Confirmation of the Validity of the Psychophysical Light Scattering Factor

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Purpose. To reevaluate the validity of the light scatter factor (LSF) formula of Paulsson and Sjöstrand, LSF = \( \frac{L}{E} \left( \frac{M_2}{M_1} - 1 \right) \), where L is the target luminance, E is the illuminance of the glare source at the eye, and M₂ and M₁ are modulation contrast thresholds measured with and without the glare source, respectively. This equation has recently been deemed invalid by Yager, Yuan, and Mathews.

Method. Ratios of contrast thresholds with and without glare were measured for three glare illuminance levels for each of three stimulus luminances. This resulted in five different ratios of L/E, spanning a range of 1.6 log units.

Results. The data show an excellent fit to the Paulsson and Sjöstrand equation, and the LSF scores conform well to previously published normative values.

Conclusion. The light scatter factor equation of Paulsson and Sjöstrand is confirmed as valid without resorting to the need for correction factors based on variables such as pupil size. Invest Ophthalmol Vis Sci. 1994;35:317-321

As a result of the imperfections of the ocular media, light from any peripheral glare source will be scattered within the eye, with some falling on the fovea. This scattered light causes a reduction in visual performance, commonly termed disability glare. A measure of the quality of the ocular media may be obtained by determining the proportion of illuminance arriving at the eye from a peripheral glare source (E), which is subsequently scattered to the fovea. This has the same effect as an equivalent veiling luminance, Leq, superimposed upon the stimulus itself.

The light scattering factor (LSF) of the eye can be defined as

\[
\text{LSF} = \frac{\text{Leq}}{E}
\]  

The veiling luminance reduces stimulus contrast by a factor \( \frac{L}{L + \text{Leq}} \), where L represents mean stimulus luminance. Therefore, the ratio of contrast thresholds measured with and without the presence of a glare source (M₂ and M₁, respectively) is given by

\[
\frac{M_2}{M_1} = \frac{L + \text{Leq}}{L} = 1 + \frac{\text{Leq}}{L}
\]

thus,

\[
\text{Leq} = \left( \frac{M_2}{M_1} - 1 \right) L
\]

substituting into [1],

\[
\text{LSF} = \left( \frac{L}{E} \right) \cdot \left( \frac{M_2}{M_1} - 1 \right)
\]

As Paulsson and Sjöstrand\(^1\) point out, this equation allows an intrinsic light scattering factor to be determined for any given glare angle. In addition, the LSF calculated in this way should remain independent of the precise stimulus conditions used for its determination. The reason for this is that variations in L and E should be counteracted by corresponding variations in contrast thresholds.
Recently, however, the validity of this approach has been questioned. Yager et al. did not find the expected constancy in LSF when two different values of L/E were used. This finding has already been used by other authors to question the validity of the formula and, subsequently, the method of assessing light scatter using contrast thresholds with and without glare. This report reevaluates the validity of Paulsson and Sjöstrand’s LSF calculation by assessing the consistency of LSFs measured with three glare luminances at each of three stimulus luminance levels.

METHODS. Contrast thresholds for the detection of 1.87 Hz sinusoidal flicker of a 50-minute-arc circular target on a 5° square background field of identical mean luminance were measured with and without the presence of glare. The stimulus was presented on the face of a CRT (WTDS phosphor) at a viewing distance of 2 m and was controlled by a Venus Visual Stimulator (Neuroscientific Ltd., Farmingdale, NY) under application software control. This localized target was favored because its visual eccentricity can be accurately specified relative to the glare source. This is not true for wide-field grating stimuli in which different parts of the stimulus lie at different angular distances to the glare source. This results in an uneven distribution of veiling luminance across the stimulus. Yager et al. avoided this problem by using a vertical antisymmetric Gabor stimulus. In addition, the equal mean luminance of the background field reduces potential problems associated with improvements in contrast sensitivity resulting from the background retinal illuminance produced by the glare source.

Mean stimulus luminance was 49.0 cd m⁻². Additional luminance levels of 12.3 and 4.9 cd m⁻² were obtained by superimposing neutral density filters on the stimulus and its background. After an appropriate choice of starting modulation, a method of increasing contrast was used to measure thresholds. To reduce flicker adaptation effects, flicker was presented in four cycle sequences (lasting 2.14 seconds) separated by 1-second intervals of mean luminance. The contrast of each successive presentation was increased by 0.1 log units. Threshold was recorded as the contrast level at which flicker was first perceived. The final threshold was calculated as the mean of at least four such threshold estimates. The order of measurement was randomized. In addition, to avoid the possibility of observers responding on the basis of time elapsed, a random time delay was inserted at the beginning of each sequence.

For the glare source, we used a 1,000-W tungsten-halogen bulb housed in a projector unit. Light from the bulb was projected through a filter centered at 580 nm wavelength with a half-height bandwidth of 20 nm. The glare source had a maximum luminance of 368 cd and was placed at 6.5° visual angle from the stimulus. The illuminance arriving at the eye from the glare source was measured photometrically by a spectrophotometer (Bentham Instruments Ltd., Reading, UK) and was varied between 361 and 22.8 lux by means of neutral density filters. Contrast thresholds were measured for each illuminance level (E) for each of the three stimulus luminances (L), giving a total of nine conditions. Five different ratios of L/E were investigated, spanning a range of 1.60 log units.

Three experienced observers 30, 24, and 24 years of age participated in the study. All had normal ocular health, visual acuity of 6/5 or better, and wore their appropriate refractive correction. Informed consent was obtained, as was approval of the human experimentation committee of the institution, and the tenets of the Declaration of Helsinki were followed. Measurements were made using the natural pupil, which varied in diameter from 7 mm (observer DW), 7 mm (RS), and 6.5 mm (IM) for the no-glare, low-stimulus luminance condition to 5, 5, and 4.5 mm, respectively, for the high-glare, high-stimulus luminance. To determine whether the improvement in the optical quality of the retinal image associated with the miosis had a significant effect on contrast thresholds, we measured thresholds for these two pupil size conditions for each observer. Pupil size was controlled using the miotic thymoxamine hydrochloride, and retinal illuminance changes were avoided by increasing stimulus luminance by 0.3 log units to compensate for the reduction in pupil size. No significant change in contrast thresholds were observed as a function of pupil size for any of the observers (P > 0.1).

The reliability of our disability glare measurements (the ratio of contrast thresholds with and without glare) was assessed by taking test-retest data for the medium stimulus luminance at each glare illuminance level (including the no-glare condition). Coefficient of repeatability (95% confidence limits for the discrepancy between test and retest data) averaged 0.15 log units for the three observers. This compares favorably with a range of other disability glare tests.

RESULTS. Figure 1 shows contrast thresholds as a function of ocular illuminance for the three stimulus luminance levels for each observer. An illuminance level of zero denotes the absence of glare. In this no-glare condition, there is no significant difference between contrast thresholds for the three stimulus luminances (P > 0.1 for all three observers). As glare illuminance increases, however, contrast thresholds for the low-stimulus luminance increase dramatically, whereas the increase in contrast thresholds for the high-stimulus luminance is less marked.

Figure 2 shows the ratio of contrast thresholds with and without glare (M₂/M₁) plotted against E/L.
FIGURE 1. (A, B, C) Contrast thresholds as a function of ocular illuminance produced by the glare source. Each graph represents data from a different observer. Different symbols represent the three stimulus luminance levels: filled squares, 4.9 cd m$^{-2}$; open squares, 12.3 cd m$^{-2}$; circles, 49 cd m$^{-2}$. Data points represent a mean of at least four threshold estimates, and standard error of these estimates are shown.

FIGURE 2. (A, B, C) Ratio of contrast thresholds with and without glare ($M_2/M_1$) against E/L for each of the three subjects. Different symbols represent the three stimulus luminance levels: filled squares, 4.9 cd m$^{-2}$; open squares, 12.3 cd m$^{-2}$; circles, 49 cd m$^{-2}$. Standard errors of each data point are shown. The data are fitted with the best-fitting linear regressions weighted according to the inverse variance of each point.
for each observer. The best-fitting linear regression, weighted according to the inverse variance of each point, is shown. From equation 2,

$$M_2/M_1 = 1 + \text{LSF} \cdot E/L$$

If this equation is valid, the y-intercept of the linear regression shown in Figure 2 should equal 1, and data points for different conditions should all lie on the regression line. The actual y-intercepts (±1 SE) for the three observers were 0.93 ± 0.06, 1.11 ± 0.14, and 0.95 ± 0.10 (Figures 2A, 2B, 2C, respectively). R² values for each observer exceed 0.95. The gradient of the linear regression predicts the LSF. Values for LSF (±1 SE) were 0.16 ± 0.01, 0.11 ± 0.02, and 0.11 ± 0.02 for Figures 2A, 2B, 2C, respectively. The highest LSF occurred for the oldest subject.

**DISCUSSION.** The highly linear relationship between $M_2/M_1$ and E/L and the closeness of the y-intercept to a value of 1 confirm the validity of the Paulsson and Sjöstrand equation (equation 2). Our conclusion is therefore contradictory to that of Yager et al.2 Although we used a criterion-dependent method of threshold determination, all three observers were experienced in making these psychophysical measurements, and test-retest repeatability of scores was good. Of course, unreliability in any part of the methodology is more likely to lead to the conclusion that there is not a linear relationship between $M_2/M_1$ and E/L rather than the reverse.

Our LSF scores conform to previously published normative data. LSF is dependent on the angle of the glare source θ. Many formulae have been determined empirically to explain this angular dependency,6 but in their recent report Yager et al2 cite the formula of Vos, Walraven, and van Meeteren7:

$$\text{LSF} = \frac{29}{\theta + 0.13}^{2.8}$$

According to this equation, LSF at 6.5° should be 0.15. At an angle of 7°, IJspeert et al7 found a mean LSF of 0.12 (95% confidence limits of 0.08 to 0.20) for a group of 20- to 30-year-old subjects. Our three LSF values of 0.16, 0.11, and 0.11 are therefore in good agreement with these values. Using a glare angle of 1.7°, Paulsson and Sjöstrand found mean LSF scores for five subjects at two E/L values (0.4 and 4) of 4.9 ± 1.9 and 4.5 ± 1.1, which are not significantly different ($P > 0.1$). Equation [3] predicts an LSF at 1.7° of 5.3, which is consistent with Paulsson and Sjöstrand’s data.

Yager et al used a glare angle of 3.5° and recorded mean values of LSF for 12 subjects (age range, 22 to 50 years) at two values of E/L (1.87 and 9.26) of 0.26 ± 0.18 (SD) and 0.49 ± 0.34, respectively. Equation [3] predicts an LSF of 0.78. IJspeert et al give mean values of 3.5° LSF for 20- to 30-year-old subjects and 40- to 50-year-old subjects, respectively, of 0.57 (95% confidence range of 0.38 to 0.89) and 0.67 (95% confidence range from 0.44 to 1.02).9 Therefore, Yager et al’s values appear to be significantly lower than established normal data, particularly at the low E/L condition. They measured LSF for two values of E/L, and a Student’s t-test analysis indicated that LSF scores for 12 subjects at the two E/L values were significantly different ($P < 0.03$). It may be pertinent to note that if any one of three outliers from their 12 subjects is removed, the difference between the two sets of LSF data becomes insignificant. Two of these outliers had LSFs of 0.01 at the low E/L condition, and the other had an LSF of 1.32 at the high E/L condition.

Yager et al’s skepticism of the the validity of equation 2 has led some authors to doubt the usefulness of measuring LSF using contrast thresholds with and without glare6,4. This doubt was reinforced by results showing a nonlinear relationship between straylight values measured with the van den Berg straylight meter and scores using contrast thresholds measured with and without glare on the Vistech MCT8000.5 This leads to the important consideration of the optimum stimulus conditions that should be used to determine LSFs by measuring contrast thresholds with and without glare. First, it is essential that the luminance of the stimulus not be too low and is within the region of Weber’s law (where contrast thresholds are independent of luminance). Performance will therefore not be improved by the increase in retinal illumination produced by the glare source. In this respect, it is preferable for the stimulus to be of low spatial and temporal frequency content because such stimuli become dependent on retinal illumination at lower levels than at higher frequencies.9 Second, the stimulus should be surrounded by a field of the same mean luminance. It is well-established that contrast sensitivity is reduced by the presence of a dark border, and deWaard et al8 have suggested that, under such conditions, the addition of a veiling luminance on the retina from a glare source could improve sensitivity by brightening the border to the stimulus. Finally, a spatially localized target is preferred because all parts of the stimulus then lie at approximately the same visual angle from the glare source, resulting in an even veiling luminance over the entirety. A further point is that neural adaptation effects should be avoided by ensuring that no part of the target is within 1° of the glare source.6

Abrahamsson and Sjöstrand10 updated equation 2 to include a correction factor to account for changes in pupil size caused by the glare source. They suggested an empirically determined factor of 1.2. It is questionable whether any correction factor for pupil size is necessary. Equivalent veiling luminance (Leq) is
defined as the luminance that, when superimposed upon the stimulus (Ls), has the same effect as a veiling retinal illuminance (Ev) upon the retinal illuminance of the stimulus (Es).

Therefore,

\[ \frac{Ev}{Es} = \frac{L_{eq}}{Ls} \]

Because both Ev and Es depend to the same extent upon pupil size, Leq should remain independent of variations in pupil size. Hence, from equation 1, this will also hold true for LSF. The reasoning is that pupil size changes affect retinal illuminance of the stimulus and the glare source equally. Of course, original pupil size is important insofar as it determines retinal illuminance. It should also be noted that the change in pupil size with glare is likely to have a significant effect in cataract. This is particularly true for posterior subcapsular cataract in which the decrease in pupil size with glare means that the opacity takes up a much greater proportion of the pupillary area. Obviously, in such cases, the difference between thresholds with and without glare is not simply a measure of light scatter alone but it is, nevertheless, representative of real-life performance. Many patients with posterior subcapsular cataract can see perfectly well under normal levels of luminance but are markedly affected in glare conditions.

In conclusion, our results confirm the validity of the Paulsson and Sjöstrand equation [equation 2] for a sample of normal, experienced observers. We argue that corrections to the formula to account for factors such as pupil size changes are unnecessary. The results confirm the suitability of measuring the LSF using contrast thresholds with and without glare, provided (as with any psychophysical procedure) that appropriate methods are used.

**Key Words**

light scattering factor, disability glare, straylight.

**References**