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The ocular stress monitor: a new device for measuring discomfort glare

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Discomfort glare is always accompanied by a strong contraction or spasm in the muscles surrounding the eye. A portable device for measuring the electrical activity generated by this muscle spasm is described. The device samples the signal from electrodes placed around the eye. It is composed of a narrow-band amplifier/transmitter, a receiver/frequency converter and a tone generator. The signal amplitude is proportional to the vertical illuminance at the eye and can therefore be used as an objective index of the discomfort induced. The results compare favourably with subjective assessment.

1. Introduction

Light sources of excessive brightness or uneven distribution in the field of view can cause discomfort glare of varying degrees from a mild sensation to an intolerable feeling of pain. Discomfort glare is an important aspect of lighting design and much research effort has been concentrated on its measurement. For the most part, the phenomenon has been characterized using the subjective judgements of panels of expert observers who have ranked glare sources of different luminance according to the discomfort sensation they induce.[1–3] The equations derived from these experiments have been used to draw up guidelines for lighting installations such as the Glare Index[4] and the Unified Glare Rating system.[5]

Although it is relatively easy to perceive the sensation and elicit a graded response to the presence of a glare source, the precise physiological origin of the pain experienced remains obscure. Some have considered the activity of the pupil as a candidate because it is richly invested with pain receptors. Hopkinson[6] claimed that, for a variety of stimulus configurations and intensities, the subjective sensation of glare is not related closely to the variations of pupil size, but was due to the opposing (antagonistic) actions of the dilator and sphincter muscles, which attempt to adjust the pupil to the conflicting requirements of the retina when simultaneously exposed to a bright glare source and low background illuminance. This was supported by similar findings[7] which showed that at high background lighting levels the eye becomes adapted to the brighter levels and tolerates a higher level of luminance without discomfort. Furthermore, Hopkinson[6] and Fry and King[8] reported that the pupil becomes unstable in conditions producing discomfort glare, implying that the dynamic characteristics of pupillary hippus (the involuntary changes of pupil size of a normal healthy eye under steady lighting conditions are commonly known as 'hippus'. This physiological pupillary unrest is presumed to be due to the antagonistic activity of sympathetic and parasympathetic innervation of the iris muscles) are exaggerated under discomfort glare conditions. However, recent attempts[9] to verify possible changes in the temporal characteristics

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of hippus when discomfort and no discomfort was present, showed no differences, even when the reported discomfort was nearly intolerable. Howarth *et al.*[9] concluded that it is very unlikely that discomfort glare could be associated with pupillary hippus.

Regardless of its origin, discomfort glare is always accompanied by a strong flinch reflex in the extra-ocular (facial) muscles surrounding the eye (i.e., the *orbicularis occuli*, which is the principle muscle responsible for closing the eye, and other nearby muscles such as the *corrugator supercilii*). Muscles spontaneously generate easily measured electrical activity which can be monitored using small electrodes. The intensity of this activity, called the electromyogram (EMG) increases when a bright light is directed toward the eyes and this change in activity has been used as an indicator of the severity of discomfort.[10–13] In all of these studies, the signals were amplified using broad-band physiological amplifiers. The signal amplitude increased across a wide range of temporal frequencies in the presence of a glare source. Murray *et al.*[12] showed that, under dim viewing conditions and for constant stimulus size, the signal strength increased almost linearly with the log of the luminance of the glare stimulus.

One of the limiting factors to the utility of this objective approach to the assessment of glare is that the method is confined to a laboratory environment because of the delicacy and non-portability of the amplifiers. This paper describes the development and testing of a device composed of a portable transmitter and narrow-band amplifier. The device is capable of monitoring the activity of the extra-ocular muscles remotely under many different viewing conditions ranging from motorways to offices. Objective EMG-based data are compared with conventional subjective measurements. The new device is referred to as the Ocular Stress Monitor (OSM).

2. Methods

2.1 Subjects

EMG-based glare responses were obtained from two groups of subjects. For the first group (10 subjects, aged 19–24) only the broad-band, Medelec amplifier was used. For the second group (six subjects, aged 24–49) some responses were obtained using both the Medelec and the OSM simultaneously.

All subjects were established as having no ophthalmological or neurological abnormalities. No glasses or contact lenses were used. Three of the subjects (SP, IJM, LG) had participated previously in eyelid recording experiments.

2.2 Electrophysiological recording

Electrical activity of the extra-ocular muscles was recorded using two small surface electrodes (e.g., Ag–AgCl) positioned one below the lower eye lid (active electrode) and the other lateral to the eye but as close as possible to the edge of the eye (reference electrode). Electrode impedances were maintained below 10 KΩ. A third electrode, placed on the forehead served as a ground. Electrode locations are illustrated in Figure 1.

The EMG signal from the electrodes (approximately 100 μV) could be fed into the OSM, described below, and a Medelec Sensor amplifier simultaneously. The Medelec has variable gain (usually 6–10 K was used) and bandwidth 10–250 Hz. The signal from the Medelec was digitized using a CED 1401 (CED Electronics, Cambridge, UK) smart interface at 512 Hz.

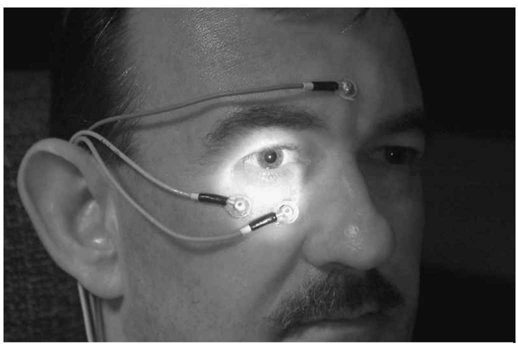

Figure 1 The location of electrodes. The active electrode is placed below the lower eye lid. The reference is at the temporal margin. The forehead electrode acts as earth

2.3 The Ocular Stress Monitor (OSM)

The new EMG processor consists of two units, one of which is illustrated in Figure 2:

i) a radio transmitter unit which incorporates an input amplifier and a narrow band filter (see Figure 2a), and
ii) a separate receiver unit which contains low and high pass filters which give the narrow-band tuning characteristics illustrated (see Figure 2b), a peak detector and integrator, a tone generator output buffer amplifiers and a small loudspeaker. The receiver is tuned to the same frequency as the transmitter.

2.3.1 Input amplifier

The input amplifier is a simple commercially available device with a common mode rejection of 130 dB and input impedance greater than 1000 MΩ. To minimize saturation problems, some bandpass pre-filtering was used and the gain of the first stage was designed to optimize signal-to-noise ratio.

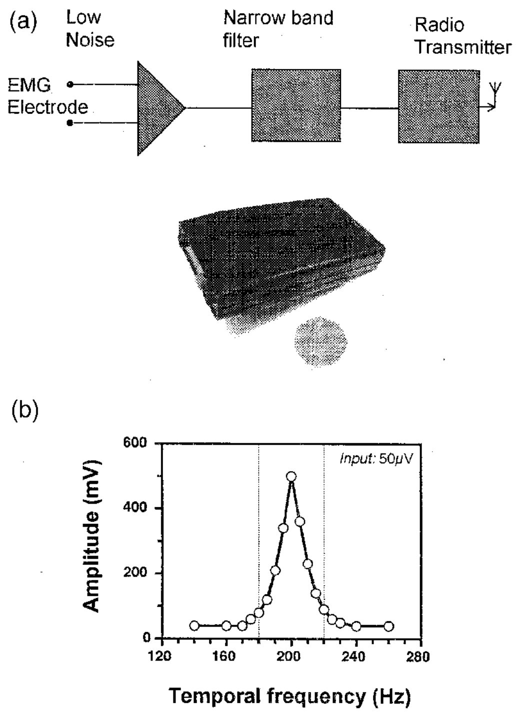

Figure 2 The OSM. (a) Schematic diagram of the pre-amplifier, filter and transmitter unit accompanied by a photograph of the unit. (b) Frequency characteristics of the unit, illustrating the half-height band-width of 180–220 Hz

2.3.2 Narrow band filter

A stable narrow band filter, tuned to 200 Hz, with a half-height bandwidth of 20 Hz (see Figure 2b) was achieved using a multi-order continuous time active filter. The overall system gain was approximately 5000. Signals from this device were integrated using a 1 s time constant and this voltage was converted to frequency in the range 200–1500 Hz so that it produced an audible tone which varied with the amplitude of the EMG. In this way the response of the observer to varying intensities of glare source could be constantly monitored.

2.4 Procedure

The glare stimulus was a projector fitted with a 150 W tungsten lamp, which was directed towards the subject. The glaring effect of the lamp was determined in terms of vertical illuminance (lux) at the subject's cornea and was varied between 20 and 6000 lux. The aperture of the projector was masked so that for all experiments the stimulus subtended 1.2 degrees at the 1140 mm viewing distance. Subjects sat in a darkened room and fixated a dim red LED placed at 5 degrees peripherally to the glare stimulus. Typically EMG activity was recorded for a 4-s period after the onset of the glare stimulus. Stimulus onset period was variable, but 2 s was used. The stimulus onset and the start of EMG data sampling were electronically timed to be simultaneous. Before each presentation of the glare stimulus, the spontaneous EMG activity (noise) was sampled for 4 s with the subject in a relaxed state and with eyes open. A recovery period of at least 1 min was allowed between successive trials. Natural pupils were used.

2.5 Data analysis

Most of the data in this report are derived from performing a fast Fourier transform (FFT) (2048 points sampled at 512 Hz) on the raw data from the OSM using a standard software package. With the 4-s epoch this gives a resolution of 0.25 Hz/bin. The strength of the response was calculated from the area under the frequency spectrum. The advantage of this approach is that energy at specific frequencies can be digitally filtered off-line. When using the OSM however, this procedure is not necessary because of the tuning characteristics which have been selected. The choice of 180–220 Hz was made for the following reasons:

i) the signal/noise ratio is favourable for most subjects in this region
ii) minimal interference due to UK mains supply (50Hz) and its harmonics and
iii) this frequency range can readily be stored as an audio tone.

2.6 Subjective estimate of glare

Subjective assessment of glare was conducted in a conventional way. Subjects were asked to grade the intensity of perceived glare on a 10-point scale. Instructions and the scale were given to subjects in advance of each experiment and pre-training in applying the various criteria was given. During the pre-training session subjects experienced all intensity levels and the criteria were reinforced. In particular, they were shown the two extreme conditions of discomfort which were classified as follows; a grade '1' indicating no glare sensation and the opposite extreme – grade 10 in which the subject could not avoid closing his/her eyes. Objective and subjective ratings were assessed in a single experimental session. The subjective rating was indicated verbally immediately following the 4-s period of EMG recording

3. Results

Figure 3 illustrates the effect of a glare stimulus on the EMG obtained using the broad-band Medelec amplifier. The data are represented in the frequency domain and averaged across 10 subjects. As discussed earlier, the increase in power derived from the FFT (absolute units are microvolts squared – the power at all frequencies

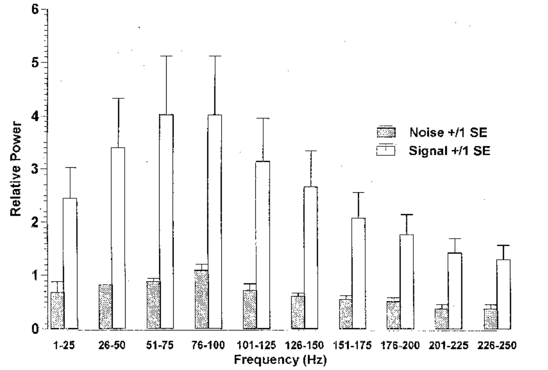

Figure 3 Mean power spectra and standard errors obtained from the Medelec (broad-band) amplifier for signal and noise condition ($N = 10$). Corneal illuminance was 120 lux

is normalized with respect to maximum) resulting from the glare stimulus is more or less evenly distributed across all frequencies. In fact the best signal-to-noise ratio, r (defined as $r = s/n$ where s and n are signal and noise) was obtained for 51–75 Hz, but this was regarded as unsuitable because it is close to UK mains frequency. At 176–200 Hz, $r = 3.47$, and at 201–225 Hz, $r = 3.76$, and these were selected as optimum for the OSM for the reasons outlined in Section 2.5.

Figure 4 illustrates the advantage of using the narrow-band OSM compared with the Medelec broad-band amplifier. The Medelec reveals low frequency drift making the signal difficult to measure. Note that this figure shows signals from the two set-ups, Medelec and OSM, recorded simultaneously and from the same electrode. The two top traces show the noise obtained (mean of three trials) with the two methods.

The stimulus timing is indicated by a horizontal dashed line. The signal consists of a series of muscle spasms of short duration which for this luminance level build to a maximum about 1.7 s after the stimulus onset. These gradually reduce over the subsequent 2 s after the stimulus has been turned off. As in the noise trace, the Medelec-based response shows low frequency activity.

Immediately after the stimulus is turned on

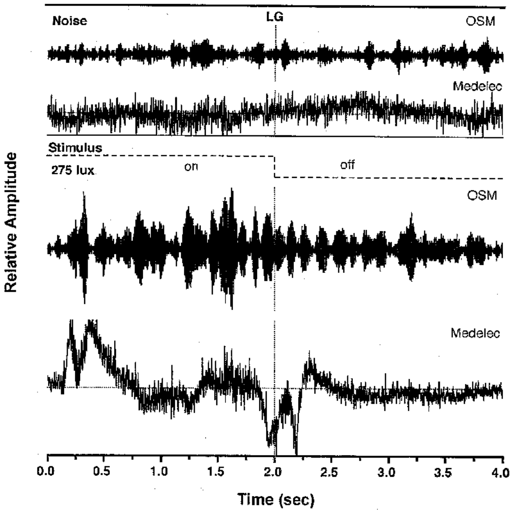

Figure 4 Comparison of noise (upper panel) and raw signal produced by a glare source of 275 lux (lower panel) obtained from the OSM and the Medelec (subject LG). Stimulus timing is depicted by a dashed line

there is a sharp positive–negative wave. This is likely to be due to: i) signals generated in the retina (the Electroretinogram, ERG); and ii) the blink reflex which generates a short latency response. This slow wave activity is artefactual and makes the trace difficult to measure. An example is the spontaneous blink which occurs 0.25 s prior to the stimulus being turned off in the Medelec trace. Blinks may occur any time during a recording session and are effectively removed by the filtering of the OSM. Both the ERG and the blink reflex are sharply time-locked to the stimulus and can be extracted, if required, using conventional signal averaging techniques. Note that the same gain and scale are used for the signal and noise but the OSM has a slightly higher gain than the Medelec. The ERG and blink artefacts are not present in the OSM data which is a clean, relatively easy to measure response.

Figure 5 shows the techniques used to quantify the response. The response to a glare stimulus of 950 lux (lower panel) is compared to the spontaneous activity (noise) obtained in the dark (upper panel). The data may be analysed in the time (left) or frequency domain (right) depending on the question under investigation. The frequency spectra on the right are the Fourier Transforms of the time series data on the left. On the left, the time-domain data are shown in raw and rectified form. The stimulus timing is indicated by the dashed line.

The EMG in response to the 950 lux stimulus is, as expected, much larger than that for the 275 lux seen in Figure 4. It builds up in a spasmodic nature reaching a maximum in this case at 1 s after the stimulus onset. When the stimulus has been turned off the response remains well above noise levels for a further 1–2 s, depending on the intensity and duration of the glare source. The raw data are shown in rectified form in the next row. The main advantage of the time-series data is that the time course of the response can be studied. This point is considered in more detail in the Discussion (Section 4). Note that different subjects (SP and LG) are utilized in Figures 4 and 5. These figures are presented mainly to show the different ways of plotting the data, rather than to compare the effects of the two different stimuli. Comparison of subjects and stimulus strengths are made in Figure 6.

The area under the rectified curve is easily calculated and used as an index of response in both time- and frequency-domain data. In the present paper the shaded area under the frequency domain curve (180–220 Hz) is used as an indicator of the strength of the EMG activity. In Figure 5, the area obtained under the noise frequency spectrum is 14.57 and the corresponding value for the signal is 83.0.

In Figure 6 the amplitude of the signal, in terms of signal-to-noise-ratio, r, is shown for six subjects as a function of log corneal illuminance. The least squares linear regression drawn through the data shows an r^2 value between 0.596 (for TL) and 0.910 (for AL). All reach statistical significance with $P < 0.001$. Note that all data points are illustrated to indicate response variability. In all cases three determinations were made. In cases where only two data points are shown recordings were obscured by excess blinking. Apart from the linearity of the data, the striking feature is that the gain between subjects

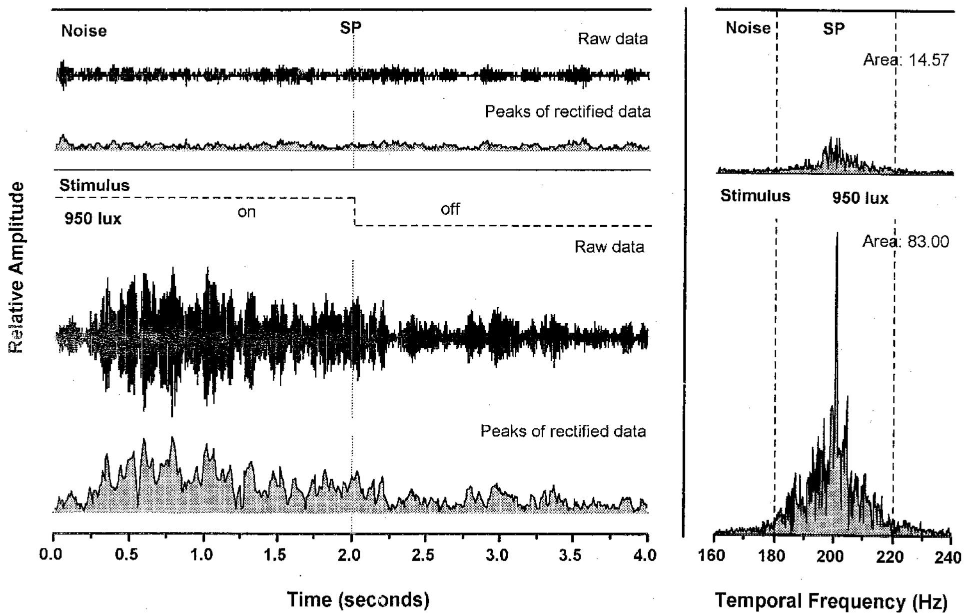

Figure 5 Methods of deriving an index of OSM-based discomfort glare in terms of time (left panel) and frequency (right panel). Noise (upper) and raw signal (lower) are illustrated (subject SP). For the time series, the peaks of rectified data are also plotted. The discomfort glare response is defined as the integrated area for both time and frequency domain analysis. Stimulus timing is depicted by a dashed line

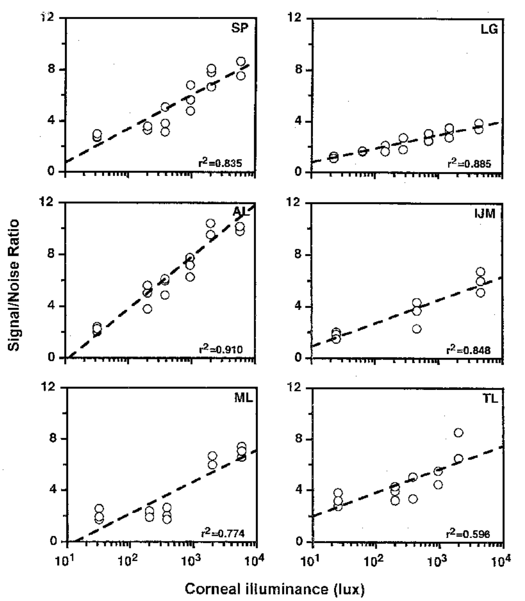

Figure 6 Signal-to-noise ratios obtained with the OSM for six subjects as a function of corneal illuminance. The dashed line is the least squares regression line. The regression coefficients are indicated

is quite consistent. Gain is defined as the increase in response amplitude for unit increase in stimulus. Here the smallest gain is obtained from LG whilst the largest was obtained from AL. The data were obtained for each subject in a single session. Individuals were highly repeatable. Note that the minimum level of glare stimulus tested was between 22 and 32 lux and this was easily distinguished above the noise. Possible reasons for individual differences in gain are outlined in the Discussion (Section 4).

Figure 7 illustrates the relationship between the EMG-based index of glare and the subjective magnitude estimate approach. Data from six subjects are shown. In these preliminary data a high correlation is obtained between the two measurements. It is clear from these data that a strong quantitative relationship holds between the two measures, varying from a maximum coefficient of determination r^2 of 0.817 to a minimum of 0.659. In all cases the obtained correlation coefficient is statistically significant at $P < 0.001$. It should be stressed that a range of viewing con-

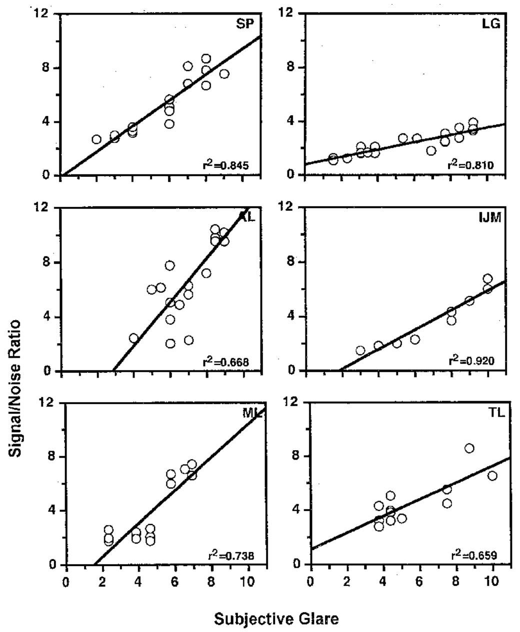

Figure 7 Comparison of subjective rating data and signal-to-noise ratios obtained with the OSM. The dashed line is the least squares regression line. The regression coefficients are indicated

ditions such as stimulus size and eccentricity must be tested before the question of correspondence between the two measures can be fully addressed.

4. Discussion

An objective method of assessing discomfort glare has been developed using two different populations of subjects and two types of equipment: a broad-band commercially available amplifier, and the Ocular Stress Monitor (OSM). The OSM is a narrow-band and portable amplifier/transmitter. It was designed and built in the Visual Sciences Lab in order to conduct surveys of road lighting installations. In this paper, data are presented comparing the two systems and test the performance of the OSM under a range of illuminances. It is evident that discomfort glare assessed using the OSM predicts subjective ratings for the same stimuli satisfactorily.

Characterizing the ocular EMG response for glare sources of various intensities is important for the utility of the OSM. It is apparent from this and a previous study[12] that the amplitude of the response is directly proportional to the log of the corneal illuminance. The illuminances tested, range from relatively low levels (20–30 lux; just above noise) to levels of extreme discomfort for each subject (6000 for SP, AL and ML, but only 2000 for TL) and there were no indications of strong saturating effects, as seen in Figure 6. A simple relationship between the amplitude of the ocular EMG and glare source illuminance was also shown in an earlier study.[10,11] Berman *et al.*[10,11] used a broad-band amplifier, filtered blinks and other artefacts digitally and derived an index of discomfort glare by calculating the ratio of EMG power spectrum with and without a glare source. There are two major differences between the OSM and the technique described by Berman *et al.*[10] First, a narrow range of frequencies is extracted by the OSM and secondly, it is designed so that duration effects can be assessed.

In this paper frequency-based measurements are used to assess discomfort. However, it is evident when comparing the raw data in Figures 4 and 5, that the time course of the response varies with illuminance. There is always a dramatic increase in the muscle fibre activity immediately following the onset of the glare stimulus. If the stimulus is very bright, or is present for a long period, the subject feels extreme discomfort and this is reflected in the raw EMG, by a persistent series of muscle spasms. Although in this study only data for stimuli of duration of 2 s are presented, it is clear that the intensity of the response is not a simple function of glare source duration and illuminance.[14] To study the relationship between the two, it is important to characterize the time course of the response. Hence in some cases it may be appropriate to analyse the response in terms of time rather than frequency. Comparing the effects of duration and stimulus intensity requires good resolution in time and the ability to vary the period over which the analysis is made. This can be done with the OSM and our analysis as shown in Figure 5.

The extent to which the few subjects tested in the present study are representative of the population at large is as yet unclear. In Figure 6, signal-to-noise ratios of EMG activity are shown for different subjects for a range of corneal illuminances. The amplitude of the response is obtained from the area under the curve of the Fourier transform as illustrated in Figure 5. Individual data points rather than means are plotted to show the within-response variance. As might be expected, there is some inter-subject variability. This is reflected in the different gains obtained; probably due to anatomical and physiological variation between subjects. Some individuals have a particularly wide palpebral aperture (vertical distance between upper and lower lid), some have tight eyelids which generate high levels of electrical activity. Whether an individual has pale or dark irides almost certainly affects his/her susceptibility to discomfort glare. In this study only young subjects were tested, but age may influence the EMG response, perhaps due to loss of muscle tonus and the scatter and absorption of light by the ocular media.

Figure 7 shows that perceived glare corresponds well to EMG activity. This observation is crucial for the validity of the technique because the majority of previous estimates of discomfort glare are based on subjective rating. There are many potential advantages of the objective method; the intra-individual variations are reduced, inexperienced subjects can be used, the dynamic range of responses is physiological rather than psychological and it lends itself to measuring under rapidly changing conditions. The test of the association between subjective and objective glare awaits further examination. It requires larger numbers of subjects and at least one additional dependent variable. An obvious candidate for this is background luminance, which at photopic levels dramatically reduces perceived glare. For the moment it appears that the objective measurements of glare described, predict subjective ratings with satisfactory levels of accuracy.

Normally, discomfort glare is regarded as an acute, short-term phenomenon. An added concern with respect to response timing (discussed earlier) is whether there may be more long-term or chronic discomfort glare effects. These may persist for many minutes or perhaps hours and are difficult to measure. This form of glare may be subliminal in that observers are initially unaware of any gross sensations of discomfort. An example might be the fatigue caused by following a vehicle with particularly bright rear lamps. These effects accumulate so that observers eventually experience discomfort without being aware of the underlying cause. The celebrated example of glare is that experienced when driving on motorways, where the main source of discomfort appears to be due to the headlamps of on-coming vehicles.[15–17] A frequently overlooked point is that the design of the overhead lighting installation, when present, almost certainly contributes to driver discomfort. Characterizing these effects with traditional methods of assessing discomfort would be operationally difficult because the moment-to-moment changes in the viewing conditions vary dramatically. The OSM described in this report is ideally suited to assessing dynamic situations like driving.

The method described could be extended to many other situations which have been reported as inducing mild sensations of glare over an extended period. An obvious example would be the discomfort described by office workers after prolonged viewing of PC monitors.[18] When lighting is non-optimal, observers report fatigue after a relatively short period. These effects would almost certainly be accompanied by above-average levels of EMG activity which, crucially, would be recordable prior to the onset of any sensations of tiredness. Although this is not discomfort glare as classically described, it is nevertheless discomfort induced by non-uniform illumination.

Extreme discomfort glare can induce considerable pain/ocular discomfort and it would be surprising if there was not a physiological explanation for this. As discussed in the Introduction, early studies concentrated on the pupil activity as a candidate. One possibility, not previously considered, is that pain detectors in the extra-ocular muscles are the basis of discomfort glare. It is known[19] that in order for a blink or an ocular flinch to occur, the activity in the levator muscle (which lowers the upper lid) must be momentarily suppressed. Hence, under normal conditions, immediately prior to the initiation of a blink, the levator relaxes briefly, allowing the orbicularis to contract. In the presence of high intensity lights, the spasm in the orbicularis may reduce the ability of the two muscles to co-ordinate, thus forcing them to contract simultaneously and induce extreme pain.

Finally, the technique described is radical, but its practical usefulness remains to be established. The present paper describes relatively short-term, flinch-type responses, whereas on roads discomfort glare is usually a cumulative process resulting in fatigue and the urge to close the eyes. Experiments are presently being conducted to test the ocular stress induced by different lighting installation designs and road environments.

Acknowledgements

John Simpson of the Visual Sciences Lab, UMIST, built the OSM. The project (IST 062) was supported by a research grant from the LINK IST programme between DTLR and EPSRC (1999–2001). The industrial partners were Industria/WRTL Exterior Lighting Ltd, Dolland and Aitchison Optometrists, and Bu-Val Buses. Industria/WRTL Exterior Lighting Ltd are currently supporting the extension of the research (2001–2002).

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Discussion

Comment 1 on 'The ocular stress monitor: a new device for measuring discomfort glare' by IJ Murray, S Plainis and D Carden

PR Boyce (Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA)

This is an interesting paper describing what would be a useful technique for quantifying discomfort glare, if the EMG magnitude could be shown to be closely related to discomfort glare. There can be little doubt that the proposed device is a convenient means to measure the strength of the contractions of the muscles around the eye, in the laboratory and in the field, although that maybe is all it does measure. The paper does contain evidence that the EMG magnitude is related to discomfort glare but there are three reasons why I do not find it convincing. First, the EMG values are only measured for the two seconds immediately following the onset of the glare source. Thus the EMG values represent the response to a bright light to which the observer is not adapted. Most studies of discomfort glare are done in conditions where the observer is adapted to the background luminance. Second, the participants were pre-trained to use the subjective scale by exposure to the actual conditions to be seen before any recordings were taken. Given such training it is hardly surprising that high correlations were found between the measured EMG values and the subjective ratings when they were taken together. Third, the photometric quantity used to measure the level of glare was the illuminance at the eye, for a glare source seen at a fixed deviation from the line of sight in otherwise dark conditions. This metric and these conditions are conventionally associated with disability glare rather than discomfort glare.

To establish that the EMG values are reliably related to the perception of discomfort glare, three things need to be shown. First, that the EMG values are maintained at a higher level when glare is perceived to be present over a prolonged period, certainly long enough for adaptation to the lighting conditions to be complete. Second, that the EMG values show a consistent relationship to the subjective ratings of discomfort made by untrained observers, naive in lighting. Third, that the EMG values vary in the expected way with the variables known to determine discomfort glare, namely, the luminance of the glare source, the solid angle subtended by the glare source, the luminance of the background and the deviation of the glare source from the line of sight. Until these demonstrations are made, the meaningfulness of the EMG measurements as regards the perception of discomfort glare must remain open to doubt.

Comment 2 on 'The ocular stress monitor: a new device for measuring discomfort glare' by IJ Murray, S Plainis and D Carden

RH Simons (Lighting Projects Consultant, Bishops Stortford, Hertfordshire, UK)

At present there is no way of quantifying discomfort glare in road lighting which is accepted worldwide. CIE 115–1995 (Recommendations for the lighting of roads for motor and pedestrian traffic) describes three methods of calculating discomfort glare. Of these, the Glare Control Mark was the accepted CIE method of calculating discomfort glare, introduced in the 1970s. However, it was found that it did not give predictions which accorded with subjective evaluations and for this reason has largely dropped out of use. The work being done by Dr Murray and his colleagues is, therefore, timely.

In the paper it is stated that discomfort glare is always accompanied by a strong flinch reflex in the extra ocular muscles. This is tantamount to defining discomfort glare as that lighting situation which produces a strong flinch reflex. Figures 6 and 7 would seem to support this. However, the illuminances in Figure 6 are much greater than those that would be experienced in a normal road lighting installation. How do we know that it is not disability glare that is producing this reflex? This is some evidence to support this contention in the paper in that glare sensation is shown to be related to illuminance at the cornea, which is known to be related to disability glare. I believe that more experimental work needs to be done to establish the connection between the discomfort glare evaluated subjectively in a range of lighting situations and the flinch reflex.

The high corneal illuminances shown in Figure 6 will never be attained in a normal road lighting installation – the operative part of these graphs, as far as road lighting is concerned, is well to the left hand side. In fact the illuminances will rarely reach 25 lux. I would expect the illuminance from rear lights be to even less, but the situation as regards oncoming headlights may well be different.

The authors say that a frequently overlooked point is that the design of overhead lighting almost certainly contributes to driver discomfort. I would agree with this statement, but feel that in most cases this is far outweighed by the amelioration of the discomfort and disability glare produced by the oncoming traffic, which is a great source of annoyance and reduces ease with which objects can be seen. I personally find that the transition from an unlit road, especially a motorway, to a lit road gives a great sense of relief, and *vice versa*. This may partly be because of my age (over 70 years) but the authors' indicate that it is a common experience.

I would also like to say that discomfort glare has not been overlooked by road lighting designers and those responsible for drawing up codes of practice and standards. The problem is that they do not have the tools to deal with it at present. I hope the findings of Dr Murray and his colleagues will see an end to this unsatisfactory situation.

Authors' response to PR Boyce and RH Simons

IJ Murray, S Plainis and D Carden

The referees have made perfectly valid points about the paper and we thank them for their comments

Reply to PR Boyce

It is agreed that more work is required to test the extent to which the EMG represents discomfort glare as measured conventionally. Whether this is an important issue is open to conjecture. The point about the sampling period of the EMG compared with the onset of the glare stimulus is important, and we have tried various possibilities. For example, we have looked at varying the duration of the glare source and using a matching EMG integrating period. We have also varied the length of the EMG integrating period used with a constant stimulus duration. These experiments have not yet been completed but it is clear the EMG response is virtually zero for durations of less than 0.5 s. It is also apparent that the EMG response increases with the duration of the stimulus, and this will be shown in the next series of experiments.

Glare source intensity is expressed in terms of illuminance because the stimulus was a projector which made calibration in luminance slightly inaccurate. A new version of the stimulus has now been developed based on LEDs and a diffuser, and this will enable the use of luminance and, when pupil size is controlled, retinal illuminance (Trolands).

The points made on how to validate the EMG in terms of subjective glare are quite correct. The third point made, that the EMG corresponds to luminance, solid angle and deviation from the line of sight, is particularly important . Equally important is the issue of individual variation which is seen in the different slopes of the EMG *vs* Glare source illuminance functions. Given the many variables, it may be that the EMG does not precisely represent subjective discomfort glare. It seems clear though, that the EMG can provide an index of ocular activity that can be related to non-uniform lighting. We have chosen to refer to this as ocular stress and show the first of the many experiments needed to establish the link between the ocular EMG and discomfort glare.

Reply to RH Simons

As this is the first publication describing the OSM, we agree there is much to be done to establish the meaningfulness of the measurements, especially their relationship, if any, with discomfort glare. The illuminance levels shown are much higher than on roads, and the next series of experiments have simulated road conditions much more closely.

It is true however, that overhead lighting, though contributing to ocular discomfort under some circumstances, reduces the overall effects of glare from other vehicles. As pointed out, the benefits of overhead lighting are experienced by all observers. We now have data to confirm this from on-road surveys using the OSM. What remains puzzling however, is the extraordinary difference in individual susceptibility to glare on the roads. It may be that, rather than concentrating on the largely academic exercise of how the OSM data is related to conventional discomfort glare, the OSM should be used to determine why some individuals are so affected by glare that they are unable to drive at night, whereas others regard it as a minor irritation.