Proceedings of BS2013:
13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28

PREDICTING VISUAL COMFORT CONDITIONS IN A LARGE DAYLIT SPACE BASED ON LONG-TERM OCCUPANT EVALUATIONS: A FIELD STUDY

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ABSTRACT

We present a method for predicting visual comfort conditions of occupants in daylit spaces. Using an online survey, 67 occupants of a multi-story open plan studio space evaluated long-term visual comfort at their workstations in a substantially daylit space which is known to have glare problems. Visual comfort simulations of each occupant's specific location were conducted and compared to the survey results. Simulations included discomfort glare, monitor contrast, visibility of the sun in the field of view and the presence of direct light on the workplane. It was found that combining all four modes of discomfort analysis allows close agreement with occupant assessments ranging from 69% of morning assessments up to 87% of afternoon assessments. In contrast, following current practice by only considering a single source of discomfort, leads to under-predicting the glare problem. Only 29 to 47 percent of significant visual comfort assessments in this study were caused by a solitary type of discomfort. These findings show that visual discomfort is often caused by multiple independent effects, which must be evaluated simultaneously for a reliable visual comfort analysis.

INTRODUCTION

For over eighty years, visual comfort prediction has remained one of the 'holy grails' of daylighting research. In this context, the authors define visual comfort as the absence of discomfort such as glare, insufficient visual contrast or the presence of visible direct sunlight. The goal of being able to predict discomfort during design is to avoid it altogether. With simultaneous growing interest in passive strategies to increase comfort and in greater transparency of building envelopes, designers are more than ever in need of reliable metrics to assess visual satisfaction in daylit spaces.

Most comfort analyses focuses on only one parameter such as discomfort glare or the presence of direct sunlight. Such analyses tell only a small part of the story of perception in daylit spaces. Furthermore, no annual metric exists to assess the visual satisfaction of occupants in daylit spaces. As a result, the application of visual comfort analysis to design problems is seriously limited. A number of comfort metrics have been proposed in the past that were created in the laboratory or via controlled studies; however, there has been little work applying these metrics to real, daylit interiors (Rubiño et al., 1994; Jakubiec and Reinhart, 2012). This research aims to validate the applicability of visual comfort metrics for design by applying them in the field.

To this end, the authors performed a comprehensive visual comfort analysis of the Harvard University Graduate School of Design studio spaces. The analysis accounts for discomfort glare probability, monitor contrast, visibility of the sun and direct sunlight on the workplane. The space is a five storey terraced open plan arrangement that houses over 500 graduate students. It features clerestory windows and fully glazed north and south facing walls. The studio space is known to have visual comfort problems because each term students located in the most offending areas erect their own shading devices. An online survey was administered in which 67 occupants participated who were either comfortable or experienced discomfort from daylight.

The authors compare occupants' reported visual comfort assessments against detailed simulations of their workspaces. The resulting visual comfort analysis detects when occupants will be uncomfortable. It also relates to the spatiality of a place, the time of occurrence and the primary causes of discomfort. Therefore, the analysis constitutes helpful clues to avoid discomfort problems during the design of a building.

In this paper, a review of existing discomfort metrics is presented, followed by a detailed description of the simulation setup and an analysis of results. From this holistic analysis, detailed maps of occupant visual satisfaction at different times of day, categorized by primary cause and the intensity of discomfort, are created. The relative importance of discomfort glare, reduced monitor contrast and the presence of direct sunlight in determining occupant satisfaction as observed in this study are describe. In the discussion section, the importance of integrated visual comfort analysis that considers multiple sources of discomfort is explored within the context of existing comfort prediction methodologies.

DISCOMFORT METRICS

In daylit spaces, there are several possible causes of discomfort: discomfort glare, reduced monitor contrast ratios from reflected daylight, visibility of the sun, and the presence of direct sunlight on the workplane. Discomfort due to electric lighting is not considered in this study.

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 our 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 (2012) showed that DGP is the most robust of existing discomfort glare metrics and the least likely to give false positives. The specific expression of DGP is described in Equation 1 below,

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

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.

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 Equation 2,

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

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, 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 suggests that illuminance from direct solar exposure over 1000 lux will cause discomfort (IESNA, 2012).

METHODOLOGY

Survey on Visual Comfort

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. Students were asked to select their desk using a numbered seating plan of the school or the label affixed to their desk and to describe in detail their visual satisfaction with the space. Students 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 ranked their comfort in one of four categories: comfortable, perceptible discomfort, disturbing discomfort or intolerable discomfort. Students were also given the opportunity to describe the cause or causes of their discomfort and what actions they took in response.

Visual Comfort Simulations

A calibrated daylight simulation model was constructed of Gund Hall in the Radiance simulation engine. Radiance is a validated program created by the US Lawrence Berkeley National Laboratory, which employs a reverse raytracing algorithm based on the physical behavior of light in a volumetric, three-dimensional model (Ward, 1994). The model is geometrically accurate including its context and the glazing of nearby buildings.

In accordance with the comfort metrics section, each survey respondent's work area was the subject of discomfort glare, monitor contrast and direct sunlight simulations. DGP and monitor contrast were assessed hourly from January 24 until April 15. DGP predictions were made using the enhanced simplified DGP (eDGPs) method (Wienold, 2009). The eDGPs method substantially decreases calculation time by using a Radiance-based daylight coefficient method (Reinhart and Walkenhorst, 2001) to calculate vertical eye illuminance and rendered images of direct sunlight to determine contrast. Monitor contrast ratios were predicted based on illuminances calculated using a daylight coefficient method. 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 screen) at 5.4% diffuse reflectance. L_H and L_L 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 when used with Equation 2. Specular reflections were not considered. Because of the many small clerestory windows relative to the size of the space, the presence of direct sunlight is a transient phenomenon in Gund Hall for those not seated near the large North or South windows. Therefore, visibility of the sun and the presence of direct sunlight on student's work areas were simulated in six-minute intervals.

Weather data was acquired from a weather station approximately one kilometer (0.62 mi) away from the site for the period of the study (Cambridge, Massachusetts Weather, 2012). Measured global horizontal solar irradiation was converted into direct and diffuse components using the Reindl method (Reindl et al., 1990) and used as input information to the Perez all weather sky model (Perez et al., 1993).

Studied Space, Gund Hall Studios

The studio space of Gund Hall, portrayed in Figure 1 as a rendering of the simulation model, provides desks for approximately 500 students of architecture and urban design. It is a five storey tiered space filled with daylight, which comes from clerestory windows and large floor-to-ceiling glazing at the north and south ends of the space. Student desks either are directly underneath the clerestory windows or sheltered by the level above.

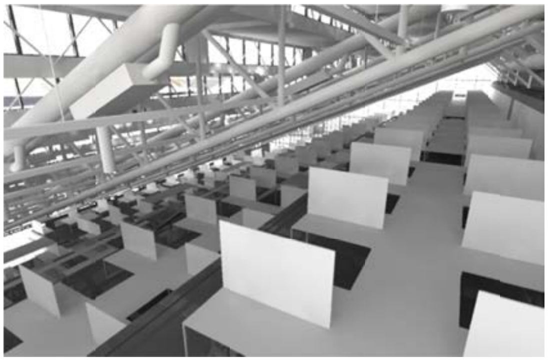


Figure 1 A rendered image of the simulation model looking South from the fourth level corner

Our simulation model accounts for measured visible window transmissivity (Voit et al., 2007) and diffuse reflectance values for opaque surfaces in the space, described in Table 1. The ceiling was modeled using a standard 80% reflectance, as it was inaccessible for measurement purposes. Electric lighting is supplied by louvered fluorescent fixtures, which are on for most hours of the day; however, discomfort from electric lighting is not considered in this paper.

RESULTS

Survey Results

The survey received 194 responses of which 90 were valid. The 67 respondents who did not experience discomfort caused by electric lighting are studied henceforth.

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
Cinder block walls	0.759
Handrails	0.048
Ceiling	0.800

Overall, the survey results suggest a relatively high dissatisfaction with the space. This is represented in Figure 2, which details the occupant-reported comfort for each of the three intervals. Comfort is represented by green and intolerable discomfort is represented with red, a standard maintained throughout this paper. As the building's clerestories face east, the morning hours yield the most discomfort with 52.3% of occupants reporting discomfort. During midday, fewer users report discomfort (36.9%), but the intensity of reported discomfort is the highest with 9.2% of respondents reporting intolerable discomfort. 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.

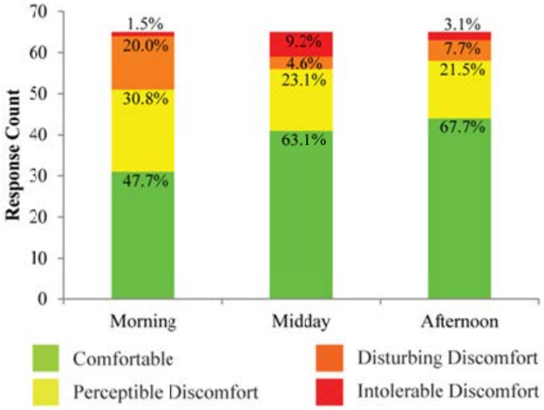


Figure 2 Histogram of reported comfort

Predicting Long-Term Occupant Evaluations

With a complete set of discomfort glare, monitor contrast and direct sunlight (visible and workplane) simulation results for each survey respondent in Gund Hall, it is possible to analyze the intensity and frequency of discomfort from multiple 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 within the space to be uncomfortable? We found that the percentage of occupied hours above a certain comfort threshold has a strong correlation with reported comfort values. Any time with a DGP value above 0.3, classified during a moment in time as 'perceptible' (Wienold, 2009), predicted monitor contrast ratio below four (Moghbell, 2012) or with direct sunlight on the eye or desk is considered uncomfortable for this purpose. Occupants tended to be more sensitive to direct sunlight and reduced monitor contrast, by factors of four and three respectively. This sensitivity to direct sunlight and contrast was also reflected in the survey comments. It was found that a typical occupant experiencing predicted discomfort glare for more than 13.5% of occupied time is likely to feel that a space is intolerably uncomfortable; however, if direct sunlight is experienced a mere 3.4% of occupied time, the occupant reaches the same conclusion. It was observed that multiple types of discomfort contribute to the overall evaluation of visual satisfaction in a space. Figure 3 documents the observed relative importance of different discomfort causes. For example, the purple dots and dashed lines in Figure 3 mark discomfort glare 5.6%, low monitor contrast ratio 2.25% and direct sunlight 0.55% of occupied time. This results in an overall visual satisfaction of 'disturbing' although individual causes of discomfort never reach a classification above 'perceptible.'

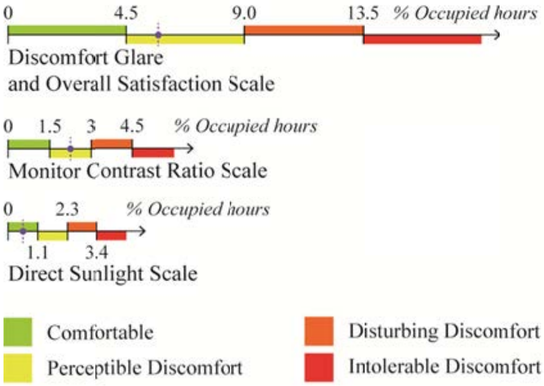


Figure 3 Scale of visual satisfaction by occ. hours.

Spatial Display of Results

Predictions using simulation results are compared to the survey responses gathered from occupants in Figure 4. Results are overlaid on a plan of the Gund Hall studio spaces showing all four levels simultaneously. Shaded areas indicate desks that are covered by the floor above or shaded by a custom, student-built shading device. A small circle is located at each desk representing the occupant-reported spatial visual satisfaction color-coded from comfortable (●) to intolerable discomfort (●). Surrounding each small circle is a larger shape color-coded according to the author's predictions. Circles (◉) indicate discomfort primarily caused by direct light, squares (◘) indicate discomfort primarily caused by reduction in monitor contrast and triangles (▲) indicate discomfort caused primarily by discomfort glare. Perfectly matched predictions will appear as one solid color; however, over and under-predictions will be apparent by the color difference between the interior circle and the enclosing shape.

During the morning (Figure 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 (Figure 4B), from 12:00 to 14:00, is when the altitude of the sun is at its peak. Thus, predicted discomfort is primarily localized to the southern side of the space. In the afternoon (Figure 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 neighboring building and afternoon sun penetrating from west to east across the space.

Ability to Predict Occupant Visual Satisfaction

Table 2 documents the predictive ability of our analysis for each time interval when compared to the survey results. Exact matching to actual occupant evaluations ranges from 40.3% in the morning to 64.2% for the afternoon period during the semester. This may seem low; however, the percentage of matching within one comfort threshold is relatively high, from 68.7 to 86.6 percent. This suggests that simulations are capable of tracking occupant visual satisfaction trends within a space but that occupant assessments vary based on personal preferences.

Table 2

Discomfort Predicted by Analysis

MATCHING CRITERIA	MORNING	MIDDAY	AFTERNOON
Exact match	40.3%	64.2%	64.2%
Within one	68.7%	85.1%	86.6%
Over-prediction	47.8%	19.4%	11.9%
Under-prediction	11.9%	16.4%	23.9%

Most importantly, spatial agreement between the survey results and comfort predictions are overall high. The morning visual satisfaction predictions (Figure 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 (Figure 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 our predictions indicate the opposite due to the presence of direct sunlight. Potential reasons for this discrepancy are discussed in the following section.

A. Morning visual satisfaction from 8:00-12:00.

B. Midday visual satisfaction from 12:00-14:00.

Figure 4 Predicted semester-long visual satisfaction categorized by cause compared to actual response.

C. Afternoon visual satisfaction from 14:00-18:00.

Figure 4 Predicted semester-long visual satisfaction categorized by cause compared to actual response.

DISCUSSION

What does the ability for simulation to predict occupant visual satisfaction in spaces mean for architecture, the building simulation community and design? One impact is that designers have the ability to evaluate clear analysis and spatial mappings based on several potential causes of discomfort. The authors' process can be used to assess designs of daylit spaces for maximum comfort without the use of operable shading devices. The same methodology can be applied to furniture and seating layouts. Space layout has a large impact on visual satisfaction, 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 yet a fully automated method to produce and evaluate such metrics.

The comfort maps shown in Figure 4 and the accuracy of predicted occupant responses presented in Table 2 show that there is a reasonable correlation between the authors' predictions of visual satisfaction and occupant-reported visual satisfaction; however, deeper understanding of the significance of this result is probably warranted.

Using Multiple Visual Comfort Criterion

Occupant behaviour models 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) all 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 visible spectrum irradiation falls on the workplane. DGP-based shading control implemented in Daysim closes the blinds when a DGP probability 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-83-12 suggests that all shades should be closed when greater than 2% of the space receives direct sunlight.

The authors' results in predicting visual discomfort allow important reflection on the assumptions made by the aforementioned models. Foremost, we challenge the use of a single metric for determining comfort. Results at each workspace were tallied separately for each time interval and for each type of predicted discomfort that occurs for greater than one percent of occupied time. During the morning interval, only 28.6% of workspaces with predicted discomfort originated from one 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 explaining visual discomfort with a single metric is inadequate because several factors contribute to the assessment of comfort. It is reasonable to infer that occupant behavior models and comfort prediction methods analyzing only direct sunlight or discomfort glare will necessarily miss some periods of discomfort.

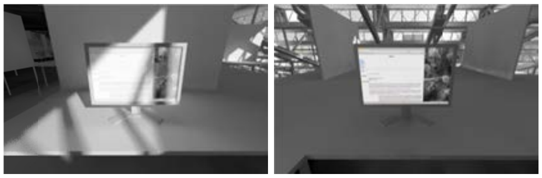
That single-metric models do not adequately quantify discomfort in daylit spaces is further reinforced by Figure 5, which compares hourly discomfort metrics using temporal maps for two desks labeled 'Example 1' and 'Example 2' in the plans of Figure 4. Discomfort glare probability, monitor contrast ratio, 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. The color scale for each metric is calibrated such that dark red (■) indicates a threshold at which discomfort would be predicted by a typical occupant behavior model. In these examples, all four causes of discomfort are observed. Furthermore, for both example 1 and 2, visible direct sunlight and direct sunlight on the desk have morning and afternoon periods of discomfort. 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 desks experience discomfort, especially during morning and midday periods but from disparate causes, suggesting occupant comfort models that consider multiple sources of discomfort are necessary.

Occupant Variability

Occupants are highly variable in their assessments under similar conditions. For example, the student labelled 'Example 3' in Figure 4 reports disturbing or intolerable visual discomfort for all three intervals despite that during midday and afternoon his or her neighbors are all relatively comfortable.

Adaptation

The student indicated by 'Example 4' constantly feels more comfortable than our method predicts with the primary cause of discomfort being a reduction in monitor contrast. The view directions of each student in the study were modeled 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 Figure 6. By turning 90-degrees, the student is able to avoid direct light falling on his or her monitor.



A. Original view *B. Adaptive view*

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

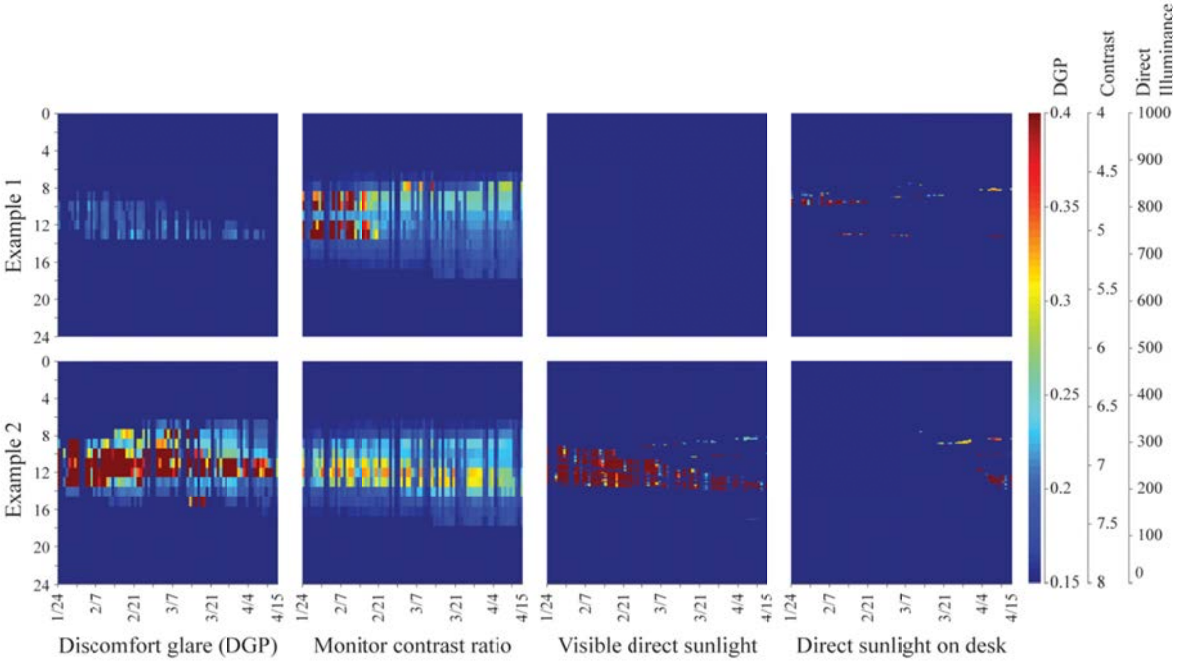


Figure 5 Comparison of predicted discomfort for two desks.
Values that might be associated with the closing of blinds are colored dark red (■).

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 satisfaction for students who built their own shading devices were accordingly more prone to error. 42.9% (9) of the morning, 40.1% (4) of the midday and 44.6% (4) of the afternoon predictions varying from the survey by more than one comfort threshold are accounted for by students who built custom shading devices.

CONCLUSION

This work shows that it is possible to use current visual comfort metrics to predict occupant's long-term assessments of visual satisfaction in a complex daylit space. Our assessment explains, within one comfort threshold, between 68.7 and 86.6 percent of polled occupant responses depending on the time of day. Spatial trends of discomfort show good agreement with reported occupant values. In this study, using a single cause of discomfort would have resulted in missing significant periods and areas of discomfort within the space. It is reasonable to assume this is the case in other spaces as well, because discomfort glare, monitor contrast and the visibility of direct sunlight may occur independently in any space.

Limitations of Study

The survey data that is used to calibrate our semester-long occupant assessment is the same data by which the analysis is evaluated. 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 and experimental data. Therefore, the authors suggest that the trends observed in this study are already applicable to the design of comfortable, daylit spaces. The ability for occupants to adapt to a space is not currently considered in the authors' visual comfort assessments; however, simulated adaptation data is available and will be included in future iterations of the study.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation project in Emerging Frontiers in Research and Innovation (award: EFRI-1038264).

REFERENCES

Cambridge, Massachusetts Weather. Retrieved on 07/21/2012. http://weather.keneli.org/index.html.

IESNA, IES LM-83-12. IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). New York, NY, USA, IESNA Lighting Measurement, 2012.

ISO 9241-3. 1992. Ergonomic requirements for office work with display terminals (VDTs), Part 3: Visual display requirements.

ISO 9241-303. 2008. Ergonomics of human-system interaction Part 303: Requirements for electronic visual displays.

Jakubiec, J.A., Reinhart, C.F. 2012. The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces. Lighting Research & Technology 44 (2) 149-70.

Moghbell, N. 2012. New Model for VDT Associated Visual Comfort in Office Spaces. PhD disseratation, Department of Architecture, Karlsruhe Institute of Technology.

Perez, R., Seals, R. and Michalsky, J. 1993. All-weather model for sky luminance distribution—Preliminary configuration and validation. Solar Energy 50 (3): 235-45.

Rubiño, M., Cruz, A., Garcia, A., and Hita, E. 1994. Discomfort glare indices: a comparative study. Applied Optics 33 (34): 8001-8.

Voit, P., White, D., and Bummele, A. 2007. Gund Hall- Analysis of Envelope Performance and Thermal Comfort. Transsolar Inc. report to Harvard University.

Reindl, D.T., Beckman, W.A., and Duffie, J.A. 1990. Diffuse fraction correlations. Solar Energy 45 (1): 1-7.

Reinhart, C.F. and Walkenhorst, O. 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings 33 (7): 683-97.

Reinhart, C.F. 2004. Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. Solar Energy 77: 15-28.

Ward, G.J. 1994. The RADIANCE Lighting Simulation and Rendering System. Proceedings of the 21st Annual Conference on Computer graphics and interactive techniques, Orlando.

Wienold, J., Christoffersen, J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings 38: 743-757.

Wienold, J. 2009. Dynamic Daylight Glare Evaluation. Proceedings of Building Simulation 2009, Glasgow.