in Fig. 4 reports disturbing or intolerable visual comfort for all three time intervals despite that during the midday and afternoon time periods his or her neighbours are entirely comfortable. Comfort metrics in other domains target 90% acceptance [ASHRAE 2012], so even at ideal conditions, some will be dissatisfied.

Adaptation

The student indicated by the label '4' in Fig. 4 constantly feels more satisfied during each time interval than the authors' method predicts. The primary cause of the model-predicted discomfort is a reduction in monitor contrast. The view directions of each student in the study were modelled as observed during the start of the semester; however, over time some students opted to use their side tables as the main workspace. In the case of example 4, this means that the student would face east rather than north. Simulated images of monitor visibility and direct sunlight for the two seating scenarios on January 31st at 10:30, during the morning measurement period, are displayed in Fig. 6. By turning 90-degrees, the student is able to avoid direct light falling on his or her monitor for much of the semester.



(a) Original view *(b) Adaptive view*

Fig. 6 *Example 4 monitor visibility at January 31st, 10:30 during morning survey period.*

Besides adapting themselves, students also adapted the environment to their comfort needs. Student-built horizontal shading devices were accounted for in the simulation; however, some students additionally erected vertical shades during the semester, which were not considered. Predictions of visual comfort for students who built their own shading devices, indicated in Fig. 4 by the dark shaded areas, were accordingly more prone to error. 33.3% (5) of the morning, 50.0% (4) of the midday and 27.3% (3) of the afternoon predictions varying from the survey by more than one comfort threshold are accounted for by students who built their own shading devices.

Finally, the survey results themselves lend credence to the concept of adaptation in order to avoid visual discomfort, at least in spaces such as Gund Hall where daylight qualities are highly dynamic and there is no user-controllable window shading system (except on the eastern mezzanine area of floor 2). Harkening back to Question 3 where students were asked how they reacted to increase visual comfort when uncomfortable, the below answers were given.

- 25.6% (23) did not experience any discomfort.
- 21.1% (19) experienced some discomfort, but did nothing.
- 21.1% (19) changed position in front of the desk.
- 20.0% (18) built their own shading device.
- 30.0% (27) changed their orientation or view at their desk.
- 12.2% (11) moved to a completely different location (could not adapt).

Note that 20 of the 90 students who answered opted to include a free response, but most free response answers fell into the listed responses. In other words, in the culture of Gund Hall, it is commonplace to adapt to the specific luminous environment. Adaptation in this case involves both long and short-term responses. Building shading devices is a long-term response to visual discomfort, and the presence of personal shading devices in Gund Hall at all is an indicator of visual discomfort in those areas. Changing position or orientation is a short-term adaptation to the visual environment, often to avoid some glaring reflection on the monitor or to look away from glaring surfaces. These survey results give evidence to the adaptive zone concept where occupants have the freedom to look in different directions within a space and avoid visual discomfort [Jakubiec and Reinhart 2012].

Survey Bias

One important question raised by this study is, can people actually assess how they feel about a space over a long period of time, or are their impressions strongly biased by recent events? This question is especially important to the relevance of this paper, as the questions asked of students are specifically targeted to inform researchers about their long-term impressions of the space, and most other studies of this type look only at instantaneous visual comfort [Painter, Fan, and Mardaljevic 2009; Van Den Wymelenberg, Inanici, and Johnson 2010; Hirning et al. 2013; Van Den Wymelenberg and Inanici 2014]. One way to address this line of thinking is simply to see if students who report negative feelings about the space did so during times where discomfort was likely to be experienced. Figure 7 illustrates this by plotting the number of predicted discomfort incidents for each student in a certain time interval preceding their survey response (4 hours, 24 hours and 1 week) against their reported visual comfort. In the case where bias is present, one would expect to find large quantities of predicted discomfort incidents in the 4 and 24 hour period for those who rank the space 'disturbing' or 'intolerable;' however, this is not the case. In fact, towards the end of the semester a higher solar altitude resulted in fewer discomfort incidents overall.

Beyond the findings shown in Fig. 7, in the free response sections of the survey students are extremely eloquent when discussing the source of visual discomfort and the time at which it was experienced. Students were able to differentiate visual discomfort by time and location in the space and did not seem to be reacting to current conditions. A full accounting of these free response results has been reported elsewhere [Jakubiec 2014]; however, some excerpts are included below,

> *There are a small, select number of hours I have noticed where the sun is shining in my eyes or through the glazing in the stepped area of Gund's roof (either early morning or late afternoon); however these are very infrequent.*
>
> *Late afternoon sun gets reflected from the CGIS façade into the studio space.*
>
> *Reflection off of [the CGIS] building to the east (only for a few minutes, only when the blinds are up, which is now a choice we have to make).*
>
> *My desk faces north so I get south sun reflected [from] my monitor in early afternoons.*
>
> *[Glare] rarely happens... not so much now in the spring. In winter mornings there is a point the sun shines directly at my face / desk.*
>
> *I sat at the very South end of the 4th [floor] in previous semesters (facing away from the windows). I found there was constantly disruptive glare, and the temperature was consistently either hot or cold. Sitting on the North end of the building has definitely positively influenced my productivity and happiness with my desk situation!* [Note: This final quote came from the end of survey comments.]

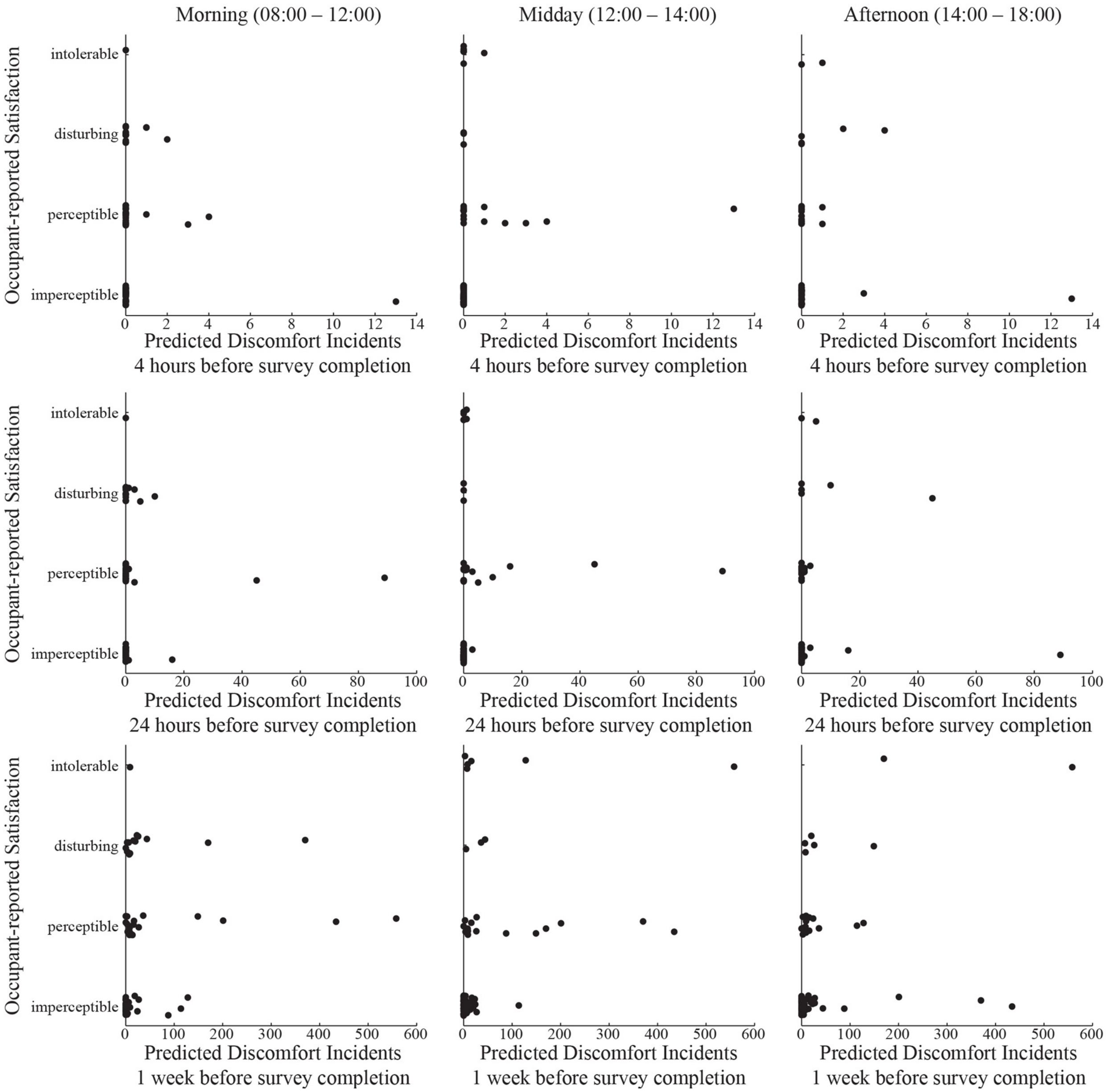


Fig. 7 *Plots showing the number of predicted discomfort incidents during the time before answering the survey for each user.*

Furthermore, analysis of the 6-minute split solar radiation weather data suggests that experiencing uncomfortable conditions over the 5 day period during which the survey was administered is unlikely. This data is summarized in Figure 8 below, which plots five days of solar data across the horizontal axis in 6 minute intervals. Dashed black lines indicate global horizontal solar irradiation, and solid black lines indicate direct normal solar irradiation. Vertical lines with accompanying time labels indicate sunrise and times at which the sun becomes predominantly unobscured by clouds. During survey days 1, 2 and 4, the morning hours when direct sunlight would enter from the East were entirely or predominantly overcast. Day 3 had entirely overcast sky conditions. Only on the final day of the survey was there a significant amount of direct solar irradiation during morning hours when light reaches deep into the building, and only 8 survey responses were collected on that day. Of the 24 survey data points on comfort for the morning, midday and afternoon periods, 3 instances of disturbing long-term discomfort were reported, and no instances of intolerable were reported. Three of the 8 respondents cited here belong to those who reported electric lighting as a source of visual discomfort and were therefore removed from the analysis portions of the paper; however, none of the 3 reported disturbing long-term discomfort.

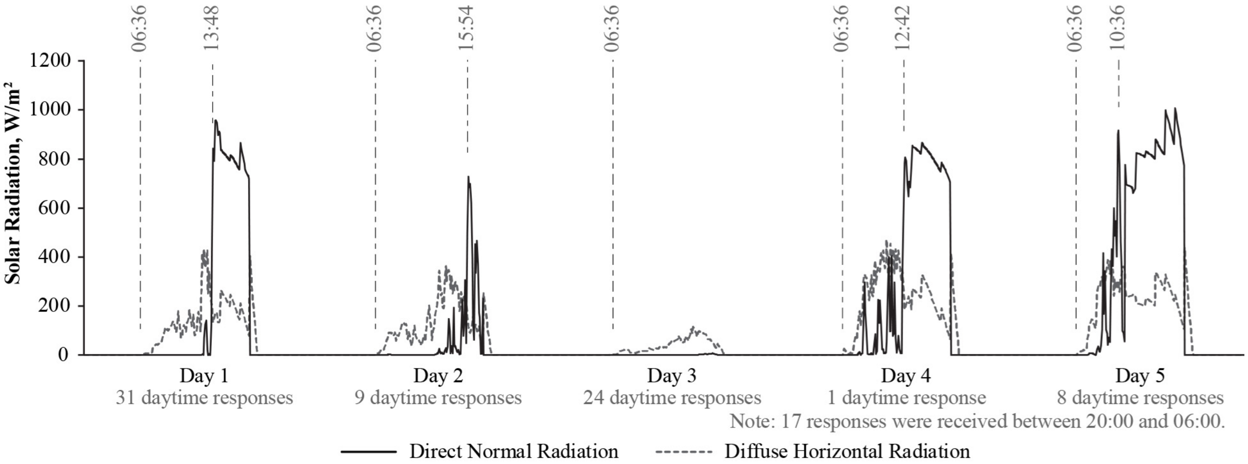


Fig. 8 Measured 6-minute weather data during the period the survey was active. The time of sunrise and an initial direct solar peak as well as the distribution of responses is included.

Overall it is not possible to claim that bias is not present in the survey data collected. This section presents reasonable claims that the occupants of Gund Hall are capable of recalling and considering past visually uncomfortable events and not consider only their most recent experiences.

Limitations of Study

There are some limitations to the study as it currently stands. The monitor contrast simulation methodology is not yet well established in research or practice. In reality, reflections from monitors have diffuse and specular components, but they are also easily adjusted to avoid specular reflections. For this reason, this paper uses illuminance incident on monitor surfaces and lambertian reflection models to qualify contrast reduction. The survey data that is used to calibrate the semester-long visual comfort model is the same data by which the analysis is evaluated. This was done because only a small number of intolerable or disruptive survey responses were available. An independent data set is desirable for evaluation; however, the visual comfort metrics used to evaluate each hourly or six-minute time step are based on a wealth of research, experimental data and accepted standards. Also, it was found that the frequency of occurrence of instantaneous visual comfort predictions can be used to identify the overall visual comfort of occupants at least in this one example. Therefore, the authors feel comfortable recommending the analysis and mapping methodologies documented in this paper for application to the design of daylit spaces while realizing that the specific recommended rate of discomfort occurrences requires further research.

Conclusion

This work describes the long-term visual comfort of space occupants in contrast to typical instantaneous visual comfort assessments. The authors' method is novel because it fits in with other annual building performance metrics such as energy use intensity and daylight availability that allow designers to quickly assess the annual performance of a building. As visual experience is position and view dependant, the analysis presented here allows for the display of annual spatial visual comfort. A paired study consisting of occupant surveys and detailed 6-minute timestep comfort simulations was performed for the studio spaces of Gund Hall, holding over 500 occupants. The results of the study illustrate that it is possible to use current visual comfort metrics to predict occupants' long-term visual comfort in a complex daylit space. Four ways of experiencing visual discomfort contribute to the evaluation of visual comfort in this paper: discomfort glare, monitor visibility, the visibility of the sun with the eye and direct sunlight on a workplane. The visual comfort prediction methodology explains between 53.7% and 70.1% percent of polled occupant evaluations depending on the time of day and generally follows the spatial distribution of occupants who report discomfort. Spatial visual comfort information provides understandable results which can be acted upon to improve visual comfort in buildings being designed. In future research, it is necessary to test the concept of long-term visual comfort in different building and use types and with more voluminous data to aid in validation of the concept.

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