An Objective Measure of Discomfort Glare

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THIS PAPER WAS PRESENTED AT
THE 1993 IESNA ANNUAL CONFERENCE

Introduction

More than 60 yrs have transpired since Luckiesh and Holladay,[1] and Stiles[2] independently proposed that illumination conditions can present two different types of glare effects. These attributes are referred to as disability glare and discomfort glare. In the first case, the glare condition produces veiling luminance, which reduces the contrast of the retinal image with a resultant decrease in visual performance. Detailed quantitative studies have evaluated disability glare (e.g., Vos[3]), and the phenomenon appears reasonably well understood.

The same cannot be said of discomfort glare, which is a measure of negative subjective reaction to the presence of a glare condition. Although there are extensive studies based on measures of subjective response, no clearly identifiable, objective correlate has been established. Hopkinson[4] and later Fry and coworkers[5] have claimed that the small, random, uncontrolled oscillation of the pupil aperture (hippus) is affected by the presence of discomfort glare. Recent attempts to verify possible changes in the power spectrum of hippus when discomfort and no discomfort occurred (average pupil size remained the same) showed no differences,[6] even when the reported discomfort was nearly intolerable.

Thus, although it is relatively easy to perceive the sensation and elicit a negative response to the presence of discomfort glare, the absence of a reliable objective correlate remains both a puzzle for vision science and a barrier to rational optimization of the quality and efficiency of lighting design. Modern design trends toward smaller and higher-luminance lighting systems coupled with a desire to increase the use of daylight provide a further impetus for achieving a better understanding of the nature of discomfort glare.

It has been known for some time [through the use of electromyographic (EMG) techniques] that the frontalis muscle region of the forehead has increased activity in response to conditions of increased stress or excitement.[7-9] Furthermore, EMG responses in facial muscles have demonstrated strong evidence for correlations between EMG activity and psychological states such as sadness, anger, disgust, fear, and happiness.[10] More recently, both cognitive and affective states, which are not normally observable by inspection of facial expression when studied on video tapes, have shown detectable differences in EMG responses.[11-14] Furthermore, Cacioppo[15] has reported in his study of affective state and EMG responses that lighting levels during experimentation should not be excessive.

We have studied the EMG activity of facial muscles in the vicinity of the eye as a measure of a possible different pathway response to a discomfort glare sensation. The working hypothesis is that the discomfort sensation gives rise to an incipient aversion response to the glare in the form of a subtle, involuntary contraction of muscles around the eyes. This response would manifest as heightened EMG activity in the orbicularis oculi, which is the principal muscle responsible for closing the eye, or other nearby muscles such as the corrugator supercilii. Our preliminary experiments demonstrated that the presence of a small, bright, uncomfortable glare source produced demonstrable changes in the EMG. **Figure 1** shows an EMG recording from a young subject. The glare source is exposed halfway through the recording and produces a clear increase in EMG activity.

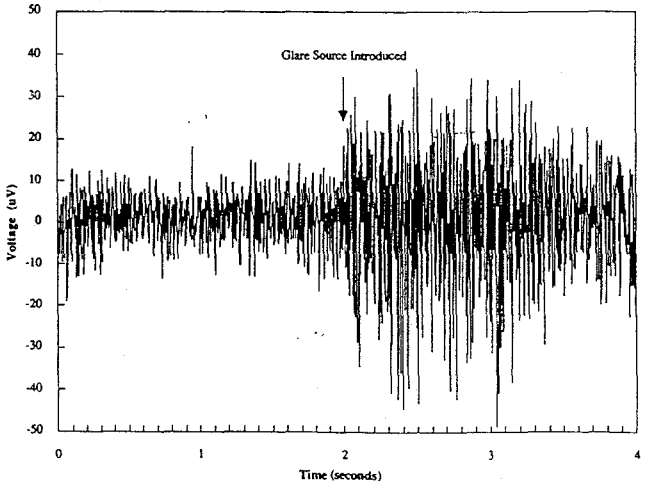

Figure 1—The influence of a glare source on the EMG. A 4-s sample of the raw EMG (in microvolts) is shown. An uncomfortable glare source is introduced after 2 s, which produces a clear increase in EMG amplitude

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In preliminary studies we experimented with electrode placement, analysis techniques, and investigated some sources of artifacts. Electrical activity of the orbicularis oculi was recorded, using two surface electrodes positioned on the brow. A third electrode attached to the forehead served as a ground. Other locations, including the earlobe, gave equivalent results. The electrodes were connected to a Grass amplifier, which in turn, was interfaced to a PC via an A/D board. EMG activity was typically recorded for 5-s periods, sampled at 1000 Hz. A small, intense glare source, whose exposure was electronically controlled by a shutter, was employed for all preliminary studies. For additional details see test conditions below.

Preliminary studies

Analysis methods

The EMG has been used in other fields of ergonomics, notably in posture evaluation (e.g., Corlett[16]). In clinical EMG studies, it is often the quality of the signal that is of interest. In human factors research, however, it is usually the quantity of the response that is important. There are three major methods of analysis of the quantity of the EMG response:

- integrated EMG (IEMG) analysis
- Fourier analysis
- amplitude probability distribution function (APDF) analysis

The IEMG gives a measure of the power of the EMG by summing the rectified signal over a period of time. This can be accumulated to give a single value representative of the muscular activity. Alternatively, the signal can be integrated until a certain total value has been reached and then starting the addition again. The visual record will show a series of triangular waves with equal peaks, but spaced more closely when the EMG signal is greater. The number of peaks per unit of time provides values representative of the muscular activity.

Fourier analysis is a procedure that breaks down the waveform into its sinusoidal, temporal-frequency components. Typically, short EMG samples are taken, analyzed, and the activity is characterized as a frequency power spectrum. The advantage of this analysis is that energy at specific frequencies can be digitally filtered. This is particularly important if there are 60-Hz power-line artifacts in the EMG or if a range of certain frequencies are contributing to a confounding or artifactual response (e.g., blinks).

Jonsson[17] and Hagberg[18] have demonstrated the utility of APDF analysis, which analyzes the EMG in terms of the amplitudes present in the signal. EMG samples are taken and amplitudes of all the peaks counted and grouped. These may be plotted as an amplitude spectrum or a cumulative amplitude distribution function.

We experimented with a variety of analysis techniques, including Fourier analysis and IEMG. We chose to adopt Fourier analysis because it gave the cleanest results and facilitated frequency-specific filtering. The latter property was particularly important given the potential contamination of the results by power-line artifacts. Power-line artifacts appear in the Fourier spectrum as spikes at 60 Hz and its harmonics. Fourier analysis permits the use of post-hoc digital filtering to eliminate the contamination at these frequencies. We found that integrating the derived FFT provided a reliable index of EMG activity. The integrals obtained with and without a glare source were compared to give us an index of the discomfort response.

Blinks

We considered the possibility that the observed changes in EMG activity were due merely to blinking. This also raised the question as to whether periodic blinking by subjects would contaminate our results. Inspection of EMG activity revealed that blinks were easily identifiable as large, slow changes in potential lasting some 250 ms (**Figure 2**). While blinks show a completely different waveform to the increase in activity induced by the glare source (**Figure 2**), we wanted to quantify their influence on the Fourier spectrum.

We therefore collected EMG samples under constant glare conditions and divided them into those

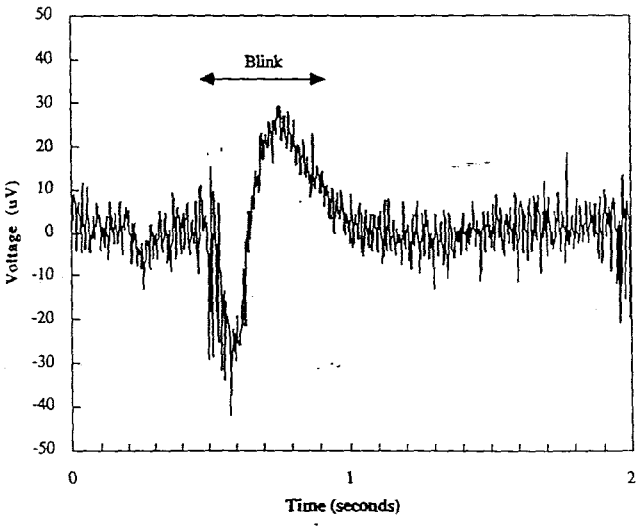

Figure 2—The influence of a blink on the EMG. The blink causes a large, slow change in potential lasting some 250 ms. The appearance is very different from the effect of a glare source. The influence of the blink on the FFT spectrum is shown in Figure 3

containing blinks and those containing no blinks. Fourier analysis was performed on both subsets, and the results for one comparison are displayed in **Figure 3.** The analysis revealed that the only substantial difference between the two samples occurs at low frequencies (<10 Hz). This is consistent with the blink waveform in **Figure 2.** In all subsequent experiments we eliminated all frequencies below 10 Hz from our analysis of EMG activity, thereby removing the influence of blinks.

Onset and offset artifacts

We also considered whether the onset of the glare source produced transients in the EMG that were responsible for our encouraging preliminary results. We compared two protocols in which a small, intense glare source was exposed for 5 s. One was a gradual onset: the glare-source luminance increased gradually over the first 3 s and then was kept constant for 2 s. The second was a rapid-onset condition in which the maximum luminance was reached immediately and maintained for 5 s.

For the rapid-onset condition there was little variation in EMG amplitude for the duration of the recording. For the gradual-onset condition, the EMG increased in amplitude for the first 3 s and then stabilized. Between the protocols there was no difference for the final 2 s of glare exposure. We concluded that rapid onset of the glare source does not produce any significant artifacts and that it is acceptable to use a shutter to control exposure of the glare source.

Electrode placement

We have experimented with a number of electrode placements, including cheek, canthus, lid, forehead, and various locations along the brow. We found that positioning the electrodes along the inner brow gave the most reliable, robust recordings as well as being relatively unaffected by between-subject variations in facial musculature.

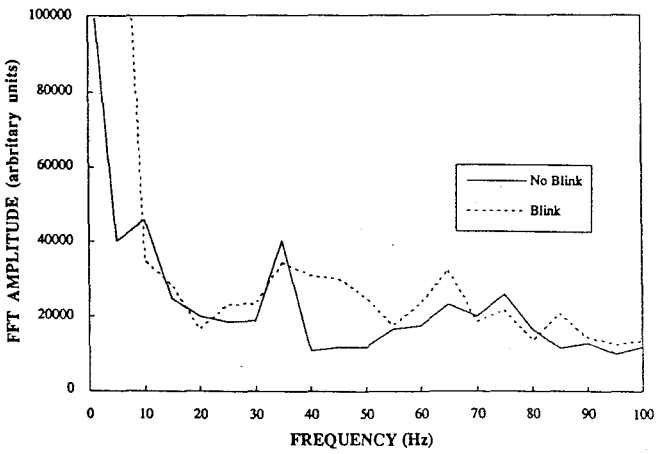

Figure 3—The influence of a blink on the EMG as reflected in the FFT power spectrum. The blink spectrum is derived from the first second of EMG activity shown in Figure 2. The no-blink spectrum is derived from the last second of the trace. Notice that most of the difference occurs at 10 Hz and below

Subject posture

We had observed that periods of a few minutes on a chin rest resulted in increases in EMG amplitude even without the presence of a glare source. This was not unexpected because EMG recordings have been used in the evaluation of postural comfort. Placing a subject in a comfortable chair and avoiding the chin rest effectively eliminated such contaminants.

Eye movements

A further possible contaminant was change in EMG activity due to eye movements. We compared EMG activity in the absence of any glare source under two conditions. In the first, the subject steadily fixated on a target on a monitor. In the second, the subject alternately fixated on two targets separated by 15 degrees on the screen. This required relatively large saccadic eye movements. We observed no difference in EMG activity between these two conditions. In particular, there were no transient changes in the EMG associated with the saccades.

Following these preliminary investigations, we embarked on a study of 20 subjects to compare the assessment of discomfort glare using our new objective technique with an established subjective methodology.

Subjects and methods

Subjects

Twenty subjects, aged 18–36 yrs (mean = 25.2 ± 3.7), each participated in a single session lasting approximately 90 min. Informed consent was obtained from all subjects after explanation of the purpose of the study. The volunteer subjects were students and were paid for their participation. Eight of the subjects were male, thirteen were Caucasian, five were Asian, and two were of mixed race. Seven subjects wore spectacles, and seven wore contact lenses.

Electrode placement and application

At the beginning of the session, three silver-silver chloride surface electrodes, 3 mm in diameter, were placed on the subject (**Figure 4**). Two were positioned just above the eyebrow: the first vertical from the inner canthus and the second 10 mm to the temporal side of the first. The use of two closely placed electrodes allowed for a significant reduction in noise due to distal muscular activity by using the common-mode rejection technique. In this case, the signal

Figure 4—A subject wired for EMG recording. Two electrodes are placed just above the brow while a third serves as a ground. For this recording, electrodes are placed at both the orbicularis oculi and the corrugator supercilii (LBL XBC-910-8313)

difference between the paired electrodes at the orbicularis oculi was recorded and amplified by the signal processing system. Distal signals were likely to be common to both electrodes and could be eliminated by the differencing procedure. This common-mode rejection technique is generally recommended by EMG researchers.[19]

The third electrode served as a ground and was placed high on the subject's forehead. Prior to application, the skin was cleaned with alcohol and skin resistance lowered by light rubbing with a mildly abrasive skin preparation lotion (Omni-Prep). Annular self-adhesive electrode washers (In Vivo Metric E401) were then placed on the appropriate skin locations. The electrodes were then affixed with a conductive electrode paste (Ten 20). The electrodes were connected to a Grass amplifier. The amplified signal was then relayed to an IBM 80386 computer via an analog-to-digital converter (Data Translation). Data were sampled at 1000 Hz.

Testing conditions

Subjects sat in a comfortable chair and fixated on a monitor at 1 m (8 × 10 degrees, luminance = 69 cd/m^2) on which a large symbol was displayed (**Figure 5**). The glare source was provided by a 300-W tungsten halogen projector lamp with its beam positioned 11

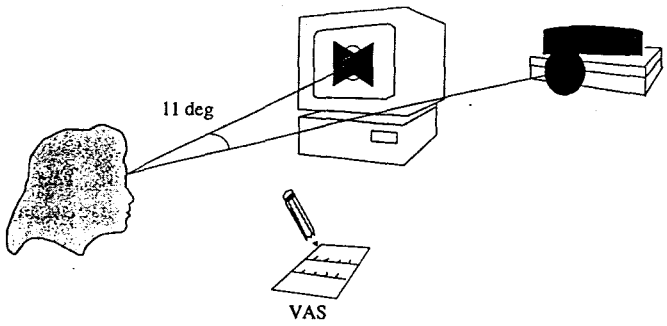

Figure 5—Experimental apparatus. The subject fixates on a monitor on which a large symbol is displayed. The glare source is provided by a projector lamp with its beam positioned 11 degrees to the right of fixation and directed at the subject. Exposure to the source was controlled by an electronic shutter in front of the projector lens. Subjects record their subjective responses on a visual analog scale

degrees to the right of fixation and directed at the subject. Exposure to the source was controlled by a electronic shutter in front of the projector lens. The size of the glare source could be varied by placing a 1-degree or 2-degree aperture in the plane of the shutter. The luminance of the glare source (maximum = 6.9 log cd/m^2) was modified by neutral density filters in 35-mm slide mounts and stored in a standard carousel. The shutter and carousel were controlled by a second computer.

Discomfort glare was assessed under three conditions in a randomized order:

condition 1: moderate room illumination (wall luminance = 12 cd/m^2) and a 2-degree glare source

condition 2: low room illumination (wall luminance = 0.5 cd/m^2) and a 2-degree glare source

condition 3: moderate room illumination and a 1-degree glare source

The results of previous works[20] led us to believe that these conditions should produce small but measurable variations in discomfort.

For each of the three experimental conditions, discomfort was assessed using both objective and subjective methods in a single experimental session lasting approximately 1 hr. The order was randomized with respect to both experimental condition and measurement method. For both methods, each experimental run comprised 36 trials. Each subject was exposed to six different glare luminance levels, ranging from 4.4 to 6.9 log cd/m^2 in equal logarithmic steps. Each luminance level was presented six times in a randomized order. Subjects were instructed to look at the center of the monitor and not at the glare source.

Subjective method

For the subjective assessment of discomfort glare, we used a visual analog scale, an approach sim-

ilar to that employed in several works.[21,22] This technique has been found to be more reliable than the method of adjustment and two-alternative forced-choice testing.[23]

The visual analog scale comprised a 100-mm horizontal line with a series of demarcations. These marks were positioned to signify the borders between perceptible, annoying, disturbing, and intolerable discomfort. Subjects were provided with written descriptors of each of these sensations at the beginning of the experimental session (**Appendix**), and the key words were displayed at the top of all recording sheets. Subjects were instructed to place a line or check mark on the scale to indicate their perceived level of discomfort. For example, a source that the subject felt was annoying but did not approach disturbing discomfort might prompt the subject to mark the scale as shown in **Figure 6**.

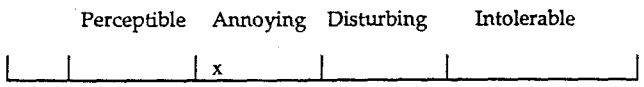

Figure 6—Visual analog scale used in the subjective assessment of discomfort glare. The check mark corresponds to a glare source that is annoying but does not approach disturbing. See Appendix for full description of the scale

For each trial, the glare source was exposed for three 2-s exposures, each separated by 2 s. The subjects then marked their response on the visual analog scale. The next trial commenced after they had recorded their response and had resumed fixating on the monitor. The experimental run finished when all 36 trials had been completed. Each experimental run lasted approximately 9 min for the subjective method.

Objective method

Discomfort glare was assessed using the objective technique under identical conditions. For each of the 36 trials, however, the glare source was exposed for only one 2-s exposure, again controlled by the electronic shutter. Each trial was separated by a randomly varied period of between 5 and 9 s. EMG activity was recorded for 4 s, commencing 2 s before the shutter opened. Each experimental run lasted approximately 6 min for the objective technique.

Results and analysis

Subjective method

For the subjective measures of discomfort, the subjects' marks on the VAS scale were identified to the nearest millimeter by values ranging from 0—100. Values were averaged across trials and plotted as a function of glare-source luminance for each experiment condition. Data from a typical subject are shown in **Figure 7**.

For a given condition, increasing source luminance produced a monotonic increase in discomfort rating. The reduced ambient illumination consistently produced higher discomfort ratings while the reduced source diameter resulted in lower values. In order to

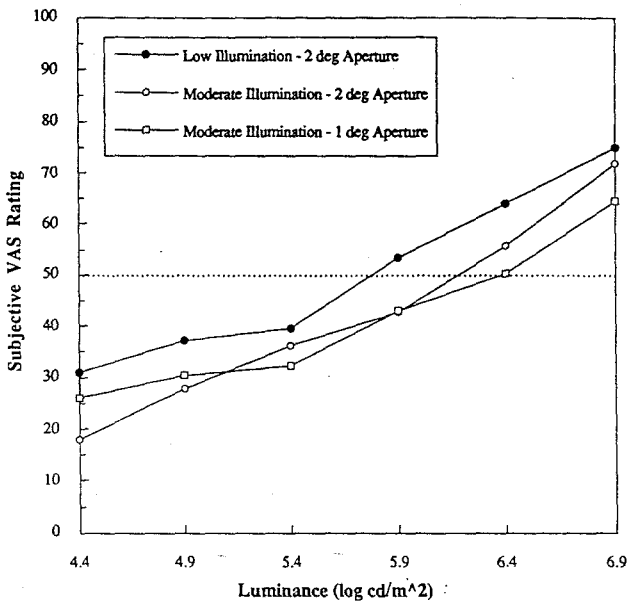

Figure 7—Subjective VAS ratings for subject BH plotted as a function of glare-source luminance for each experiment condition. The dashed line corresponds to VAS_{50}, the glare luminance necessary to just produce "disturbing discomfort."

allow quantitative comparisons between conditions, across subjects, and with objective findings, we determined the log luminance of the glare source, termed VAS_{50} and corresponding to a discomfort rating of 50, by linear interpolation. This value represents the luminance to achieve the border between "annoying" and "disturbing discomfort." The mean VAS_{50} values for the 20 subjects and for each condition are given in **Table 1**.

Table 1—Mean (± standard deviation) luminance values (log cd/m^2) corresponding to a subjective rating of 50 on the VAS scale (VAS_{50}) and a 25 percent increase in the objective EMG ($ODR_{0.25}$)

Source	Low illumination 2-degree source	Moderate illumination 2-degree source	Moderate illumination 1-degree source
Subjective VAS_{50}	5.58 ± 0.57	6.02 ± 0.48	6.26 ± 0.58
Objective $ODR_{0.25}$	5.82 ± 0.37	6.17 ± 0.49	6.50 ± 0.42

Objective method

The objective EMG data were analyzed on a trial-by-trial basis. The 4-s sample of EMG activity was divided

into two 2-s parts: the first reflecting the absence of the glare source and the second reflecting the presence of the glare source. Each 2-s EMG sample was subjected to Fourier analysis, which determined the relative amount of power at each frequency. Frequencies below 10 Hz and at 60 Hz and its harmonics were removed to eliminate blink and power-line artifacts.

The fast Fourier transfer (FFT) power spectrum was then integrated (by determining the area under the power spectrum) in order to provide an index of EMG activity. An example of the FFT spectrum with and without the glare source is shown in **Figure 8**. The relationship between these two integrals (before and during glare exposure) was used as an index of discomfort. We calculated an objective discomfort ratio (ODR) by applying the following formula:

$$ODR = \frac{\text{Integrated EMG power spectrum with glare source}}{\text{Integrated EMG power spectrum without glare source}} - 1$$

A value of zero for the ODR reflects no change in EMG activity, while a value of one represents a doubling of activity. Objective discomfort ratios were averaged across trials and plotted as a function of glare-source luminance for each experimental condition. Data from a typical subject are shown in **Figure 9**.

Following the trends seen with the subjective technique, reduced ambient illumination tended to produce a greater response and higher ODRs, while the reduced source diameter resulted in lower values. However, the functions determined by the EMG response appear to have a somewhat different shape from the subjective data, mainly showing little change in ODR at low glare luminances but an abrupt exponential increase in activity occurring at higher values. One subject exhibited little change in EMG activity for any of the experimental conditions. His data have been excluded from subsequent objective analysis.

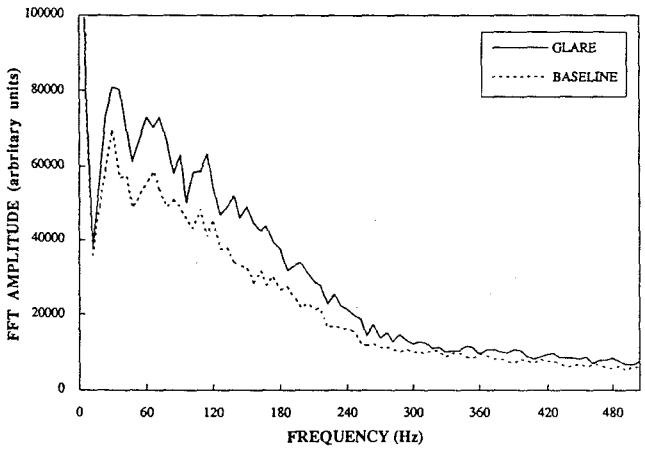

Figure 8—The influence of the glare source on an FFT power spectrum. The baseline FFT power spectrum is derived from the first 2 s of the EMG trace shown in Figure 1. The glare FFT power spectrum is derived from the last 2 s of the EMG trace. The introduction of the glare source produces a marked increase in power at all temporal frequencies above 10 Hz. Note that power-line artifacts have been removed by digitally filtering frequencies at 60 Hz and its harmonics.

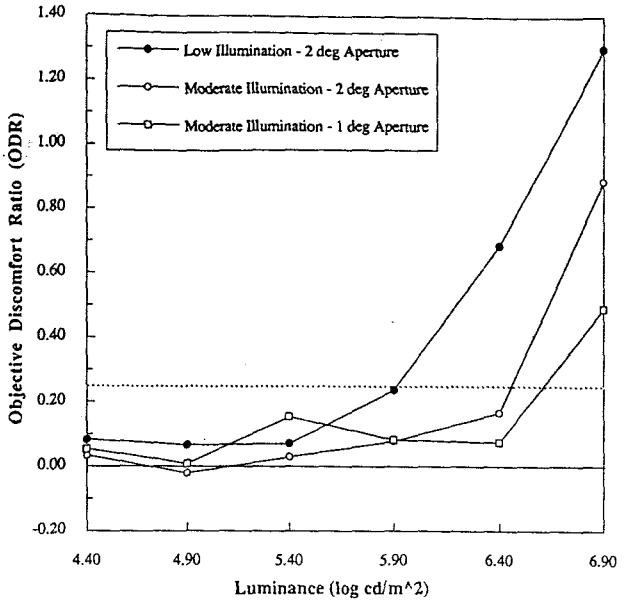

Figure 9—Objective discomfort ratios (ODR) for subject BH as a function of glare-source luminance for each experimental condition. The dashed line corresponds to $ODR_{0.25}$, the glare luminance necessary to produce a 25 percent increase in EMG activity

In order to facilitate quantitative analysis and comparison with the subjective data, we attempted to find a continuous function that would yield a reasonably good fit to the data for each subject and experiment condition. We eventually chose the following function:

$$ODR = 0.25e^{1.5(LogL - ODR_{0.25})}$$

where ODR is the objective discomfort ratio introduced above and logL is the log glare-source luminance in cd/m^2. The exponent multiplier of 1.5 was adopted because it gave a reasonable fit to most subjects' data. The quantity $ODR_{0.25}$ is the log glare-source luminance at which the objective discomfort ratio is equal to 0.25, equivalent to a 25 percent increase in EMG activity. The mean $ODR_{0.25}$ values averaged over 19 subjects for each condition are given in **Table 1**.

Comparison of objective and subjective methods

For virtually all subjects, there appeared to be good

qualitative agreement between the objective and subjective results (**Figures 7** and **9**). Furthermore, the mean subjective (VAS_{50}) and objective ($ODR_{0.25}$) values show good agreement for all conditions. The objective $ODR_{0.25}$ and subjective VAS_{50} values for each subject are plotted for each condition in **Figure 10**. It can be seen that, while the three conditions form clusters, there is substantial between-subject variation. This raises the question of how well the objective method correlates with the subjective method.

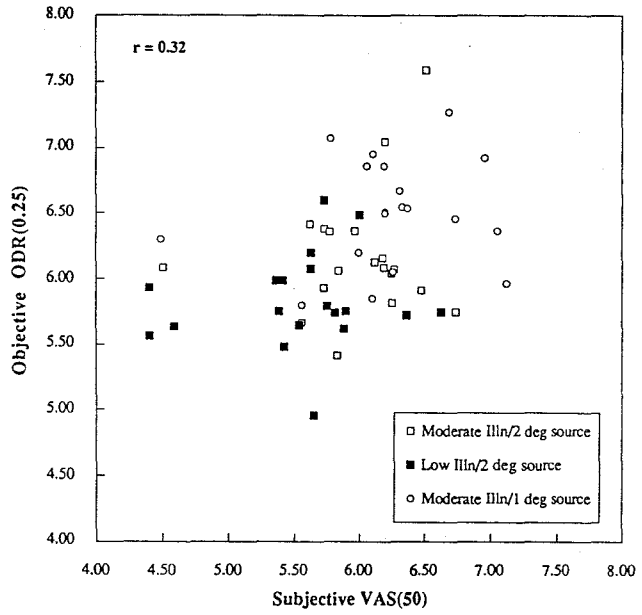

Figure 10—$ODR_{0.25}$ values as a function of VAS_{50} (both in log cd/m^2) for each subject and experimental condition

In order to address this issue, we performed a second analysis making use of within-subject comparisons. We used the log glare luminance that yielded the criterion values of VAS_{50} and $ODR_{0.25}$ from condition 1 (moderate/2-degree) to define a baseline. We then calculated the change in log glare-source luminance necessary to produce the same criterion discomfort level (VAS_{50} and $ODR_{0.25}$) for the other conditions.

It should be expected that a reduction in room illumination (condition 2) should produce lower VAS_{50} and $ODR_{0.25}$ values. Conversely, a reduction in the size of the glare source (condition 3) should produce higher VAS_{50} and $ODR_{0.25}$ values. These values are plotted in **Figures 11** and **12**. Subjects have been ranked based on their subjective VAS_{50} value for condition 1.

For the subjective method, lowering the room illumination produced the anticipated lower VAS_{50} values in all 20 subjects (**Figure 11**). Reducing the size of the glare source produced the expected higher VAS_{50} values in 16 of 20 subjects. For the objective method, lowering the room illumination produced the anticipated lower $ODR_{0.25}$ values in 15 of 19 subjects (**Figure 12**), and reducing the size of the glare

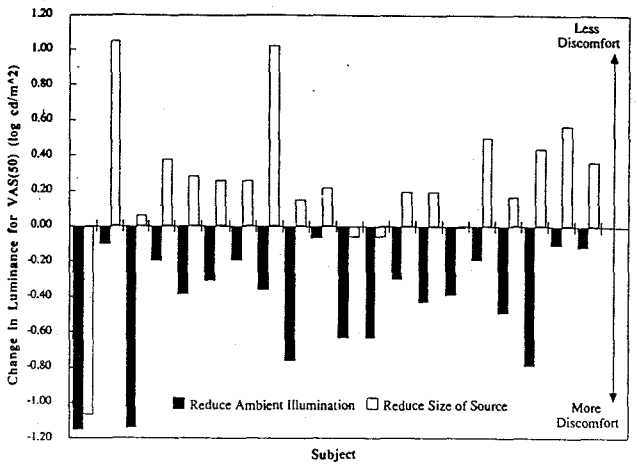

Figure 11—Change in subjective VAS_{50} values produced by a reduction in ambient illumination and a reduction in the size of the glare source. Data are shown for all 20 subjects, ranked by the glare luminance required to achieve their subjective VAS_{50} value under condition 2 (moderate/2-degree)

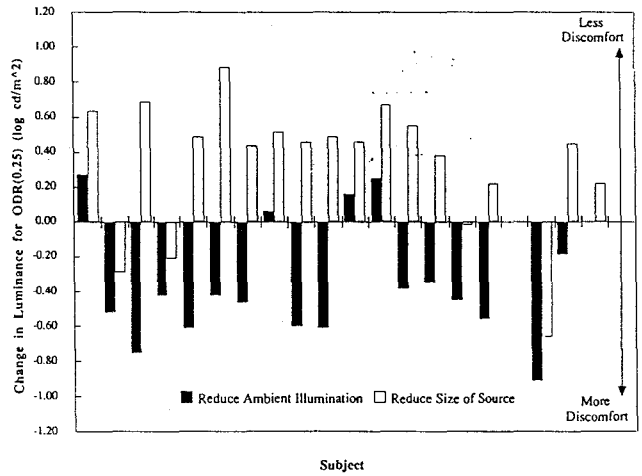

Figure 12—Change in objective $ODR_{0.25}$ values produced by a reduction in ambient illumination and a reduction in the size of the glare source. Data are shown for 19 subjects, ranked by the glare luminance required to achieve their subjective VAS_{50} value under condition 2 (moderate/2-degree)

source produced the expected higher $ODR_{0.25}$ values in 15 of 19 subjects. Significant between-subject variation is evident for both techniques.

Discussion

As displayed in **Figure 10**, the between-subject variation in responses is similar to that reported in previous studies.[24,25] For most conditions, the glare luminances required to achieve the subjective VAS_{50} response for individual subjects spanned a two-log-

unit range. The glare luminances required to reach the objective ODR criterion generally exhibited a narrower range. This may indicate that the between-subject variation found in the subjective assessment of discomfort glare is due, in part, to individual criterion differences that do not contribute to the EMG response. Alternatively, the lower range of values observed for the objective EMG method may be a product of our curve-fitting procedures.

The large between-subject variation in subjective estimates of discomfort make us wary of adopting the subjective VAS_{50} values as a gold standard against which the objective EMG technique should be evaluated. For this reason, we performed the within-subject analysis detailed in the results section. We feel that this gives a much truer indication of the validity of the subjective and objective techniques without any *a priori* assumption that the values from one technique are superior. This analysis indicates that both techniques are sufficiently sensitive to demonstrate reliable changes in discomfort due to modest changes in glare-source size or background illumination.

With the objective EMG technique, and the within-subject comparison, the changes in the $ODR_{0.25}$ value (the glare-source log luminance required to increase EMG activity by 25 percent) are in the expected direction for 79 percent of comparisons (**Figure 12**). This agrees acceptably with the subjective data where changes in the VAS_{50} value are in the anticipated direction for 90 percent of comparisons. Furthermore, the magnitude of the differences between each condition's mean $ODR_{0.25}$ are very similar to differences in the VAS_{50} values (**Table 1**).

The change in both the objective $ODR_{0.25}$ and subjective VAS_{50} values produced by altering the experimental conditions (**Table 1**) are in the direction predicted by accepted discomfort glare theory. Furthermore, the magnitude of these objective and subjective differences are similar to those determined by Bennett.[24,25]

The mean values shown in **Table 1** demonstrate that the glare luminance required to produce a 25 percent increase in EMG activity ($ODR_{0.25}$) is higher than that corresponding to the subjective measure of disturbing comfort (VAS_{50}). The decision to reference all objective results to an ODR equal to 25 percent was made somewhat arbitrarily, and it seems appropriate to calculate the exact ODR corresponding to the subjective rating of disturbing discomfort. We found that an ODR of 0.18 corresponded most closely to the subjective rating of disturbing discomfort. It should be noted that adopting this modified value for the ODR of 0.18 does not influence the analysis displayed in **Figure 12**.

We plan to our extend our investigations in a number of directions. First, we are investigating discomfort glare for larger sources to simulate light fixtures and windows, using both subjective and objective measures. In addition, we are assessing the influence of the spectral composition of the glare source on discomfort. Finally, we are developing a portable device for use by lighting engineers capable of facilitating objective assessment of discomfort glare in the field.

As mentioned earlier, the EMG activity measured here is presumed to reflect an incipient muscular response manifested in the increased electrical activity of the orbicularis oculi. It is unlikely that this facial muscle or any other facial muscle is the source of the discomfort, i.e., the particular pain or other nerve fibers where the discomfort initiates. The measured electrical activity is a response to the pain sensation, whose specific origin is yet to be determined. Nevertheless, we have shown that one can obtain an objective measure of response to discomfort glare that correlates well with subjective perceptions. We expect that EMG techniques will lead to tools that are useful in the evaluation of lighting environments.

Acknowledgments

We thank Paul Leondis for technical assistance and Daniel Greenhouse for useful discussions. This work was supported by the assistant secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Equipment Division of the US Department of Energy under Contract No. DE-AC03-76SF00098.

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Appendix

Instructions to Subjects

We will require you to rate the glare source using the scale provided. The scale consists of these four levels:

Perceptible—The point at which you would prefer the light not to be present. Imagine that it is a pilot light on a computer and you are obliged to set the pilot light on/pilot light off. This is the level at which you would begin to care about such a decision.

Annoying—You could live with this glare source present if you were borrowing someone else's computer for a day. If this glare source were present, you would prefer to remove the glare source if it were possible, but could live with this annoyance for the next hour or so.

Disturbing—This makes you feel uncomfortable. If you had to work like this for any reasonable length of time (5 minutes or so) you would do something to cover the source, shield your eyes, etc., in order to avoid the discomfort.

Intolerable—You could not imagine yourself working with the light source like this. You would certainly close your eyes or take another avoidance action.

Discussion

There has long been a need to find some objective measure of discomfort glare that could be validated against a subjective measure. The authors suggest that the EMG associated with certain facial muscles might be the objective method of choice. I applaud the authors for their work in this direction. However, I do have a couple of comments and questions regarding the research.

The electrical activity of facial muscles may actually have little to do with the actual mechanisms of discomfort glare, and the authors do suggest this possibility. One wonders if this measure just reflects discomfort in general. What would the response be to the presentation of white noise of different intensities and durations? The finding that the ear lobe also gave equivalent results to the locations used in the study is suggestive of some sort of generalized response to annoyance.

Are the authors going to utilize the concepts of VCP and DGR in their future research? It could lend more credence to their findings.

Have the response times to the glare stimulus onset of this objective measure been examined? If so, what were the findings?

Finally, their results shown in **Figures 7** and **9** would seem to indicate that as source luminance increases, there is a greater increase for condition 2 (low/2-degree) vs condition 1 (moderate/2-degree) than for condition 3 (moderate/1-degree). The same results appear to hold for both subjective and objective measures. However, the explanation used to address between-subject differences appears to suggest the opposite. The description of these results seems a bit confusing.

E.J. Rinalducci

Authors' response

E.J. Rinalducci is correct to point out that the EMG "may actually have little to do with the actual mechanisms of discomfort glare." We have stated in the introduction that it is a "possible different pathway response to a discomfort glare sensation." Also, as stated in the last paragraph of the paper, the observed increases in EMG signal are presumed to be a measure of the incipient response resulting in increased muscular electrical activity. The response could indeed reflect discomfort in general. We again acknowledge this possibility and have described our experiences using chin rests in the text.

In a further experiment, in response to the discussor, we have attempted to elicit an increase in EMG activity by means of an auditory stimulus. Using an "uncomfortably loud" de-tuned fm signal, we were unable to elicit a reliable increase in EMG activity for electrodes placed on the orbicularis oculi. The earlobe was mentioned in the text as an electrical ground point and not the position of the test electrodes.

The two ratings of discomfort glare used in lighting applications, VCP and DGR, have as their basis the subjective reporting by test subjects to various glare conditions. We believe the subjective method used here (VAS) applied to the glare indices VCP and DGR would improve their reliability. But more to the point, we are also of the opinion that these procedures have deficiencies that could be improved by replacing the present subjective measures with the objective EMG as the basis of measuring glare response. This alternative allows the possibility of placing the glare indices of lighting design on a much sounder footing. Perhaps the consideration of the EMG signal as the underlying basis for discomfort glare ratings will also provide the impetus to re-examine the rather arcane procedures used to define both VCP and DGR.

The response times have only been examined qualitatively. The onset of EMG activity occurs during the first second. Since we typically use 1-s or 2-s samples of EMG activity, we do not have quantitative data on response times.

The confusion arises from the fact that the reduction in background luminance that yields values of VAS_{50} and $ODR_{0.25}$ indicates that the condition is more uncomfortable. We have attempted to clarify our discussion of the between-subject differences by adding arrows to **Figures 11** and **12** that indicate what corresponds to increased discomfort and what constitutes decreased discomfort.