Visibility of Targets

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Traffic safety is highly correlated to the amount of visual information that can be obtained from the road and its immediate environment. It is therefore a logical consequence to base any quality judgment for lighting systems on visibility criteria. This development can be observed in indoor lighting as well, where the visibility-related CRF (contrast rendering factor) was introduced as a quality criterion. Visibility as a characteristic of roadway lighting has recently been discussed in Canada. When applying visibility as a criterion, there needs to be a metric to measure it and a method for calculation to predict the visibility level to be achieved in a certain lighting installation.

Outlined below are the basics arising from the physiology of the visual system. Assuming that achromatic light is in general white or near white, there needs to be a certain luminance difference between the target and background to perceive it.

Figure 1 shows a target subtending the angular size α seen against a background luminance L_b. The target can have a higher luminance than the background (positive contrast) or appear darker than L_b (negative contrast). For both cases, a minimal luminance difference is needed to perceive the target with a certain probability level:

$$\Delta L = L_T - L_b$$

where L_T equals target luminance. In this paper, $p = 99.93$ percent.

Figure 2 contains the results of the necessary ΔL for positive contrast as a function of the target size on a background of $L_b = 10^3$ cd/m². For small targets, this curve shows the following function:

$$\log \Delta L = -2 \log \alpha + k \Big|_{\alpha \to 0}$$

This reflects Ricco's law, for which summation is observed over a receptive field. The size of this field is indicated by the critical Ricco's angle, often taken from the intersection of that line with the abscissa. A more precise value can be obtained from the point of a defined deviation from the law expressed by that line.

For larger α, the threshold ΔL attains a contrast value independent from the target size:

$$\log \Delta L = \text{const} \Big|_{\alpha \to \infty}$$

This expresses Weber's law, indicating that for larger objects the threshold is dependent only on L_b and approaches

$$\Delta L / \Delta L_b = 1$$

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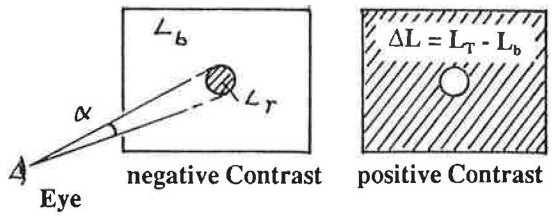

FIGURE 1 Target with angular size α against background luminance L_b. L_T is the luminance of the target.

The calculation of ΔL is based on a composite of these two laws. This study introduces two auxiliary functions: the luminous flux function, (ϕ), characteristic for the Ricco process, and the luminance function (L), reflecting Weber's law:

Ricco:

$$\Delta L = K \cdot \alpha^{-2} \Big|_{\alpha \to 0}$$

Weber:

$$\Delta L = \text{const} \Big|_{\alpha \to \infty}$$

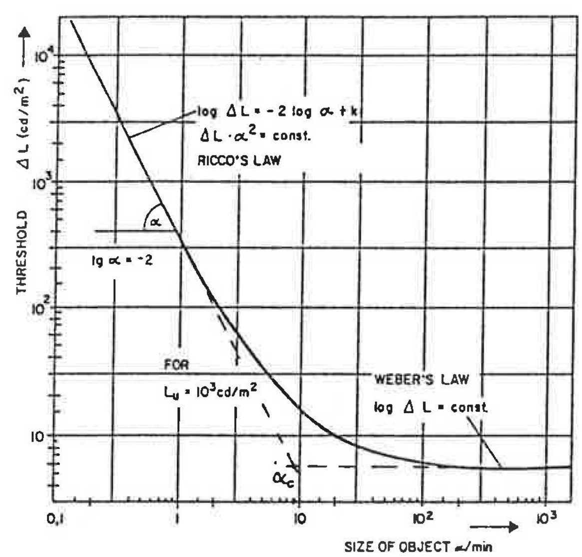

FIGURE 2 ΔL threshold as a function of α at a constant background luminance $L_b = 10^3$ cd/m². The intersection of the Ricco and Weber functions is often taken as an indicator of the critical angle α_c over which summation occurs.

Ricco:

$$\Delta L_{\alpha \to 0} = \Phi(L_b) \cdot \alpha^{-2}$$

Weber:

$$\Delta L_{\alpha \to \infty} = L(L_b)$$

ΔL is derived from the combination of the two functions in the following form:

$$\Delta L = k \cdot \left(\frac{\sqrt{\phi}}{\alpha} + \sqrt{L}\right)^2$$

From Adrian's (*1*), Aulhorn's (*2*), and Blackwell's (*3*) data, the ϕ and L functions have been derived and can be calculated as follows:

Adrian:

$$L_b \geq 0.6 \text{ cd/m}^2$$

$$\sqrt{\phi} = \log (4.1925\ L_b^{0.1556}) + 0.1684\ L_b^{0.5867}$$

$$\sqrt{L} = 0.05946\ L_b^{0.466}$$

Aulhorn:

$$L_b \leq 0.00418 \text{ cd/m}^2$$

$$\log \sqrt{\phi} = 0.028 + 0.173 \cdot \log L_b$$

$$\log \sqrt{L} = -0.891 + 0.5275 \cdot \log L_b + 0.0227 (\log L_b)^2$$

Blackwell:

$$0.00418 \text{ cd/m}^2 < L_b < .6 \text{ cd/m}^2$$

$$\log \sqrt{\phi} = -0.072 + 0.3372 \cdot \log L_b + 0.0866(\log L_b)^2$$

$$\log \sqrt{L} = -1.256 + 0.319 \cdot \log L_b$$

INFLUENCE OF EXPOSURE TIME

The data are obtained with 2 sec or unlimited observation time. For a shorter exposure time of the target, higher ΔL values are needed. This influence is measured by the following equation:

$$\frac{a(\alpha, L_b) + t}{t}$$

where a is the Blondel-Rey constant and is a function of the target size and luminance level L_b. The following equations to calculate a (α, L_b) are based on experimental data from Schmidt-Claussen (*4*) and Blackwell (*5*):

$$a(\alpha) = 0.36 - 0.0972 \frac{(\log \alpha + 0.523)^2}{(\log \alpha + 0.523)^2 - 2.513 (\log \alpha + 0.523) + 2.7895}$$

$$a(L_b) = 0.355 - 0.1217 \frac{(\log L_b + 6)^2}{(\log L_b + 6)^2 - 10.4 (\log L_b + 6) + 52.28}$$

For small targets ($\alpha < 60$ min of arc), the value of $a(\alpha, L_b)$ can be best approximated by

$$a(\alpha, L_b) = \frac{\sqrt{a(\alpha)^2 + a(L_b)^2}}{2.1}$$

The increase in threshold value ΔL for a target of $\alpha = 10$ min with a shorter observation time is illustrated below ($L_b = 1$ cd/m²):

Observation Time (t sec)	$\frac{a(\alpha, L_b) + t}{t} = \frac{\Delta L_t}{\Delta L_{t=2\ sec}}$
2	1
.1	2.11
.01	12.66

$$\Delta L_t = \Delta L_{t=2\ \text{sec}} \cdot \frac{a(\alpha, L_b) + t}{t}$$

DIFFERENCE BETWEEN ΔL THRESHOLDS FOR POSITIVE AND NEGATIVE TARGET CONTRAST

So far, only targets of positive contrast have been considered. Aulhorn (*2*) reported that, at the same ΔL, a target in negative contrast could always be seen better than a target in positive contrast. She wrote: "We face this phenomenon whatever visual function we consider" (she had investigated the luminance difference sensitivity and its relationship to the visual acuity). She produced considerable data for both positive and negative contrast. From the data, it can be concluded that the threshold differences between negative and positive targets are dependent on L_b and also on target size α. For an explanation of these phenomena, it is helpful to study the results of Remole (*6*). He investigated the border contrast and found inhibitory effects on either side of borders. Figure 3 is taken from Remole's publication. The lengths of the inhibitory zones are different, and the ratio between them varies with the luminance level, which accounts for the dependency on α and L_b. The arrows indicate the widths measured. Remole (*6*) has shown that the ratio a/b and the absolute value of b depend on the luminance level.

To obtain the difference between ΔL for positive and negative contrast, a factor (F_{CP}) was derived from Aulhorn's data. ΔL_{neg} follows from the term

$$\Delta L_{neg} = \Delta L_{pos} \cdot F_{CP}$$

where ΔL_{pos} is the value for exposure time $t = 2$ sec. F_{CP} is computed according to the following equation:

$$F_{CP}(\alpha, L_b) = 1 - \frac{m \cdot \alpha^{-\beta}}{2.4\ \Delta L_{pos_{t=2}}}$$

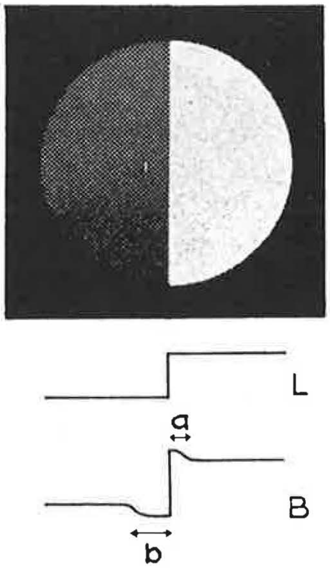

FIGURE 3 Stimulus field with illuminated portion of hairline visible in the dark field.

where

$m = 10^{-10^{-(.125(\log L_b + 1)^2 + .0245)}}$ for $L_b \geq .1$ cd/m^2

$m = 10^{-10^{-(.075(\log L_b + 1)^2 + .0245)}}$ for $L_b > .004$ cd/m^2

$\beta = 0.6 L_b^{-.1488} \quad \forall\, L_b$ cd/m^2

Threshold ΔL for a target with negative contrast (darker than the background) is obtained by

$$\Delta L_{\mathrm{neg}} = F_{CP} \cdot \Delta L_{\mathrm{pos}_{t=2}}$$

Figure 4 shows the function for the contrast polarity factor (F_{CP}) versus target size for luminance levels as used by Aulhorn in her investigations (she chose the unit asb as a basis, which leads to the odd numbers when expressed in cd/m^2). The curves indicate that F_{CP} is always <1, which yields smaller ΔL thresholds for negative contrast. Figures 5, 6, and 7 allow a comparison between Aulhorn's data and the calculated function according to the method described in this paper, which is based on Adrian's and Blackwell's data. ΔL_{pos} and ΔL_{neg} thresholds are plotted versus the target size for different levels of L_b.

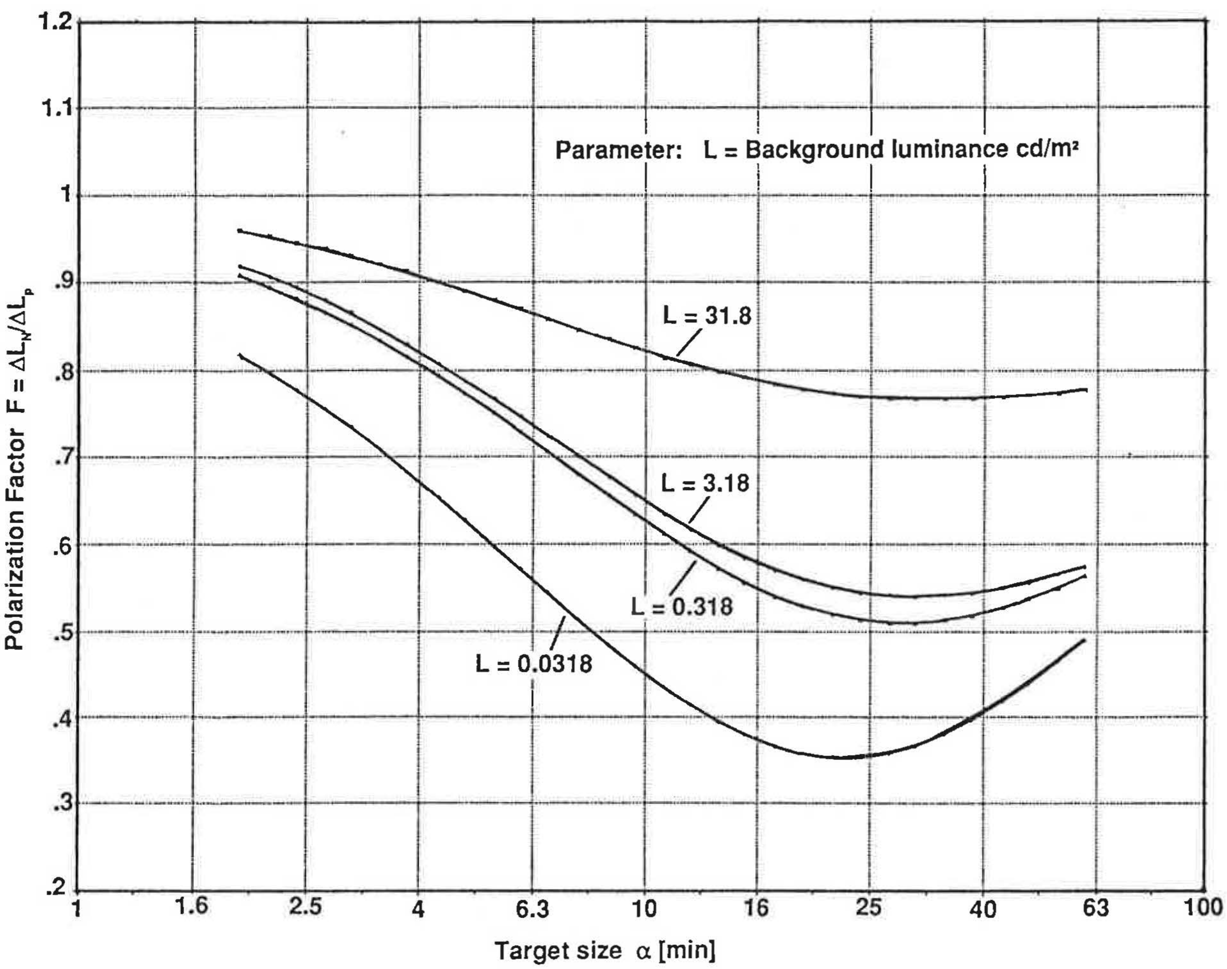

FIGURE 4 The contrast polarity factor, F_{CP}, dependent on target size α and the background luminance. The curves show the relationship between positive and negative target contrast. In negative contrast the threshold of a target of a defined size is always lower than in positive contrast at the same background luminance, so darker targets appear to be better perceived than brighter targets at the same luminance difference.

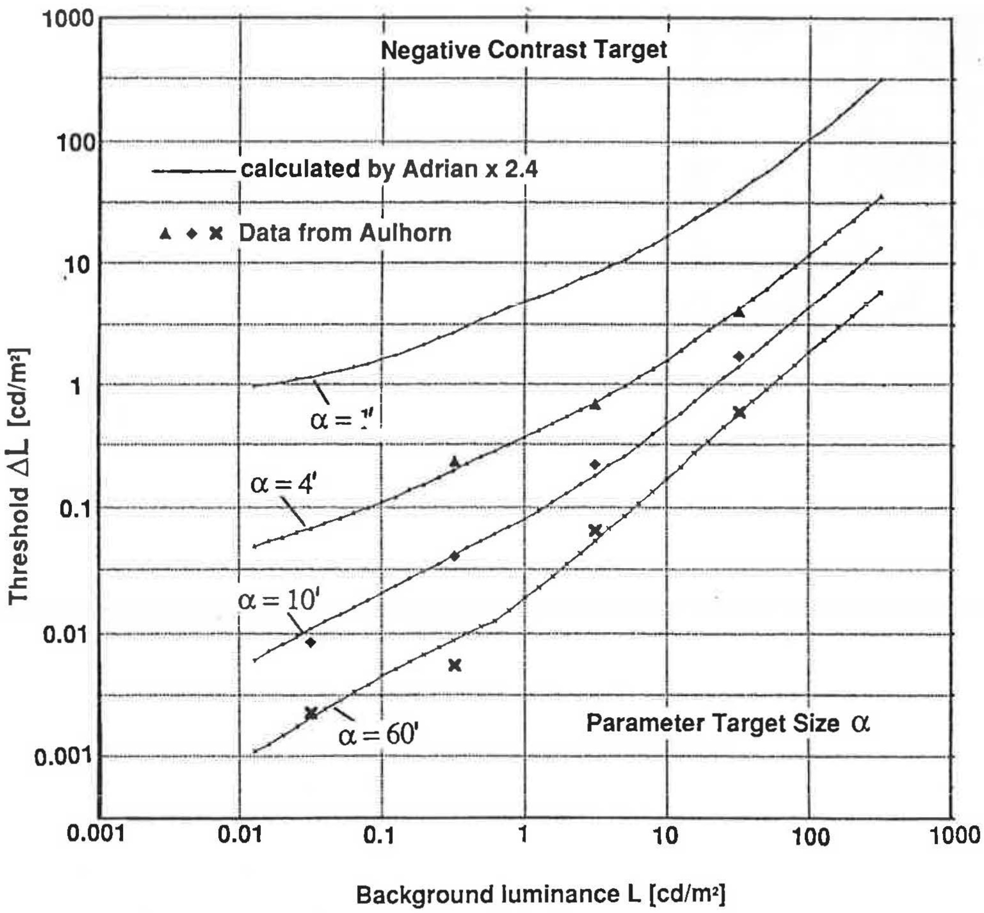

FIGURE 5 Comparison between Aulhorn's data for negative contrast targets and Adrian's ΔL_{pos}. The data have been multiplied by F_{CP} to convert them to negative contrast. A factor of 2.4 had to be applied to account for Aulhorn's monocular observation conditions and the age difference of her subjects. There are no data for $\alpha = 1'$ measured by Aulhorn in negative contrast.

To obtain the best fit, the calculated values had to be multiplied by 2.4. This was due to the different observation conditions Aulhorn chose in contrast to those used in Adrian's and Blackwell's experiments. Aulhorn used only three subjects. One of them was 55 years old and requested a higher threshold due to reduced ocular transmittance. Furthermore, Aulhorn used monocular observation rather than binocular viewing, which was used in the other investigations.

Monocular and binocular observation are known to be different by a factor of around 2, although Campbell and Green (*7*) reported a higher ΔL threshold for monocular observations of 1.64 (see below). The 55-year-old person would demand on average 1.59 times higher ΔL levels than a 23-year-old subject. The weight with which the readings of the older subject were incorporated in the reported data are not available. However, if the factors of 1.64 for monocular observation and 1.59 for the higher age are considered, the total is 2.6, which explains the shift of 2.4 (keeping in mind that two younger subjects also contributed to the mean data, thus lowering the increase caused by the older one).

INFLUENCE OF AGE

Mortenson-Blackwell and Blackwell (*8*) and Weale (*9*) have measured ocular transmittance and found that it decreases with age. This results in higher ΔL thresholds for older people, as shown in Figure 8 (*8*). From those findings, a multiplier can be derived to account for the age-dependent threshold increase. The findings are obtained for positive contrast, and it is not unreasonable to assume that it holds also for negative contrast. The relatively good fit of the data for negative contrast with the calculated curves in Figure 5 justifies this assumption.

The ΔL for subjects older than 23 years, on which the function assumes unity, can be found in the following way:

$$\Delta L_{Age} = \Delta L_{23} \cdot AF$$

For	*Where Age Factor AF is*
$23 < \text{Age} < 64$	$AF = \frac{(\text{Age} - 19)^2}{2{,}160} + 0.99$
$64 < \text{Age} < 75$	$AF = \frac{(\text{Age} - 56.6)^2}{116.3} + 1.43$

Due to the parameters influencing the light perception, as described in the previous paragraphs, the visibility of a target expressed by the luminance difference threshold can be calculated according to

$$\Delta L = 2.6 \left(\frac{\sqrt{\Phi}}{\alpha} + \sqrt{L}\right)^2 \cdot F_{CP} \cdot \frac{a(L_b, \alpha) + t}{t} \cdot AF$$

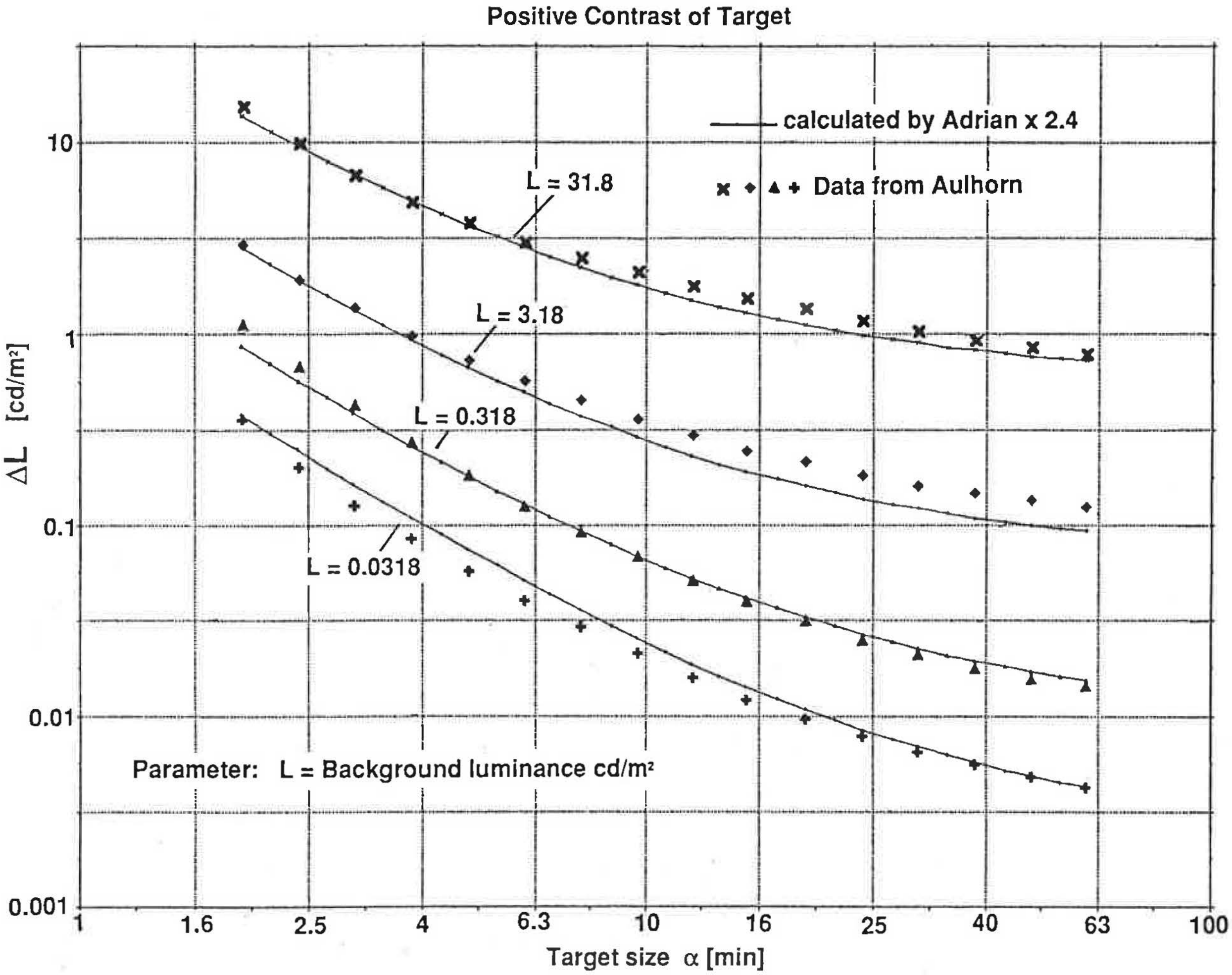

FIGURE 6 Comparison between calculated curves, as in Figure 5, and direct measurements of thresholds for targets in negative contrast. The calculated curves are obtained by using the positive thresholds of Adrian and Blackwell and applying the contrast polarity function F_{CP}.

where F_{CP} equals 1 for positive contrast and AF equals 1 for a young observer group with an average age of 23 years. ΔL is practically constant for exposure time less than or equal to 2 sec.

DISABILITY GLARE

The influence of disability glare can be incorporated in a relatively simple way. Glare sources present in the visual field impair vision and require an increase in ΔL to keep targets visible. The reason for that phenomenon is well known and lies in stray light produced by the sources of high illuminance in the various eye media, especially in the cornea crystalline lens and in the retinal layers. This stray light superimposes on the retinal image, which results in a reduction of the image layers. This can be expressed as

$$C = \frac{\Delta L}{L_b}$$

With glare,

$$C_{red} = \frac{\Delta L}{L_b + L_{seq}}$$

L_{seq} represents a uniform luminance that adds to the background luminance (L_b) and is equivalent to the glare effect on the target visibility. This effect increases with smaller angular distance between the glare source and target and with growing illumination at the eye due to the glare source, according to the following expression:

$$L_{seq} = k \sum_{i=1}^{n} \frac{E_{Gl}i}{\Theta_i^2} \text{ cd/m}^2$$

where

$E_{Gl}i$ = illumination in lux at the eye from glare source i;
Θ_i^2 = glare angle in degrees between the center of the glare source and fixation line valid for $1.5° < \Theta < 30°$; and
k = age-dependent constant (for the 20- to 30-year age group, $K = 9.2$ is obtained).

In the case of glare, the adaptation luminance around the location of the target on the retina is consequently composed of L_b and L_{seq}. In the calculation of ΔL, L_b is substituted by $L_b + L_{seq}$.

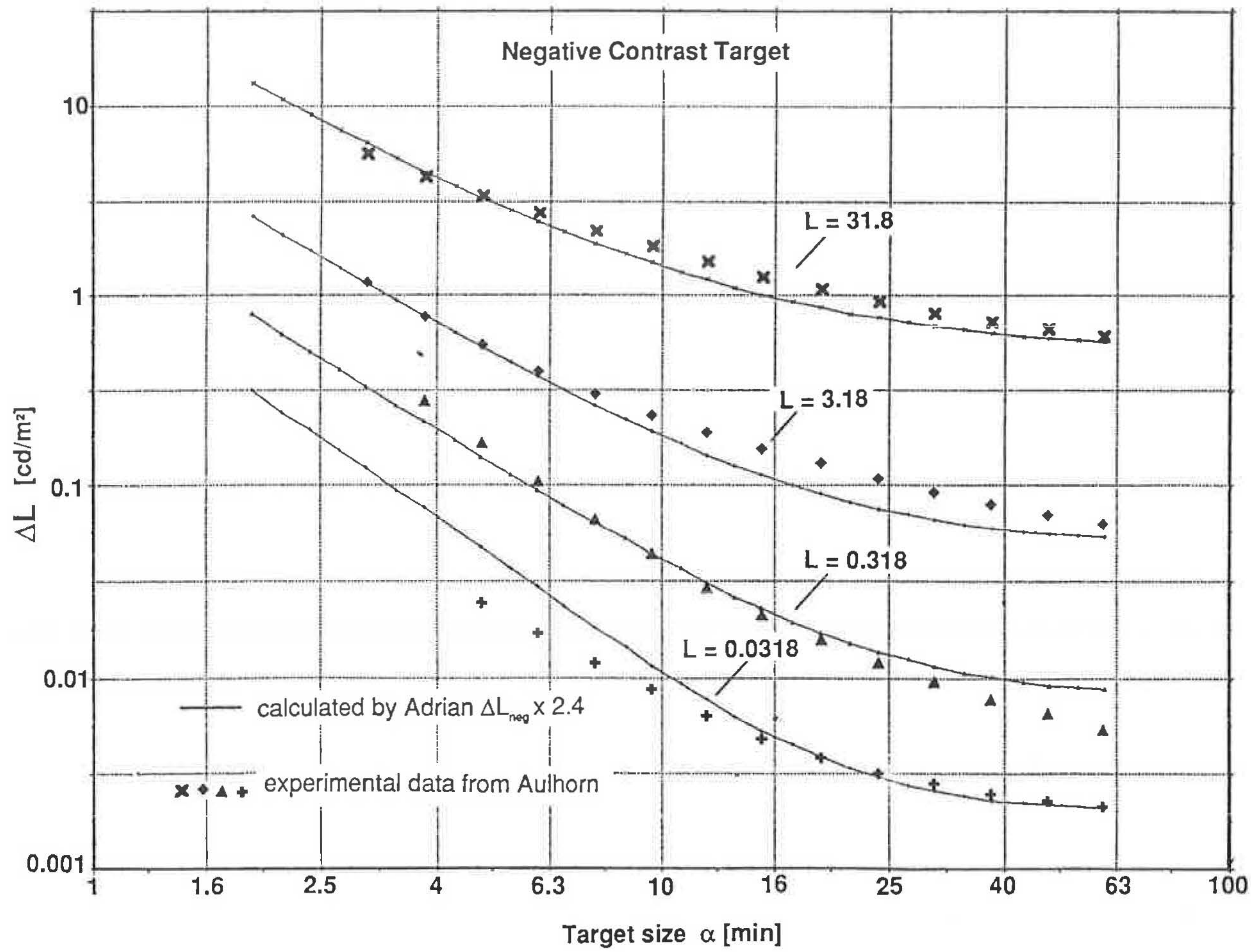

FIGURE 7 Luminance difference thresholds for ~100 percent probability of perception for targets of various size and brighter than their background. The curves are calculated and reflect Adrian's and Blackwell's measurements. The symbols are data from Aulhorn. Multiplication by 2.4 was necessary to account for different experimental conditions (see text).

VISIBILITY LEVEL *LV*

So far, this paper has dealt with the numerical description of the luminance difference threshold ΔL, based on experimental data. ΔL indicates a value at which a target of defined size becomes perceptible with near 100 percent probability under the observation conditions used in the laboratory experiments, which included free viewing with binocular observation (monocular in Aulhorn's study).

Under practical observation conditions, however, a multiple of ΔL is needed depending on the visual task demand. In most cases, the luminance difference has to reach a level that allows for form perception or that renders conspicuity to the target. One researcher in the early 1950s termed this the "suprathreshold factor." In an old DIN (Deutsche Industrie Norm) standard on signal lights, the multiple of the threshold was named the "safety factor" since it makes the target more visible. In CIE Report 19.2 (*10*), Blackwell introduced the descriptive term "visibility level (*VL*)," which indicates

$$VL = \frac{\Delta L_{\text{actual}}}{\Delta L_{\text{threshold}}}$$

The visibility level needed to secure safe traffic conditions is a function of the luminance to which the eye is adapted and the degree of form perception or visual acuity that is required. An attempt to determine necessary *VL* levels resulted in values between 10 and 20 for *VL* in the luminance range of street lighting (*11*). It has also been shown that a direct relationship exists between *VL* and the subjective rating of the visibility in street lighting installation (*12*).

The method described in this paper provides this value and allows an estimation regarding whether or not a target can be seen and how much the ΔL of the target is above the level of threshold perception.

CONCLUSION

The model presented allows the computation of the threshold luminance difference ΔL for various sizes of targets as a function of the background luminance L_b, seen in positive and negative contrast. ΔL, from which the threshold contrast $C = \Delta L/L_b$ or the contrast sensitivity $CS = L_b/\Delta L$ can be derived, applies for binocular, free viewing observations under laboratory conditions.

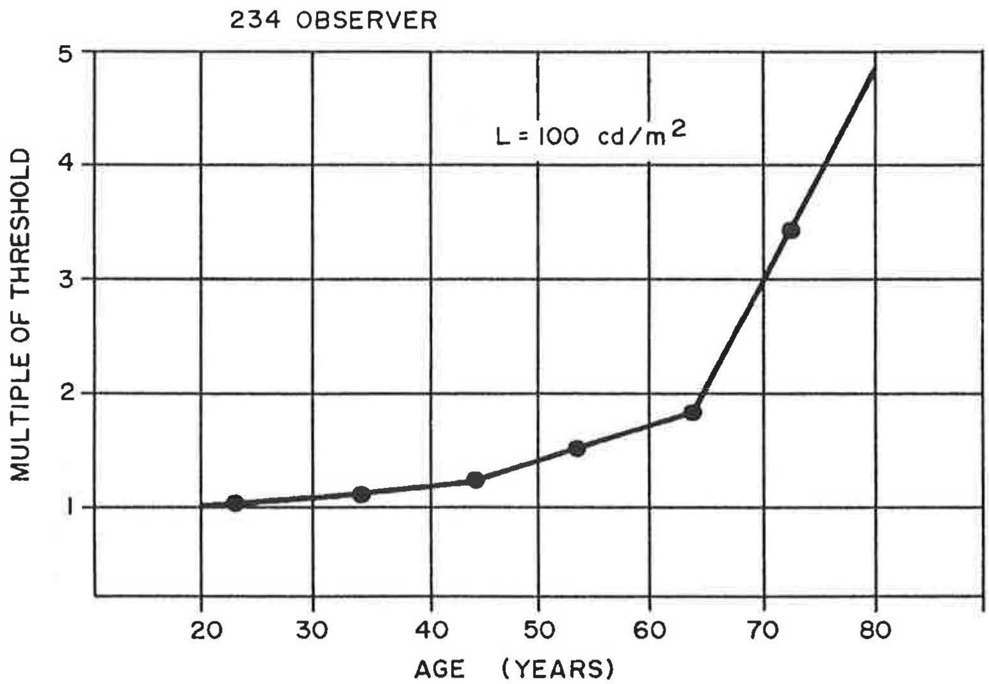

FIGURE 8 Multiple of the threshold contrast required for observer of higher age in relation to the base group with an average of 23 years [adopted from the work of Mortenson-Blackwell and Blackwell (*8*)].

The visibility level LV indicates how much the ΔL of a target is above its threshold value and can be used as a measure to evaluate visibility in lighting installations. For example, according to the latest draft of the American IES Committee, the quality of roadway lighting will be based on VL and recommendations on required visibility levels for different road categories will be made on this basis.

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