Evaluating Daylight Glare and Identifying Its Dominant Cause in Computer-Based Office Task Environment

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Abstract

Existing discomfort glare metrics have been utilized to evaluate various daylit scenes. However, existing metrics focus on reporting perceived levels of discomfort glare without identifying what causes the problem. This paper develops a new analysis method, which can inform users both the existence of discomfort glare and its dominant cause in a daylit space. Human subject study was performed inside a closed office. More than 150 glare scenes were collected with subjective evaluation surveys. The collected data was statistically analyzed to develop a new method using luminance and contrast ratio, which will help promote discomfort glare analysis in daylighting design.

Introduction

Daylighting has been incorporated in many buildings in order to promote electrical energy savings and occupant comfort. There are many existing tools and metrics for designers to evaluate and determine daylighting design performance prior to construction. As natural light is introduced into a building, occupants can experience discomfort glare from excessive sunlight penetrations through transparent building envelopes. Similar to the existing daylighting tools and metrics, significant efforts have been made to develop validated metrics that can accurately evaluate and quantify levels of perceived visual discomfort issues. Existing glare metrics and tools are sophisticated and complex enough to make very detailed discomfort glare analysis but they focus on reporting results of discomfort glare based on different glare categories without providing users actual reasons of the issue. This paper develops a new method, which can inform daylighting design professionals and academic researchers both a dominant cause and result of discomfort glare problems in a daylit space.

Discomfort glare metrics

Currently, Evalglare is one of the most widely available tool for discomfort glare evaluations. The tool has been incorporated into several building simulation software such as Diva, IESVE, hdrscope, etc. It allows users to evaluate a single glare scene by five different glare metrics. The metrics are Daylight Glare Probability (DGP), Daylight Glare Index (DGI), Unified Glare Index (UGI), Visual Comfort Probability (VCP), and CIE Glare Index (CGI). DGP and DGI were specifically developed to address discomfort glare issues caused by daylight and/or sunlight while the other three metrics were customized for architectural lighting sources. The metrics consider different variables including luminance values of background, glare sources, contrast ratio, glare source positions and sizes in a field of view (FOV) when evaluating a specific scene. Evalglare includes the five glare metrics' equations and conveniently provide five different glare evaluation outcomes to users. The calculation outcomes are numeric values of glare scores and the score scores can be translated as different glare categories such as imperceptible, perceptible, disturbing, and intolerable glare. A higher value represents more serious glare problems except VCP metric. As the variables in each metric's equation are differently weighted when calculating glare scores, the five different metrics often report different evaluation results out of a same glare scene (Suk, Schiler, Kensek 2016). This inconsistency issue can make users unsure which metric's outcome they should trust. However, Evalglare and the existing metrics still provide users very informative data that can quantify potential problems in occupant's visual comfort.

Luminance and contrast ratio thresholds

Besides the existing glare metrics, there are two different ways for designers to determine whether or not a daylit scene has discomfort glare issue. The first method is to utilize luminance values of glare sources. Many luminance thresholds have been developed by various research groups and some of the thresholds have been already incorporated into codes and standards. The Swedish National Board for Industrial and Technical Development (NUTEK) guideline for energy efficient offices requires any point of a room not to exceed 2,000 cd/m^2 (Dubois, 2001) but several researchers including Bülow-Hübe, Osterhaus, and Linney claimed that this luminance threshold is not appropriate for daylit environments as luminance ranges with natural light are normally much higher (Bülow-Hübe 2008; Osterhaus 2002, 2009; Linney 2008). 2,160 and 2,740 cd/m^2 thresholds were suggested by Linney depending on the directions of occupant's field of view (Linney 2008). Osterhause suggested 2,500 cd/m^2 as a luminance threshold for daylit indoor spaces (Osterhaus 2002, 2009). Wienold and Christoffersen recommended much higher luminance thresholds: 6,000 cd/m^2 for uncomfortable glare and 8,000 cd/m^2 for intolerable glare when

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occupant's FOV direction is parallel to windows (Wienold and Christoffersen 2005). A more recent study proposed similar thresholds to the ones defined by Wienold and Christoffersen: 5,600 cd/m^2 for uncomfortable glare and 10,000 cd/m^2 for intolerable glare (Shin, Yun, and Kim 2012). The recent findings clearly explain that occupants are more tolerable to high luminance glare sources caused by natural light than architectural lighting.

The other method is to utilize contrast ratios between glare source luminances to background or task area luminance. Similar to luminance thresholds, different contrast ratios were developed by various research groups. Veitch and Newsham found that 1 to 10 ratio between background and glare source luminances can cause visual discomfort (Veitch and Newsham 2000). Egan claimed that a higher contrast ratio than 1 to 40 between background and glare source luminances can cause intolerable glare to occupants (Egan 1983). Osterhaus suggested two different thresholds to cause visual discomfort: 1 to 10 between task and background luminances and 1 to 100 between background and glare source luminances (Osterhaus 2002).

As shown above, the biggest challenge to designers would be the inconsistency issue of the thresholds and metrics. It is not difficult to assume that discomfort glare evaluation outcomes can be quite different depending on a selection of the metrics and thresholds listed above. If a less stringent threshold is selected to evaluate a daylit space, no discomfort glare will be reported. If the same space is evaluated by a more stringent threshold, an opposite outcome will be obtained. Therefore, it is critical to validate the existing metrics and thresholds, and to develop a method that can provide a good understanding of the entire evaluation process.

Human Subject Study

Human subject study was performed to collect quantifiable luminous data and subjective evaluation survey in a computer-based office task environment. The collected data was statistically analyzed to validate the existing thresholds of luminance and contrast ratio. Newly defined luminance and contrast ratios were then utilized to develop a new daylight glare evaluation methodology. A number of precedents were reviewed prior to development of a research methodology (Konis 2013; Hirning et al. 2013; Luckiesh and Guth 1949; Hopkinson 1957; Ngai and Boyce 2000; Velds 2002; Osterhaus 2005; Linney 2008; Wymelenberg 2012).

Research setting

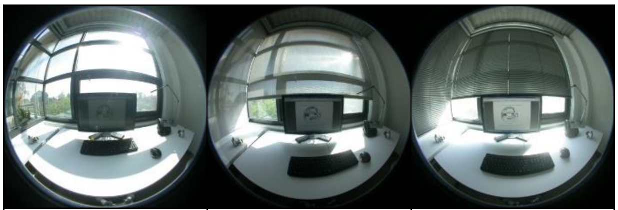
A closed office space with large south facing windows was selected in order to allow sufficient amount of daylight. The office is 9'-6" wide by 11'-4" long with a 11'-3" ceiling height. The window height is from 2'-5" above the floor to the ceiling. This setting allowed to exclude the need of electrical lighting and to provide more chances of direct sunlight penetrations that can cause visual discomfort to participants. The setting ensures that visual discomfort experienced by participants is solely from natural light. Two layers of adjustable interior shading devices (roller blinds and Venetian blinds) are located right in front of the windows. Each shading device was adjusted separately during the tests in order to control the amount of direct and diffused sunlight.

Participants

Six female and male participants without any vision related illness or color blindness were recruited. They are in between twenty and forty years old and have basic computer skills such as Microsoft Word and Adobe Acrobat Reader by using a keyboard and mouse. The recruited subjects participated more than five different sets of study under different sky conditions and sun positions. By having the same subject pool tested in different daylit conditions, it was possible to confirm their subjective evaluation consistency. Hopkinson's human subject research methodology was the basis of the research method (Hopkinson 1957).

Test procedure

Three different lighting conditions were created by using roller and Venetian blinds. Each participant was asked to perform a computer-based typing task under three lighting conditions: 1) fully open blinds, 2) roller blind partially or fully closed, and 3) Venetian blind partially or fully closed (Figure 1). When either roller blinds or Venetian blinds were partially or fully closed, the other one was fully open. The order of lighting conditions were randomly changed to avoid participants to have a same visual adaptation process from light to dark or from dark to light environment. The adjustment of each blind type was determined by each participant as he/she preferred.



Fully open blinds	Roller blinds	Venetian blinds

Figure 1: Three different lighting conditions created by adjusting roller and venetian blinds.

Participants performed a computer-based typing task for three minutes under each lighting condition and provided subjective evaluations on a survey form that was also provided on the computer screen. Participants did not need to change their FOVs to answer survey questionnaires after completing a typing task. Survey questionnaires ask participant's visual comfort, visual satisfaction, general light levels inside the office, light levels on task area, etc. in seven point Likert scale. Participants also provided their own judgment on discomfort glare categories from imperceptible to intolerable glare while indicating glare levels in a bar scale ranging 0.0 to 3.0. In addition to the written questionnaires, participants were asked to indicate any visually annoying or disturbing areas in their FOVs. A line drawing of participant's FOV was provided on the computer screen. Visually annoying areas indicated by participants were compared to their visual comfort and satisfaction evaluations. Visual discomfort can be confirmed if visually annoying areas were indicated in the FOV and visual discomfort/dissatisfaction were evaluated by a same participant.

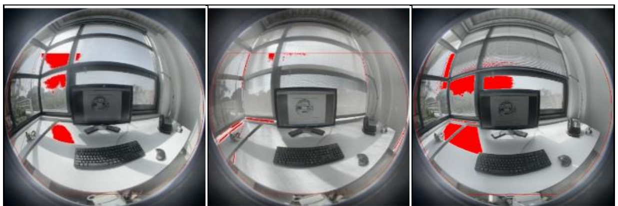
High Dynamic Range photography

High Dynamic Range (HDR) photography was utilized to document different glare scenes that were observed and experienced by each participant. HDR photography was performed right before and after each participant completed a computer-based reading and typing task. More than five full stop exposures by solely adjusting shutter speeds were captured to create a single HDR image. Wider exposures were taken in order to capture and store luminance values of the sun and/or excessively bright interior surfaces. All HDR images were carefully calibrated by a luminance meter (Cooke cal-SPOT) in Photosphere software and edited in hdrscope software (Ward 2012).

In addition to HDR photograpy, horizontal illuminance values on top of desk and vertical illuminance values at participant's eye were recorded every 30 seconds by using Li-Cor photometric sensors. Dry bulb air temperature and relative humidity were also recorded to check thermal discomfort issues that participants might have experienced.

Results Analysis and Discussion

The study was performed inside the office from February 18, 2013, to June 17, 2013. A total of 153 different HDR images and corresponding surveyed evaluations were collected. The captured HDR images were analyzed in a MATLAB code that was specifically developed to calculate crucial values for analysis, such as minimum luminance, maximum luminance, mean background luminance, task area luminance, glare source luminance range, mean glare source luminance, contrast ratio, and glare size in either a full fisheye FOV or the human eye FOV. It utilizes the existing 'hdrread' and 'tonemap' codes to read RGB values in each pixel, calculate luminance values, and render HDR images (Figure 2).

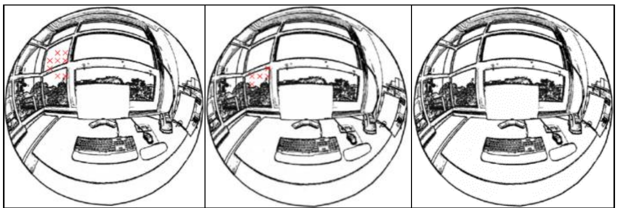


Fully open blinds	Roller blinds	Venetian blinds

Figure 2: Three different HDR images processed in the MATLAB code.

For each scene, the MATLAB code detects and indicates potential glare sources in either full fisheye or the human eye FOV by using the multiplier "5" to mean background luminance (default in Evalglare) or a luminance threshold. Both mutiplier and luminance thresholds were editable in the MATLAB code. In Figure 2, the pixels in red color represent potential glare source sizes and locations in the FOVs.

Prior to statistical analysis on the collected data, every single HDR image was processed in the MATLAB code by using either full fisheye FOV or the human eye FOV. The rendered images from the MATLAB code were compared to the line drawings of FOV marked by participants (Figures 2 and 3). The red X represents visually annoying areas in each scene. The Venetian blind scene has no glare sources detected while the other two scenes clearly include glare sources (Figure 3). Out of 108 scenes with glare sources detected, the human eye FOV accurately matched glare source sizes and locations in 105 scenes while a full fisheye FOV matched in 60 scenes only. This comparison revealed that the human eye FOV better matches to the visually annoying areas marked by participants than a full fisheye FOV. Based on this finding, the human eye FOV was utilized when calculating background luminance, glare source luminance ranges, contrast ratio, glare source sizes and locations, etc.



Fully open blinds	Roller blinds	Venetian blinds

Figure 3: Visually annoying areas marked by participants under three different lighting conditions.

As glare sensation was evaluated and collected in both a bar scale ranging from 0.0 to 3.0 and a multiple choice option of glare categories from imperceptible to intolerable glare, it was first required to accurately define glare levels for each glare category. One-way analysis of variance (ANOVA) test was performed to define glare level ranges that are strongly correlated to glare categories. The following glare level ranges were determined for each category: imperceptible glare ranges from 0.0 to 0.3, perceptible glare ranges from 0.4 to 1.4, disturbing glare ranges from 1.5 to 2.5, and intolerable glare ranges from 2.6 to 3.0. Mean values for imperceptible, perceptible, disturbing, and intolerable glare ranges are 0.05, 0.79, 1.97, and 2.84. This ANOVA test shows a P-value of 0.000 with 95% accuracy confidence. The coefficient of determination value is 93.81%, which shows that glare levels were successfully defined for glare categories.

In 153 different scenes, participants experienced various glare sensations as follows: 38.6% were imperceptible glare; 30.1% were perceptible glare; 19.6% were disturbing glare; and 11.8% were intolerable glare (Figure 4). This confirms that participants experienced the entire range of glare sensations while they performed a computer-based typing task. Percentages of visual comfort/discomfort and visual satisfaction/dissatisfaction show a quite similar pattern as well.

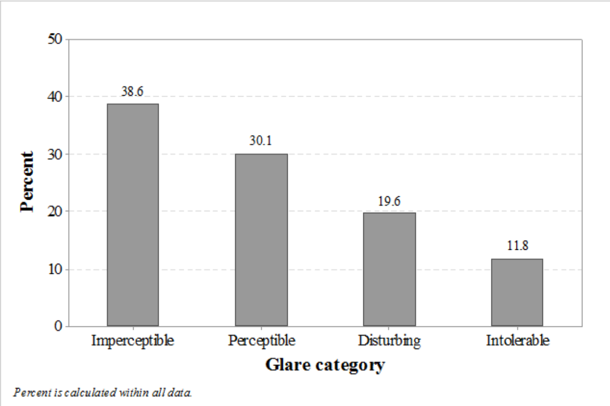


Figure 4: Percentages of glare senstations experienced by participants.

Participant's evaluations on visual comfort levels and glare categories were compared by ANOVA test (Figure 5). Imperceptible glare range is perfectly situated on the positive side of visual comfort while disturbing and intolerable glare ranges are situated on the negative side of visual comfort. Perceptible glare range is on the positive side of visual comfort while the range also includes a neutral. Based on the current data set, it is possible to claim that perceptible glare category does not represent visual discomfort. However, as the gap between the ranges of perceptible and disturbing glare exists (from 0.0 to -0.9), further study with expanded data set is required to shorten or remove the gap. It would be interesting to see if the perceptible glare range would extend to the negative side of visual comfort or it would still stop at a neutral.

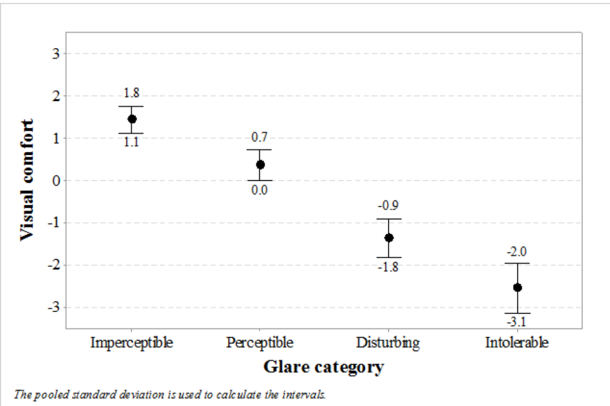


Figure 5: One-way ANOVA test between visual comfort and glare category (CI=95%, F=62.61, P=0.000, R-sq=55.76%, StDev=1.26).

Average, minimum, and maximum luminance values of glare sources were compared to glare categories by ANOVA tests. A strong correlation was found from glare source minimum luminance to glare category (CI=95%, F=76.85, P=0.000, R-sq=60.74%, StDev=2991). Different glare source minimum luminance ranges are defined for each of four glare categories and show significant differences (Figure 6). Mean values of each luminance range linearly increase as glare sensations change from imperceptible to intolerable glare. A general linear model analysis was then performed to double check whether or not the subjective responses on visual comfort and visual satisfaction are also strongly correlated to glare source minimum luminance values. It was confirmed that glare category shows the best correlation to glare source minimum luminance.

As both imperceptible and perceptible glare were on the positive side of visual comfort and satisfaction in Figure 5, it is possible to assume that a luminance value lower than 4,987 cd/m^2 does not cause visual discomfort to occupants while performing a computer-based task in a daylit office space (Figure 6). Disturbing glare is defined with a luminance range from 5,015 cd/m^2 to 8,875 cd/m^2. Intolerable glare occurs when a glare source luminance is higher than 11,719 cd/m^2. These newly defined luminance thresholds for disturbing and intolerable glare categories support the recent findings by other research groups: 5,600 cd/m^2 to 6,000 cd/m^2 for uncomfortable glare and 8,000 cd/m^2 to 10,000 cd/m^2 for intolerable glare (Wienold and Christoffersen 2005; Shin, Yun, and Kim 2012). These newly defined luminance ranges claim that a luminance value above 5,015 cd/m^2 causes visual discomfort to occupants. There is a small gap (28 cd/m^2 difference) between the perceptible and disturbing glare luminance ranges. Again, it is expected that expanded data set will shorten or remove this gap. Further study is required.

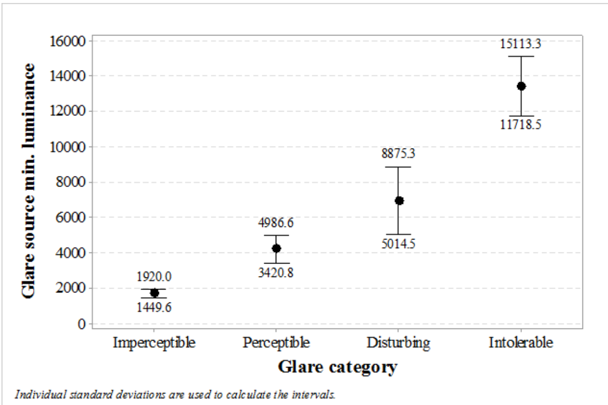


Figure 6: Interval plot of glare source minimum lumiance ranges for four glare categories.

Similar to glare source luminance ranges for different glare categories, contrast ratio ranges were also defined by ANOVA test. The test confirmed that disturbing glare occurs when a contrast ratio is beyond 39.4 between glare source average luminance and task area (computer screen) mean luminance. Intolerable glare occurs when the ratio is higher than 52.8. The ANOVA test has 95% CI and P value of 0.000 with R-square value of 42.75%. These newly defined thresholds are higher than the previously developed contrast ratio thresholds. These high contrast thresholds possibly came from the high ambient light levels in the research setting. Further study is required to investigate contrast issue in different lighting environments (with a lower window to wall ratio).

Based on the newly defined glare source minimum luminance and contrast ratio thresholds, the following scatter plot was created (Figure 7). Imperceptible glare scenes are mostly plotted on the bottom left of the graph while disturbing and intolerable glare scenes are dominant in the upper right of the graph. Interestingly, perceptible glare scenes are widely scattered. It is required to check how the scenes with high luminance and contrast ratios were evaluated as perceptible glare. It is important to check if being neutral (0.0) in visual comfort level or having the gap (-0.9~0.0) between perceptible and disturbing glare categories is the reason for this widely scattered pattern of perceptible glare. It is also possible to see a few outliers of disturbing glare scenes plotted on the bottom left corner, which represents no discomfort glare zone. Further study is required to investigate those outliers.

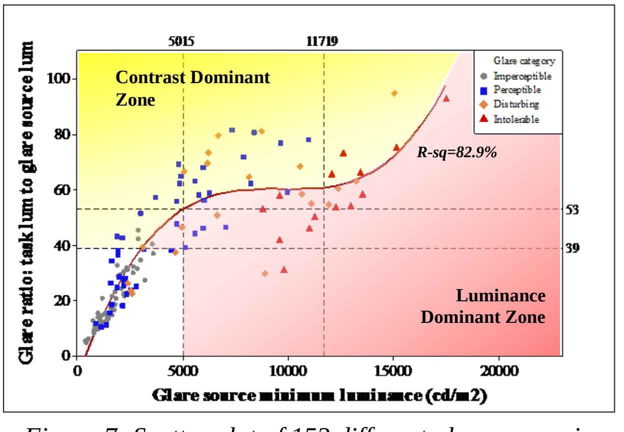


Figure 7: Scatter plot of 153 different glare scenes in absolute luminance dominant zone and contrast ratio dominant zone.

Finally, two different zones were created to graphically explain a dominant cause of each glare scene (Figure 7). The red zone at the bottom right represents absolute luminance dominant zone and the yellow zone at the top represents contrast ratio dominant zone. As each zone shows a dominant cause of discomfort glare, the zones should not include the luminance and contrast ratio thresholds of imperceptible and perceptible glare categories. Although both glare source luminance and contrast ratio are always involved together in glare scenes, one of them can be a more dominant cause than the other. The separation of the zones was made by a polynomial regression fit which has R-sq value of 82.9% with p-value of 0.000. The regression equation is as follows.

$$Glare\ ratio = -8.020 + 0.02146\ L_m - 0.000002\ L_m\text{^}2 + 0.000000\ L_m\text{^}3$$

Where L_m is glare source minimum luminance

The luminance dominant zone gradually increases and the contrast dominant zone gradually decreases as the luminance value increases. Contrast ratio becomes a more dominant factor when the glare source luminance value decreases. The plotted location of each glare scene indicates which factor is more dominant in that instance, which also allows users to determine the existence of discomfort glare in the scene. When a scene falls within the luminance dominant zone, the scene's glare issue is caused predominantly by a luminance value rather than a contrast ratio. This approach can provide designers a potential solution of discomfort glare in a daylit space.

After the luminance dominant zone and contrast dominant zone were defined, regression analysis was performed to develop the following regression equation.

$$Daylight\ Glare\ Score\ (for\ a\ computer\text{-}based\ task) = 0.206 + 0.00016{*}L_a + 0.00337{*}R_t$$

Where L_a is glare source average luminance and R_t is the contrast ratio between task area mean luminance and glare source average luminance.

The coefficient of determination became more significant when the analysis was performed by weighting the factor of task area mean luminance. The weighted analysis has a p-value of 0.000 and R-sq value of 67.5%. As stated earlier, the scenes that fall below the luminance and contrast ratio thresholds of disturbing glare can be assumed as either imperceptible or perceptible glare scenes. Again, imperceptible and perceptible glare were defined as visual comfort or neutral. Based on a daylight glare score calculated from the formula, a glare scene can be evaluated as either visual comfort (imperceptible or perceptible glare) or visual discomfort (disturbing or intolerable glare). The threshold is 1.04. A higher score than 1.04 reports a visually uncomfortable scene and a lower score than 1.04 reports a visually comfortable scene, specifically for a computer-based typing task.

As the equation utilizes two variables only, it helps to simplify the complexity hidden behind the existing glare metrics and to provide a clear understanding of a dominant cause in different glare scenes.

In summary, the goal was to develop a simplified daylight glare analysis method without compromising analysis accuracy and consistency. The new method utilizes only two variables (luminance and contrast ratio) to help determine the existence of discomfort glare while identifying a dominant cause of the problem. Luminance and contrast ratio are always involved in any glare scene as long as a certain level of discomfort glare exists. The important question for daylighting design professionals who analyze potential visual discomfort issue is which factor is more dominant in a glare scene and to what extent? Future research continues to use the method including both luminance and contrast ratio to analyze glare, as the method would greatly improve the practicality, accuracy, and consistency of daylight glare evaluation procedures. The daylight glare evaluation procedure would thereby be more widely adopted in practice and eventually help improving occupant comfort and productivity through the harvest of natural light.

Limitations

As this is a preliminary study with a limited number of subjects and luminous conditions, it requires further research to validate the findings with a larger group of subjects and a contrast dominant research setting.

Conclusion

Daylit space was investigated to verify the process and results of discomfort glare issues inside building envelopes. Many valuable findings were deduced from the human subject study. Luminance and contrast ratio thresholds were defined for different glare categories. Using these thresholds, a graphical representation of a dominant factor causing visual discomfort was created. And, an equation to calculate daylight glare score was successfully developed by using luminance and contrast ratio. Ascertaining a dominant cause of visual discomfort will assist in an understanding of the evaluation process hidden behind the complicated formulas of the existing glare metrics and guide architectural design approaches to avoid discomfort glare issue in daylit indoor spaces. This new method can be incorporated into daylighting design and analysis process; thus, it can further help improving occupant visual comfort and building energy savings. In addition to the development of a new method, the following observations were made:

- Newly defined luminance thresholds for different glare categories support the recently developed thresholds by other research groups.
- Perceptible glare category may not represent visual discomfort. Further study is required.
- The human eye FOV can accurately detect glare source sizes and locations when a glare scene includes occupant's computer-based typing task.

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