Mechanisms for discomfort glare in central vision

Gary Bargary*, Yingxin Jia & John L. Barbur

Applied Vision Research Centre, School of Health Sciences,
City University London, Northampton Square, London EC1V 0HB

*Corresponding author
Tel: 02070 40 8331
Email: gary.bargary.1@city.ac.uk

Word count: 3738 (excluding title, legends and references)

This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) (Grant reference numbers; EP/G044538/1 and EP/I003940/1).

Abstract

Purpose

The presence of a bright light source in the visual field can generate visual discomfort. Based on empirical observations we can predict to a reasonable degree of accuracy how uncomfortable a given lighting installation is likely to be; yet very little is known about the mechanism or physiological underpinnings that lead to visual discomfort. This study attempts to elucidate some of the underlying mechanisms by controlling the amount of light reaching the retina and by varying photometric properties of the glare-source.

Methods

The participants were required to view a source of light presented against a simulated residential-street background in the form of uniform flashes of light of varying intensity. Discomfort-glare thresholds were estimated using a staircase procedure; the dependent variable was retinal illuminance. The size of the glare-source and the luminance of the surrounding background were varied systematically.

Results

Across glare-source sizes or background luminances the discomfort-glare threshold varied less in terms of retinal illuminance than it did in terms of pupil-plane illuminance or light flux. A two-stage model based on saturation of photoreceptors followed by summation of an edge response signal that defines the edges of the glare-source accurately predicted the data.

Conclusions

Discomfort glare in central vision is more closely associated with the spatial properties of the glare-source, such as contrast-defined edges, than the overall amount of light entering the eye. The results suggest that discomfort glare in lighting installations could be reduced while maintaining adequate illuminance levels by an appropriate choice of illuminant source size.

Introduction

When a person views a light source that is sufficiently bright they may experience glare. There are two aspects to glare that emerged largely from empirical observations and were first described formally by Stiles and his colleagues [1]; the first is concerned with how a glare source affects the visibility of other objects in the visual scene [2,3] primarily through the role of scattered light [4–6], whereas the second examines how a glare source can distract, annoy or hinder the observer, without necessarily affecting visibility or visual performance [7]. The first of these topics is known as disability glare and by its nature has been more straightforward to define and study. The second topic is known as discomfort glare and has proved more problematic in both definition and study [8]. The lighting industry, in an attempt to minimise glare, has studied both of these phenomena and a number of metrics have arisen in an attempt to quantify them [9]. However, in elucidating the underlying mechanisms, the study of disability glare has been the more successful. It is well understood how forward-light scatter by the ocular media results in a veil of light over the retina, which reduces the contrast of the retinal image [10], and in certain conditions can impair vision [11,12]. Yet very little is understood about the mechanism or physiological underpinnings of discomfort glare.

The majority of studies on discomfort glare have focused on how different properties of the glare source affect discomfort. Glare source luminance [7,13], angular size [14], eccentricity from the observer [2,14,15], spectral content [16,17], arrangement of the glare source (or sources) and illuminance in a defined plane have all been investigated [18,19]. Measures of discomfort are typically obtained as either a rating on a 9-point scale, known as the De Boer scale [20] or by method of adjustment, whereby the observer adjusts the intensity of a glare source to the borderline between comfort and discomfort (BCD) [14]. Many of these studies have been concerned with road lighting or interior lighting, and they have led to the introduction by the CIE of a number of glare-index metrics, which attempt to quantify the level of discomfort for a given lighting installation [21,22]. The metrics involve a weighting between glare source luminance, glare source size and surrounding or background luminance. The various weightings have been estimated empirically and generally, for a given source and background luminance, increasing the size of the source increases the discomfort, but to a much lesser extent than can be achieved by increasing source luminance [8]. Little

has been said from a physiological perspective about why in many scenarios source luminance, rather than total light flux, has a greater role in inducing discomfort; the detection of each would involve different retinal and neural mechanisms [23]. Determining more precisely the contributions of source luminance and overall light flux may shed light on the mechanisms underlying discomfort glare.

There have been a number of attempts to link discomfort glare with certain physiological indices. Early work focused on pupil size fluctuations [24], particularly pupillary hippus (an involuntary, rhythmic spasm of the pupil) [25,26], however, later work showed little correlation with pupil size fluctuations and discomfort glare [27]. More recent studies employing electromyographic techniques (EMG) have examined facial muscle activity under conditions of discomfort and suggested that EMG could be used as an objective test for discomfort glare [28,29]. Stringham and colleagues employed similar techniques [17,30] and based on their findings regarding spectral sensitivity to discomfort glare [31,32] suggest that the most likely physiological mechanism is input from intrinsically-photosensitive retinal ganglion cells (ipRGC's) to the trigeminal system [32].

A different line of research has revealed that visual scenes departing from natural image statistics result in higher visual discomfort [33–35] which is thought to be caused by hyper-excitability of neurons in response to unnatural stimuli [34,36,37]. High-luminance light sources typically employed in discomfort glare studies are likely to cause hyper-excitability or saturation of a given set of neurons. However, in assessing potential physiological mechanisms for visual discomfort one needs to be aware of the large variability in the stimuli that can induce it [8]; it is quite likely that different mechanisms would underlie a visual discomfort response arising from a small centrally-viewed glare source, than from one that dominates the whole field of view.

This study measures discomfort glare thresholds for high-luminance LED light-sources viewed centrally. Pupil diameter was measured throughout allowing precise quantification of the amount of light reaching the retina. Discomfort glare thresholds were estimated using a staircase procedure. The size and surrounding background luminance of the glare source were varied systematically. To limit visual adaptation, the glare stimuli were presented as brief flashes. A simple model based on the saturation of retinal transduction mechanisms will be put forward to explain the results.

Methods

Participants

The sample for the primary experiment examining the effect of glare-source size on discomfort glare thresholds consisted of 53 participants. Prior to the experiment the participants undertook an ocular examination, which was conducted by an optometrist on-site. Based on the results of this examination three of the 53 participants were excluded; exclusion criteria included the presence of ocular disease, damage, intraocular lenses or surgery. The final sample all had normal or corrected-to-normal visual acuity and consisted of 28 males and 22 females, with an age range of 21-73 years.

A smaller separate sample of 12 participants took part in a second study to examine the effects background luminance on discomfort glare thresholds. This group had an age range of 25-35 years and was composed of 6 males and 6 females. All 12 participants had normal or corrected-to-normal visual acuity.

The complete study was approved by the Ethics Committee at City University London, and adhered to the principles of the Declaration of Helsinki. All participants provided written consent to take part in the study.

Stimuli and apparatus

The glare source used in the experiments consisted of a 4-primary LED unit (produced by PerkinElmer). A light homogeniser was mounted in front of the LED to ensure uniform luminance over a disc of ~30 mm diameter. The glare source unit was placed over a hole drilled into a large board, which was covered with a print of a residential street at night. When viewed from the front, the subject saw the glare source as a disc of light on one side of the street in the middle of the scene. A multi-aperture wheel under computer control was placed between the glare source and the board and allowed selection of glare source size. The chromaticity of the LED was set to a neutral chromaticity of x = 0.305, y = 0.323 (CIE 1931 chromaticity space). Conventional lamps were used to vary the ambient luminance of the surrounding area. The whole unit was in an otherwise darkened room.

The participant was seated 60 cm from the glare source. An infrared (IR) sensitive, 50 Hz Pulnix camera was mounted on an optics bench to the left of the

participant to record pupil diameter. The camera was synchronised with a pulsed, IR illumination system designed to produce a dark pupil. The pupil diameter was computed in real time using the programs developed for the P_SCAN system [38]. The glare source stimulus had a duration of 300 ms. 600 ms prior to stimulus onset, three dim, 50 ms flashes separated by 100 ms were used to attract the observer's point of regard.

The purpose of the study was to investigate the effects of two variables: target size and background luminance. Five different target sizes, 0.28°, 0.62°, 1.04°, 1.33° and 1.73°, were used; all were presented at the fovea and the background luminance was set to 2.6 cd/m^2. To investigate the effect of background luminance, three background luminances, 0.26 cd/m^2, 2.6 cd/m^2 and 26 cd/m^2 were used; the source size was kept constant at 1.33° and, again, all targets were presented at the fovea.

Procedure

The discomfort glare threshold was estimated using a two-alternative forced choice procedure. After viewing the stimulus, the observer indicated the presence or absence of discomfort using a keypad. The stimulus intensity was modulated according to a 1-up-1-down staircase; the step size was reduced at each of the 9 reversals used. The mean of the last 6 reversals was taken as the discomfort glare threshold. Log retinal illuminance was used as the dependent variable for the staircase. To accomplish this, pupil diameter was measured prior to stimulus onset; this value was used when setting the stimulus intensity in order to provide the required retinal illuminance.

Results

Glare source size

Mean discomfort glare thresholds from a group of 50 participants are shown in Figure 1(a). The discomfort glare thresholds are given in terms of retinal illuminance (log Td) and pupil plane illuminance (log lx). As the glare-source size increases, there is a corresponding, rapid increase in discomfort glare thresholds, when defined in terms of pupil plane illuminance; conversely, when discomfort glare thresholds are defined in terms of retinal illuminance, an opposite, but more gradual trend is observed. Both of these trends are highly significant. A one-way repeated measures ANOVA, with source size as the factor, was carried out for both dependent variables, retinal illuminance and pupil plane illuminance, and each show a significant main effect of source size, $F(4, 196) = 13.262$, $p < 0.001$, $F(4, 196) = 132.608$, $p < 0.001$, respectively. Also, the discomfort-glare thresholds in terms of flux entering the eye (not shown) had the same trend as that observed in the pupil plane illuminance results, this is because the mean pupil diameters differed little between source sizes. The mean pupil diameters were 4.71, 4.56, 4.51, 4.41 and 4.41 mm for the glare-source diameters of 0.28°, 0.62°, 1.04°, 1.33° and 1.73°, respectively

A similar pattern of results was observed in one participant tested repeatedly over a number of days, shown in Figure 1b. The data points represent the mean discomfort glare thresholds of six independent runs at each glare-source size used. Like the mean data, significant main effects of source size are present in the individual data when both retinal illuminance, $F(4, 20) = 3.347$, $p < 0.05$, and pupil plane illuminance, $F(4, 20) = 62.227$, $p < 0.001$, are used as dependent variables. The individual data presented in Figure 1(b) also illustrates the low within subject variation at each particular source size. In contrast to the low variation present in the individual data, there is substantial variation amongst observers in their discomfort glare thresholds at each source size. Figure 1(c) shows a histogram of the deviations from the mean for all source sizes in terms of retinal illuminance; the deviations are calculated separately for each source size, using the corresponding mean for that particular source size. The distribution is close to normal when expressed in terms of log retinal illuminance, and individual subjects can differ by just over one log unit with respect to the mean. However, individual participants show the same trend as observed in the mean data, regardless of large differences in their discomfort glare thresholds, see Figure 1(d).

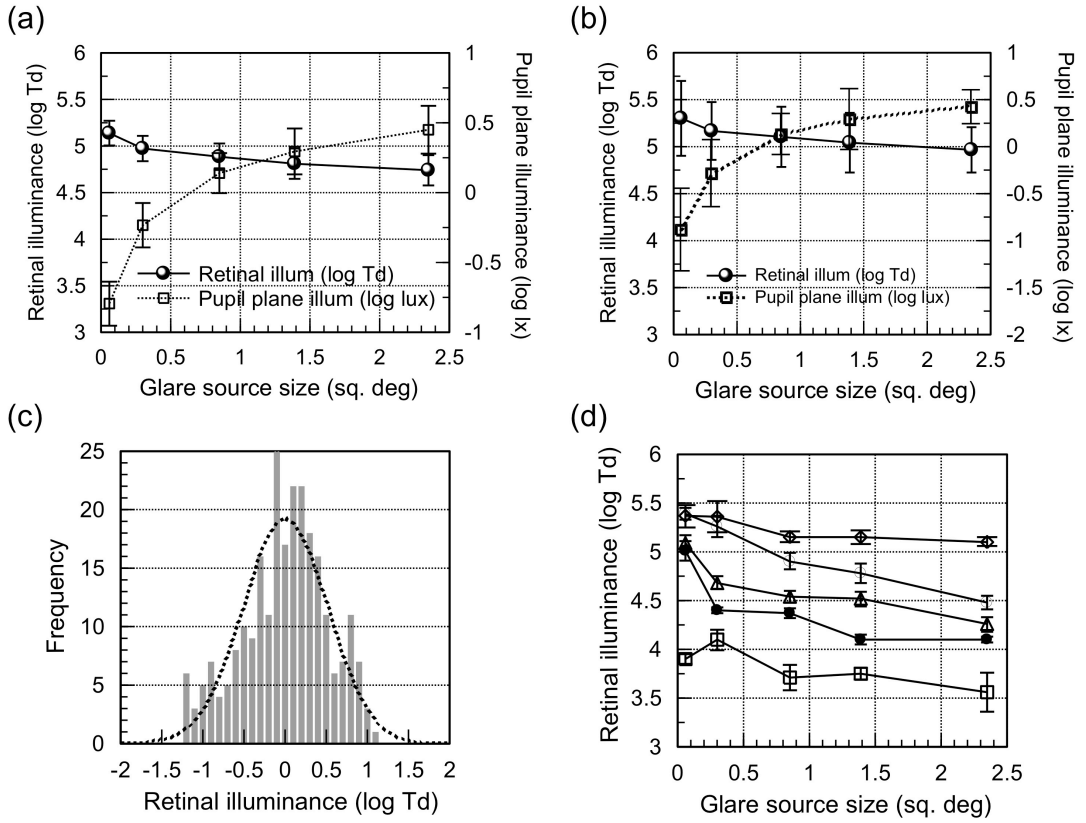

Figure 1. Source size and discomfort glare thresholds. (a) Mean discomfort glare thresholds for 50 observers. For each participant, thresholds were obtained at five different glare-source sizes and each threshold is the average of four interleaved staircases. Thresholds are given in terms of retinal illuminance (log Td) and pupil plane illuminance (log lx). The error bars represent ±2 SE. (b) Discomfort glare thresholds at different sources sizes for one young observer. Each point represents the mean of six independent runs carried out on separate occasions; each run consisted of four interleaved staircases. The error bars represent ±2 SD. (c) Histogram of the deviations from the retinal illuminance mean data shown in (a). As the means differed between source sizes the deviations were calculated separately for each source size. (d) Inter-individual variation in discomfort glare thresholds. Thresholds for five observers from the sample of 50 are shown, illustrating large inter-individual variation. The error bars represent ±2 SD.

The effect of age and sex on discomfort glare

To investigate the effect of age on thresholds for discomfort glare, the retinal illuminance data from 50 participants was binned into 5 age groups: 21-30, 31-40, 41-50, 51-60 and 61-80 years. A one-way between subjects ANOVA, with age as the factor, was carried out on the binned data, revealing no main effect of age on discomfort glare thresholds, $F(4, 45) = 0.563$, $p = 0.691$. The binned age data are shown in Figure 2.

Similarly there was no effect of sex on the discomfort glare thresholds in terms of retinal illuminance, $t(48) = 0.318$, $p = 0.752$.

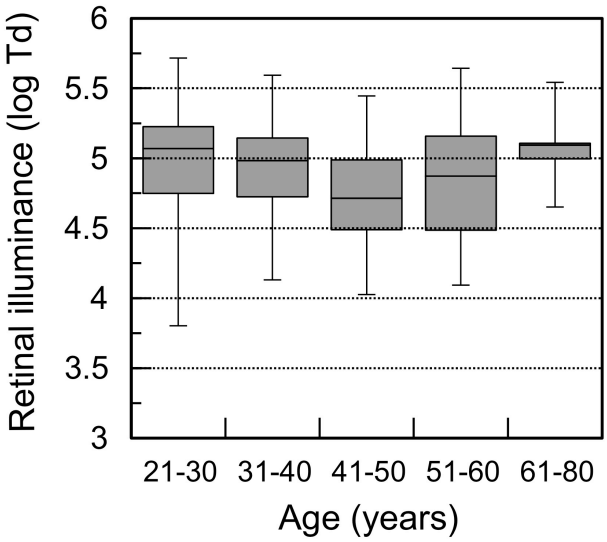

Figure 2. Discomfort glare thresholds and age.

Discomfort glare thresholds plotted as a function of age. Mean thresholds were calculated for every subject by averaging the results measured for each of five glare source sizes. The results are shown for subjects within each age group; the box shows the median and the interquartile range (first and third quartiles) and the whiskers represent the range of the data. Discomfort glare thresholds appear to be independent of age.

Effect of background luminance

Figure 3 shows the effects of background luminance on discomfort glare thresholds. Each data point represents the mean threshold in terms of retinal illuminance for 12 participants. The results show an increase in discomfort glare thresholds with background luminance. This was confirmed as significant using a repeated measures ANOVA test, $F(2, 22) = 9.001$, $p < 0.01$.

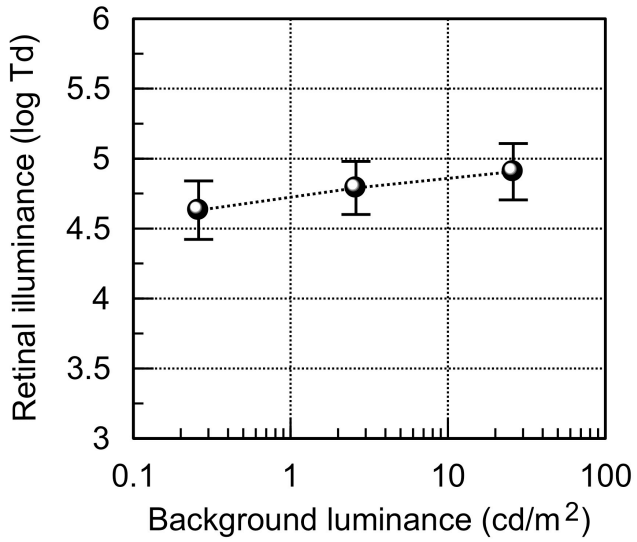

Figure 3. Mean discomfort glare thresholds measured for a sample of 12 participants for three background luminances: 0.26, 2.6 and 26 cd/m^2. There is a significant increase in discomfort glare thresholds with background luminance.

Light scatter and effective retinal illuminance

Light from a glare source is scattered by the optics of the eye causing a reduction in retinal illuminance over the glare source. This reduction is more pronounced for smaller light sources because a higher proportion of scattered light falls outside the light source. The 'effective' retinal illuminance of the target i.e. the actual retinal illuminance on the retina in the region of the target, was estimated by convolving the point spread function of the human eye [5,39] with simulated target images. There was, as expected, a larger difference between the effective retinal illuminance and the measured retinal illuminance for smaller source sizes. However, the significant trend of smaller source sizes having higher discomfort glare thresholds is still maintained, $F(4, 196) = 7.442$, $p < 0.001$.

An additional consideration in relation to the reduction of effective retinal illuminance is the directional sensitivity of the cone photoreceptors [41]. Accounting for the Stiles-Crawford effect, however, had little impact on the results (there was less than a 2% difference between the largest and smallest source size), as the mean pupil diameters for each source size were similar.

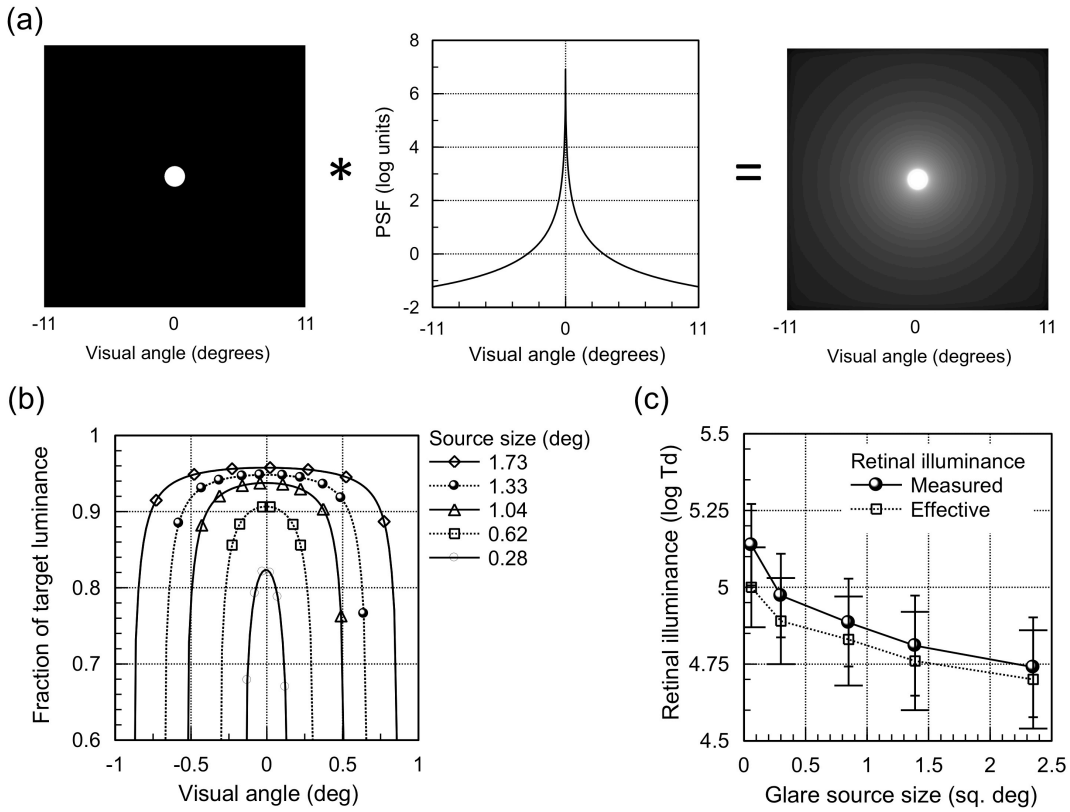

Figure 4. Light scatter and effective retinal illuminance. (a) The effective retinal illuminance for each participant was estimated by convolving a simulated glare source with the point spread function of the human eye. (b) The horizontal luminance profile of the five source sizes tested after convolution. In the target region smaller source sizes have a larger reduction in retinal illuminance due to light scatter. (c) The threshold for discomfort glare is plotted in terms of the measured and effective retinal illuminance of the target. The thresholds are lower in terms of effective retinal illuminance, particularly for smaller sources sizes, however the significant trend of smaller source sizes having higher discomfort glare thresholds is maintained.

Discomfort glare and saturation

The mean discomfort-glare thresholds for each glare-source size differed less in terms of effective retinal illuminance than in terms of pupil plane illuminance (which determines the total light flux entering the eye), the largest differences being 0.30 and 1.25 log units, respectively. We hypothesized that discomfort glare could be the result of saturation or hyperexcitability of visual mechanisms involved in contrast vision. Typically, models of contrast vision begin with the filtering of a photoreceptor signal through centre-surround midget ganglion cells, resulting in a large response to edges within an image. A simple model is presented in Figure 5, which captures the saturation of a photoreceptor response and also accounts for the size dependence of discomfort glare thresholds by accounting for the response of ganglion cells around

the effective boundary of the source. The edge response was taken as the circumference of a photoreceptor signal image weighted by the midget ganglion cell density [42]. The eccentricity of the edge response varies as a function of light level in a disproportional manner for different source sizes. Smaller source sizes have a higher proportion of scattered light outside of the source in comparison to larger source sizes, and this results in a relatively larger edge eccentricity, or radius, in the photoreceptor signal image. The difference in gradient between the blue and red dashed lines in Figure 5(d) illustrates this effect.

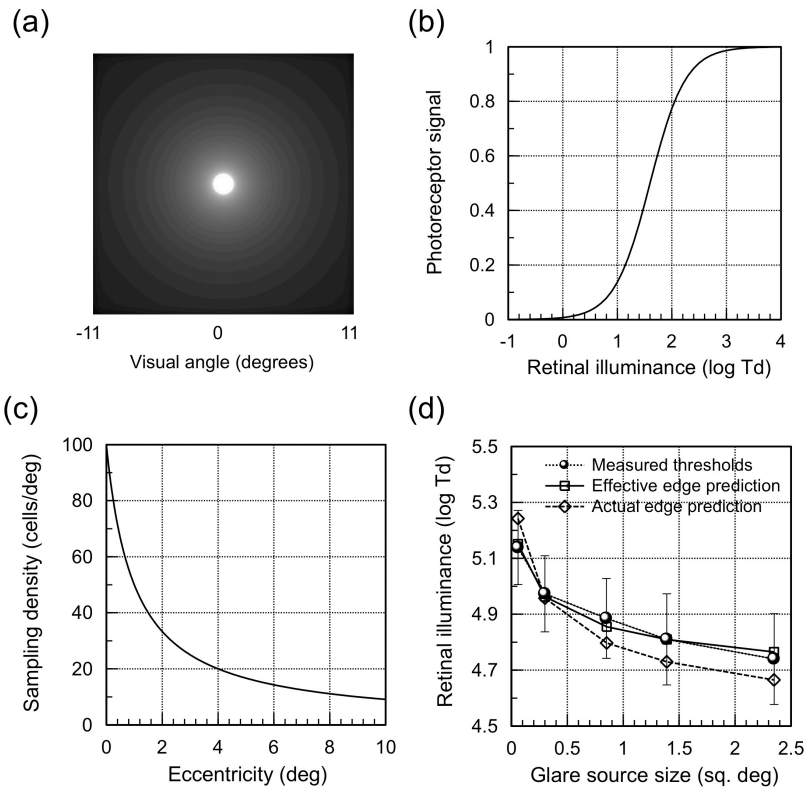

Figure 5. Discomfort glare saturation model. (a) Convolved target image with the point spread function of the eye (b) Photoreceptor response function modelled as a Michaelis-Menton function, $E^n/(E^n + \delta^n)$, E = retinal illuminance, δ = 39.81 Trolands (1.6 log Trolands) represents the half response and was based on the average background retinal illuminance, n = 1.33 resulting in approximately a 3 log-unit range response. (c) Midget ganglion cell sampling density as a function of eccentricity [42]. (d) Model predictions of discomfort glare threshold as a function of source size. The blue dashed line represents the circumference of the glare source weighted by the retinal ganglion cell density. The weighting was accomplished by multiplying the circumference of each source size by its ganglion cell density at the eccentricity of its circumference; the reciprocal for each source was then scaled so that the overall mean matched that of the measured discomfort glare thresholds. The red dashed line represents the effective edge prediction: the circumference of the target in the

photoreceptor signal image weighted by the ganglion cell density (the weighting carried out as above). The photoreceptor signal is the image generated when the convolved target image (a) is passed through the Michaelis-Menton function (b). The target image was set to the retinal illuminance at which the Michaelis-Menton function saturates: 3.5 log Trolands (corresponding to a signal of 0.997). For each source size the target radius in the photoreceptor signal image was taken as the radius at which the photoreceptor signal equalled 0.5. Each circumference, and thus effective edge, were based on such radii.

Discussion

The vast majority of studies on discomfort glare have been concerned with improving our ability to predict the discomfort level for a given lighting installation [8,43]. There has been much agreement amongst the various studies and the Unified Glare Model [44] consolidates much of what we know about how glare-source size, luminance, angular position, eccentricity and surrounding luminance affect discomfort glare ratings. However, we know very little about what mechanisms underlie each component of the Unified Glare Model. This study found that for centrally viewed light sources of different sizes the retinal illuminance, rather than illuminance at the plane of the observer, was more closely related to discomfort. The relative discomfort glare thresholds at different glare-source sizes were predicted by a simple model based on saturation of photoreceptors and ganglion cells.

Many of the results replicated what has been found previously in the literature. Discomfort glare thresholds were independent of age [45] and sex [45,46] at all glare-source sizes tested. There was large inter-individual variation [14,45] in the thresholds for discomfort. The trend for smaller source sizes having higher discomfort-glare thresholds agrees with results from the early work by Luckiesh and Guth [14,47]. These studies used a different measure of discomfort (participants adjusted the brightness of a source to the borderline between comfort and discomfort (BCD)) but, when both sets of results were expressed in terms of luminance of the source, there was agreement in both the trend and in the luminances judged to be uncomfortable. Also, as Guth and others observed, it was found that discomfort-glare thresholds tended to increase with an increase in background luminance [14,43].

In a first attempt to explain the relationship between source size and discomfort-glare thresholds, the effect of forward light scatter of the eye was

considered. Forward light scatter is the primary cause of disability glare as it reduces the contrast of the image on retina due to the addition of a veil of light [4]. In the domain of discomfort, however, it could also play a role; scattered light, particularly when the source luminance is high, could stimulate regions of the retina eccentric to the position of the light source. Also, smaller glare-sources lose more of the light from the source region than a larger glare-source, so the effective retinal illuminance is proportionally lower for small source sizes. This was indeed found to be the case, although a trend still existed where smaller source sizes had higher discomfort-glare thresholds.

Given that the discomfort-glare thresholds for different source sizes were more closely related to the retinal illuminance (a quantity proportional to the amount of light per unit area of the retina) rather than pupil plane illuminance or light flux entering the eye, a role for contrast vision was suspected. Although a mechanism for light flux detection has an important role to play in human vision and may well involve photoreceptor signals and melanopsin-driven, intrinsically-photosensitive, retinal ganglion cells (ipRGCs) at high light levels [23,48] its contribution to discomfort glare to directly viewed light-sources may be limited. Furthermore, pictorial representations of bright light sources that reproduce the appearance of glare by using saturated highlights and the gradual reappearance of spatially structured images away from the centre of the glare source can often cause a sensation of discomfort, even when projected onto screens at luminance levels that would normally be associated with comfortable viewing. These observations suggest that the sense of discomfort is more closely related to the spatial distribution of light on the retina and the corresponding changes in the appearance of objects, rather than the overall quantity of light, implying a more significant role for contrast vision.

A two-stage model, involving saturation of photoreceptors followed by estimation of an edge response, predicted relative discomfort-glare thresholds for different source sizes. The edge response was modeled by weighting the circumference of the glare-source (in the photoreceptor signal image) by the midget ganglion cell density. A similar result can be obtained using a more complex model, whereby the photoreceptor signal image is filtered through 'Difference of Gaussians' filters, which are typically used to model on-off centre surround ganglion cell activity in the retina [49]. The simpler model was preferred, given its simplicity and possible practical utility. This model can also account for the effect of background luminance

on discomfort-glare thresholds; the half-response of the photoreceptor dynamic range would be set by the surrounding or background luminance.

The model does not, however, predict an individual's discomfort-glare threshold. Each person could set their own criterion to what is uncomfortable based on the degree of saturation; this variability in criteria setting may account for the observed variability in discomfort-glare thresholds. Additionally, a model based on edges, and thus the circumference of a glare source, may not be suitable to account for discomfort glare thresholds in the periphery or when large sources sizes are used. A model based on saturation may still be accurate but the properties of the peripheral retina are very different than that of the fovea. The receptive fields of cone-driven retinal ganglion cells increase in size as one goes further into the peripheral retina, and rods are far more numerous, the signals of which are pooled over even larger areas of the retina by ganglion cells. Both of these effects in the periphery are not suited for detecting edges in an image, and may bias discomfort glare to be more associated with pupil plane illuminance rather than luminance defined edges. Indeed, results presented by Luckiest and Guth [14] found that the BCD luminance increased with horizontal eccentricity; there was over a 6-fold difference between presentation at the fovea to that at 80 degrees, using the same glare-source. However, BCD's in terms of pupil plane illuminance (our calculations) differed by no more than 0.22 log units across all eccentricities up to 80 degrees. Moreover, at 80 degrees the BCD pupil plane illuminance was nearly equivalent to the foveal presentation.

Saturation or hyperexcitability has already been implicated in a number of phenomenon related to discomfort glare, such as visual discomfort [34,37], photophobia [50,51] and light-induced migraine [52–54]. Hyperexcitability is thought to relate to visual discomfort through a homeostatic process [36]. Cortical areas that are hyperactive have a higher metabolic demand and it is suggested that the discomfort itself is a homeostatic response, which may initiate certain behavior that will reduce the metabolic load [36,37]; the metabolic demands of neuron firing and synaptic transmission are quite substantial [55,56].

The findings from this study suggest that photoreceptor saturation plays a key part in determining discomfort glare thresholds. Forward light scatter in the eye is also important since it reduces the contrast of the retinal image and it also extends the glare source boundaries by causing saturation of photoreceptor signals and the loss of spatial detail in the vicinity of the source. In addition, the amount and angular

distribution of forward scatter in the eye causes a decrease in the retinal illuminance of the glare source in a way that varies with source size. The immediate consequence of this reduction is to allow for an increase in the retinal illuminance needed to reach saturation, this may explain the absence of significant age effects, in spite of increased scatter with aging. The small but significant reduction in discomfort thresholds with increasing glare source size is well accounted for by the predicted variation in the number of ganglion cells that respond to the boundaries of the source. Although strongly related to photoreceptor saturation and the subsequent loss of spatial detail, discomfort glare thresholds reflect a subjective perceptual experience that is dependent on the subject's response criterion. It is therefore not surprising that discomfort glare thresholds vary by as much as one log unit from the mean (when expressed in terms of retinal illuminance). In spite of this variation, the relatively small dependence on glare source size may have significant implications in the design of lighting installations. The findings from this study show that desired or adequate levels of illuminance in the absence of discomfort glare could be achieved in many lighting applications through appropriate selection of source size.

Acknowledgements

The authors would like to thank Peter Raynham, Navaz Davoudian and Edward Barratt from University College London (UCL) for their collaboration, constructive criticism and recruitment of participants. We also wish to thank Alister Harlow for programming support and Ruba Alissa, both from City University, for conducting the ophthalmic examinations. This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) (Grant reference numbers; EP/G044538/1 and EP/I003940/1).

References

1. Stiles WS. The nature and effects of glare. *Illum. Eng.* 1929;22:304-312.

2. Holladay LL. The fundamentals of glare and visibility. *J. Opt. Soc. Am.* 1926;12(4):271-319.

3. Stiles WS. The Effect of Glare on the Brightness Difference Threshold. *Proc. R. Soc. B Biol. Sci.* 1929;104(731):322-351.

4. Stiles WS. The Scattering Theory of the Effect of Glare on the Brightness Difference Threshold. *Proc. R. Soc. London. Ser. B, Contain. Pap. a Biol. Character* 1929;105:131-146.

5. Van den Berg TJTP, Franssen L, Kruijt B, Coppens JE. History of ocular straylight measurement: A review. *Z. Med. Phys.* 2013;23(1):6-20.

6. Vos JJ. On the cause of disability glare and its dependence on glare angle, age and ocular pigmentation. *Clin. Exp. Optom.* 2003;86:363-370.

7. Luckiesh M, Holladay LL. Glare and visibility. *Trans. Illum. Eng. Soc.* 1925;20(3):221-252.

8. Vos JJ. Reflections on glare. *Light. Res. Technol.* 2003;35:163-176.

9. Vos JJ. Glare today in historical perspective: towards a new CIE glare observer and a new glare nomenclature. *Proc. CIE 24th Sess. Warsaw* 1999;I-1:38-42.

10. Vos JJ. On the cause of disability glare and its dependence on glare angle, age and ocular pigmentation. *Clin. Exp. Optom.* 2003;86(6):363-70.

11. De Waard PW, IJspeert JK, van den Berg TJ, de Jong PT. Intraocular light scattering in age-related cataracts. *Invest. Ophthalmol. Vis. Sci.* 1992;33:618-625.

12. Fisher AJ, Christie AW. A note on disability glare. *Vision Res.* 1965;5(9):565-71.

13. Hopkinson RG. Evaluation of glare. *Illum. Eng.* 1957;52:305-316.

14. Luckiesh M, Guth SK. Brightnesses in visual field at borderline between comfort and discomfort. *Illum. Eng.* 1949;44(11):650-70.

15. Holladay LL. Action of a light-source in the field of view in lowering visibility. *J. Opt. Soc. Am.* 1927;14(1):1.

16. Berman SM, Bullimore MA, Bailey IL, Jacobs RJ. The Influence of Spectral Composition on Discomfort Glare for Large-Size Sources. *J. Illum. Eng. Soc.* 1996;25(1):34-41.

17. Stringham JM, Fuld K, Wenzel AJ. Action spectrum for photophobia. *J. Opt. Soc. Am. A. Opt. Image Sci. Vis.* 2003;20(10):1852-8.

18. Bullough J, Brons J, Qi R, Rea M. Predicting discomfort glare from outdoor lighting installations. *Light. Res. Technol.* 2008;40:225-242.

19. Guth SK, McNelis JF. Further data on discomfort glare from multiple sources. *Illum. Eng.* 1961;56(1):46-47.

20. De Boer JB. Visual perception in road traffic and the field of vision of the motorist. In: de Boer JB, ed. *Public Lighting*. Eindhoven: Philips Technical Library; 1967:11-96.

21. CIE. Discomfort glare in the interior working environment. 1983;CIE #55.

22. CIE. Glare Evaluation System for Use Within Outdoor Sports and Area Lighting. 1994;CIE #112.

23. Lall GS, Revell VL, Momiji H, et al. Distinct contributions of rod, cone, and melanopsin photoreceptors to encoding irradiance. *Neuron* 2010;66(3):417-428.

24. Fugate JM, Fry GA. Relation of changes in pupil size to visual discomfort. *Illum. Eng.* 1956;51(7):537-549.

25. Fry GA, King VM. The Pupillary Response and Discomfort Glare. *J. Illum. Eng. Soc.* 1975;4(4):307-324.

26. Hopkinson RG. Glare discomfort and pupil diameter. *J. Opt. Soc. Am.* 1956;46(8):649-56.

27. Howarth PA, Heron G, Greenhouse DS, Bailey IL, Berman SM. Discomfort from glare: The role of pupillary hippus. *Light. Res. Technol.* 1993;25:37-42.

28. Berman SM, Bullimore MA, Jacobs RJ, Bailey IL, Ghandi N. An objective measure of discomfort glare. *J. Illum. Eng. Soc.* 1994;23(2):40-49.

29. Murray I, Plainis S, Carden D. The ocular stress monitor: a new device for measuring discomfort glare. *Light. Res. Technol.* 2002;34(3):231-242.

30. Stringham JM, Fuld K, Wenzel AJ. Spatial properties of photophobia. *Invest. Ophthalmol. Vis. Sci.* 2004;45(10):3838-48.

31. Stringham JM, Garcia P V, Smith PA, McLin LN, Foutch BK. Macular pigment and visual performance in glare: benefits for photostress recovery, disability glare, and visual discomfort. *Invest. Ophthalmol. Vis. Sci.* 2011;52(10):7406-15.

32. Stringham JM, Snodderly DM. Enhancing performance while avoiding damage: a contribution of macular pigment. *Invest. Ophthalmol. Vis. Sci.* 2013;54(9):6298-306.

33. Fernandez D, Wilkins AJ. Uncomfortable images in art and nature. *Perception* 2008;37(7):1098-113.

34. Juricevic I, Land L, Wilkins A, Webster MA. Visual discomfort and natural image statistics. *Perception* 2010;39(7):884-99.

35. O'Hare L, Hibbard PB. Spatial frequency and visual discomfort. *Vision Res.* 2011;51(15):1767-77.

36. Wilkins A, Nimmo-Smith I, Tait A, et al. A neurological basis for visual discomfort. *Brain* 1984;107 (Pt 4:989-1017.

37. Haigh SM, Barningham L, Berntsen M, et al. Discomfort and the cortical haemodynamic response to coloured gratings. *Vision Res.* 2013;89:47-53.

38. Alexandridis E, Leendertz A, Barbur JL. Methods for studying the behaviour of the pupil. *J. Psychophysiol.* 1991;5(3):223-239.

39. Vos JJ, van den Berg TJ. Report on disability glare. *CIE Collect.* 1999;#135:1-9.

40. Van den BergT. J., Coppen JE, Franssen L. Ocular media clarity and straylight. In: Dartt DA, ed. *Encyclopedia of the Eye*. Oxford: Academic Press; 2010:173–183.

41. Stiles WS, Crawford BH. The luminous efficiency of rays entering the eye pupil at different points. *Proc. R. Soc. London. Ser. B, Contain. Pap. a Biol. Character* 1933;112:428-450.

42. Curcio CA, Allen KA. Topography of ganglion cells in human retina. *J. Comp. Neurol.* 1990;300:5-25.

43. Vermeulen D, de Boer JB. On the admissible brightness of lighting fixtures. *Appl. Sci. Res. Sect. B* 1952;2(1):85-107.

44. CIE. Discomfort Glare in Interior Lighting. 1995;CIE #117.

45. Saur RL. Influence of physiological factors on discomfort glare level. *Am. J. Optom. Arch. Am. Acad. Optom.* 1969;46(5):352-7.

46. Bennett CA. The demographic variables of discomfort glare. *Light. Des. Appl.* 1977;7(1):22-24.

47. Luckiesh M, Guth SK. Discomfort glare and angular distance of glaresource. *Illum. Eng.* 1946;41:485-92.

48. Brown TM, Tsujimura SI, Allen AE, et al. Melanopsin-based brightness discrimination in mice and humans. *Curr. Biol.* 2012;22:1134-1141.

49. McCann B, Geisler W, Hayhoe M. Decoding natural signals from the peripheral retina. *J. Vis.* 2011;11:1193-1193.

50. Boulloche N, Denuelle M, Payoux P, Fabre N, Trotter Y, Géraud G. Photophobia in migraine: an interictal PET study of cortical hyperexcitability and its modulation by pain. *J. Neurol. Neurosurg. Psychiatry* 2010;81(9):978-84.

51. Denuelle M, Boulloche N, Payoux P, Fabre N, Trotter Y, Géraud G. A PET study of photophobia during spontaneous migraine attacks. *Neurology* 2011;76(3):213-8.

52. Coutts L V, Cooper CE, Elwell CE, Wilkins AJ. Time course of the haemodynamic response to visual stimulation in migraine, measured using near-infrared spectroscopy. *Cephalalgia* 2012;32(8):621-9.

53. Cucchiara B, Datta R, Aguirre GK, Idoko KE, Detre J. Measurement of visual sensitivity in migraine: Validation of two scales and correlation with visual cortex activation. *Cephalalgia* 2014.

54. Hougaard A, Amin FM, Hoffmann MB, et al. Interhemispheric differences of fMRI responses to visual stimuli in patients with side-fixed migraine aura. *Hum. Brain Mapp.* 2014;35(6):2714-23.

55. Attwell D, Laughlin SB. An energy budget for signaling in the grey matter of the brain. *J. Cereb. Blood Flow Metab.* 2001;21(10):1133-45.

56. Howarth C, Gleeson P, Attwell D. Updated energy budgets for neural computation in the neocortex and cerebellum. *J. Cereb. Blood Flow Metab.* 2012;32(7):1222-32.