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Summary The introduction of the visibility level as a criterion for the obtainable visual information necessitates a metric to allow its quantification. On the basis of Adrian's, Aulhorn's and Blackwell's data a method has been developed to compute the luminance difference thresholds ΔL of visual targets of variable size and positive and negative contrast. Another parameter relevant to ΔL is the observation time to cope with practical viewing conditions in which fixation was found to be restricted to 0.1 to 0.2 s. The effect of age on the threshold contrast and that of disability glare has been incorporated. The numerical description allows the determination of the visibility level VL of objects in the visual field. A practical example of how to obtain VL is presented.

Visibility of targets: Model for calculation

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1 Introduction

Visual performance and traffic safety are highly correlated to the amount of visual information we can obtain from the road and its immediate environment. It is therefore a logical consequence to base any quality judgement 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.

Recently the introduction of visibility as a characteristic of roadway lighting has been discussed in North America. When applying visibility as a criterion we need to have a metric to measure it and a method for calculation as a design tool to predict the visibility level to be achieved in a certain lighting installation.

With this objective in mind I would like to outline the fundamentals arising from the physiology of the visual system. Assuming that we have achromatic light, in general white or near white, we need a certain luminance difference between target and background to perceive it.

Colour differences between target and background of the same luminance can also make the target visible. In levels of mesopic vision (cone and rod vision) such as in roadway lighting visibility is however mainly sustained by brightness difference perception, and colour has a minor influence on it.

The system described here is an extended version of the Adrian model of 1969[1] which allowed the calculation of luminance differences only. It was modified in 1982 to incorporate the effect of the observation time of the target[2]. Presented here is an extended version to allow also the calculation of luminance difference thresholds ΔL for targets of negative contrast, in which the target appears darker than its surround, and the effect of age on the threshold perception.

Another approach to calculating ΔL thresholds is contained in Reference 3. That model is restricted to positive target contrast and seems not to produce appropriate threshold values, especially in lower luminance levels. Neither Blackwell's own data of 1946[4] nor those of Aulhorn[5] or the present author[1] fit the CIE-19.2 model.

It is noteworthy that the brightness difference sensitivity has been found to be independent of the wavelength of the light providing that instead of the photometric luminance L the equivalent luminance L_{eq} is used, a measure that assumes the actual spectral sensitivity of the eye in phototopic mesopic and scotopic levels. L_{eq} therefore seems to be a true correlate to the perceived brightness[6].

2 Model development

In the following the basic principle of the model is outlined. This is a repetition of the more detailed description given in References 1 and 2 which appears helpful to explain the procedure.

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 it appears darker than L_b (negative contrast). For both cases we need a minimal luminance difference

$$\Delta L = L_T - L_b \qquad (1)$$

(where L_T is the target luminance) to perceive the target with a certain probability level, which is for all further discussion $p = 99.93\%$.

This is the statistical probability that follows from a 2.6 times elevation of the threshold value found for 50% seeing probability. Blackwell[4] applied the forced choice method and his data are valid for 50% probability, while Aulhorn[5] and Adrian[1] chose the method of adjustment, raising the test stimulus from subthreshold values until it could be perceived. In order to match the 50% data with those found for threshold perception we have to multiply by a factor of 2.6. Blackwell reported[4] that his subjects could see the target with high probability at about 2 standard deviations above the 50% level, which relates to a factor of ~2.4 which is close to the value 2.6 found.

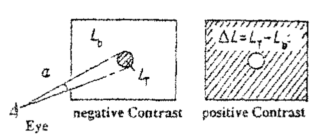

Figure 1 Target with angular size α can have positive or negative contrast to background luminance L_b. L_T is the luminance of the target.

Figure 2 contains experimental results of the necessary ΔL for positive contrast as a function of the target size on a background of $L_b = 10^3$ cd m^{-2}. This curve shows for small targets the function

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

reflecting Ricco's law for which we observe summation over the receptive field, the size of which is indicated by Ricco's critical 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 straight-line function.

For larger target sizes α the threshold ΔL assumes a constant value and becomes independent from the target size.

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

This expresses Weber's law indicating that for larger objects the threshold is dependent only on the background luminance L_b; the ratio finally assumes the value unity.

$$\Delta L / \Delta L_b = \text{const.}$$

The calculation of ΔL is based on a composite of these two laws. We introduce two auxiliary functions: Φ, the luminous flux function, characteristic for the Ricco-process, in which the luminous flux determines perception and L, the luminance function, reflecting Weber's law.

Ricco:

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

Weber:

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

Ricco: (3)

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

Weber:

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

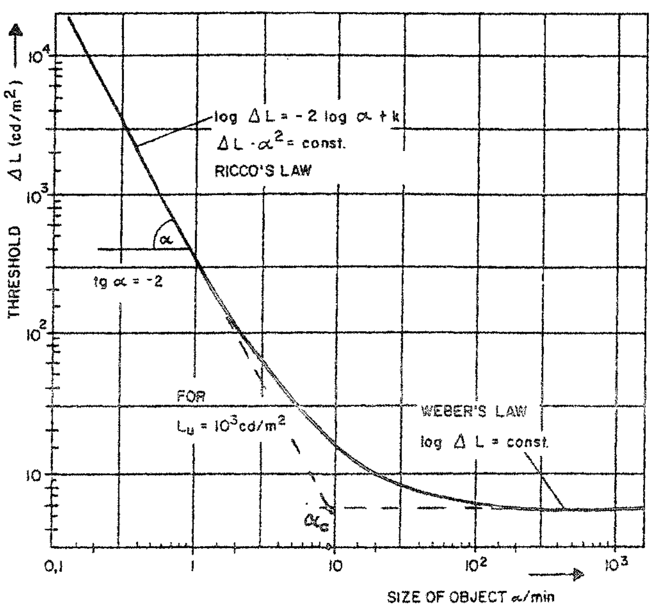

Figure 2 ΔL threshold as a function of α at a constant background luminance $L_b = 10^3$ cd m^{-2}. The intersection of the Ricco and Weber functions is often taken as indicator of the critical angle α_c over which spatial summation occurs.

Berek[7] suggested the geometric summation to obtain ΔL which assumes the form:

$$\Delta L = k\left(\frac{\phi^{1/2}}{\alpha} + L^{1/2}\right)^2 \qquad (\text{cd m}^{-2}) \quad (4)$$

From Adrian's[1], Aulhorn's[5] and Blackwell's[4] data the $\Phi^{1/2}$ and $L^{1/2}$ functions have been derived and can be calculated from the following equations:

$L_b \geqslant 0.6$ cd m^{-2}:

$$\phi^{1/2} = \log(4.1925\, L_b^{0.1556}) + 0.1684\, L_b^{0.5867} \quad (5)$$

$$L^{1/2} = 0.05946\, L_b^{0.466}$$

$L_b \leqslant 0.00418$ cd m^{-2}:

$$\log \phi^{1/2} = 0.028 + 0.173 \log L_b \quad (6)$$

$$\log L^{1/2} = -0.891 + 0.5275 \log L_b + 0.0227(\log L_b)^2$$

0.00418 cd m^{-2} $< L_b <$ 0.6 cd m^{-2}:

$$\log \phi^{1/2} = -0.072 + 0.3372 \log L_b + 0.0866(\log L_b)^2 \quad (7)$$

$$\log L^{1/2} = -1.256 + 0.319 \log L_b$$

For best fit it was necessary to subdivide the functions into three ranges of background luminance. With this set of equations, $\Phi^{1/2}$ and $L^{1/2}$ can be computed, which allows ΔL to be obtained according to equation 4 with a value for k of 2.6.

3 Influence of exposure time

The data on which the model was based were found with 2 s or unlimited observation time. ΔL has to increase for shorter exposure times in order to perceive the target. This influence is accounted for by a term:

$$\frac{a(\alpha, L_b) + t}{t} \quad (8)$$

in which a is a function of target size and luminance level L_b. The following equations to calculate $a(\alpha, L_b)$ are derived on the basis of experimental data of Schmidt-Claussen[8] and Blackwell[9].

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

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

For target sizes with ($\alpha < 60'$) the value of a (α, L_b) can best be approximated by the expression:

$$a(\alpha, L_b) = \frac{(a(\alpha)^2 + a(L_b)^2)^{1/2}}{2.1} \quad (9)$$

In consequence the threshold ΔL following from equation 4 valid for 2 s observation time has to be multiplied by equation 8 to account for shorter durations:

$$\Delta L_t = \Delta L_{t=2s} \frac{a(\alpha, L_b) + t}{t} \quad (10)$$

Table 1 gives an example for the increase of the threshold value ΔL for a target of $\alpha = 10'$ with shorter observation time for a background luminance of $L_b = 1$ cd m^{-2}.

Table 1

Observation time t(s)	$\frac{a(\alpha, L_b) + t}{t} = \frac{\Delta L_t}{\Delta L_{t=2s}}$
2	1
0.1	2.11
0.01	12.66

This illustrates that ΔL has to more than double to keep a 10′ target visible if it is seen for 0.1 s only.

4 Difference between ΔL thresholds for positive and negative target contrast

So far targets of positive contrast had been considered only. Adrian's and Blackwell's[1,4] measurements were made with targets of positive contrast only. Aulhorn[5] reported that a target in negative contrast (Figure 1) could always be better seen at the same ΔL than in positive and she wrote: 'We face this phenomenon whatever visual function we consider'. She investigated the luminance difference sensitivity and its relationship to the visual acuity and produced many data holding for targets of positive and negative contrast as well. From those it could be derived that the threshold differences between negative and positive targets are dependent on the background luminance L_b and also on the target size α. For an explanation of this phenomenon it is helpful to study the results of Remole[10]. He investigated the border contrast and measured the inhibitory effects on either side of borders. Figure 3 is taken from Remole's publication. The widths 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.

To obtain the difference between ΔL for positive and negative contrast, a factor F_{CP} (contrast polarity factor) was derived from Aulhorn's data. The luminance difference threshold ΔL_{neg} for a target in negative contrast can be computed with the term:

$$\Delta L_{neg} = \Delta L_{pos} F_{CP} \tag{11}$$

in which ΔL_{pos} has to be the value for the exposure time $t =$ 2 s. F_{CP} which is dependent on the background and target size can be calculated according to the equation:

$$F_{CP}(\alpha, L_b) = 1 - \frac{m\alpha^{-\beta}}{2.4\,\Delta L_{pos\,t=2}} \tag{12}$$

In this equation for $L_b \geqslant 0.1$ cd m^{-2}:

$$m = 10^{-10^{-(0.125(\log L_b + 1)^2 + 0.0245)}}$$

for $L_b > 0.004$ cd m^{-2}:

$$m = 10^{-10^{-(0.075(\log L_b + 1)^2 + 0.0245)}}$$

for all L_b:

$$\beta = 0.6\,L^{-0.1488}$$

In the case that a target of negative contrast is observed for a duration shorter than 2 s, ΔL_{neg} has to be multiplied by the time factor following from equation 8.

Figure 4 shows the function for the contrast polarity factor F_{CP} versus the target size for luminance levels as Aulhorn used in her investigations (she chose the unit asb as a basis, which leads to 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 reflecting the mentioned phenomenon that a target in negative contrast can be seen better than in positive of the same ΔL. Figures 5–7 allow a comparison between Aulhorn's data and the calculated function according to the described method that 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 the background luminance L_b.

In order to obtain the best fit with Aulhorn's data, the calculated values had to be multiplied by 2.4. This is caused by the different observation conditions Aulhorn chose in contrast to my own or those used in Blackwell's experiments. Aulhorn used three subjects only, one of whom was 55 years old, who requested a higher threshold due to reduced ocular transmittance. Furthermore she used monocular observation in contrast to binocular viewing as in the other investigations.

Monocular and binocular observation are known to be different by a factor slightly below 2. Campbell and Green[11] reported a higher ΔL threshold for monocular observations of 1.64. Following Figure 8 the 55-year old person would demand on average 1.59 times higher ΔL levels than a 23 year old subject. I don't know the weight with which the readings of the older subject have been incorporated in Aulhorn's data, but if the factors accounting for monocular observation of 1.64 and that for higher age of 1.59 are considered, we arrive at a total of 2.6 which explains the shift of 2.4 (keeping in mind that also two younger subjects contributed to the mean data, requiring lower thresholds than the older one).

As can be seen from Figures 5 to 7, the calculated functions derived from Blackwell's and Adrian's data reflect very reasonably the results of Aulhorn's experiments.

5 The influence of age on ΔL

Mortenson-Blackwell[12] and Weale[13] have measured ocular transmittance and found it decreasing with age. This results in higher ΔL thresholds for older people, which can be read from Figure 8 according to Reference 12. 234 subjects between 20 and 80 years have been divided in age groups of 10 years. The data points were placed at the average age in the groups. From those findings a multiplier can be derived to account for the age-dependent threshold increase. The

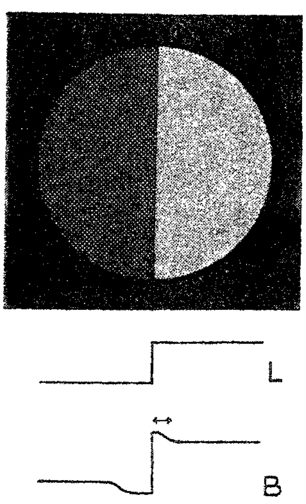

Figure 3 Stimulus field with illuminated portion of hairline visible in the dark field. L, luminance distribution; B, perceived brightness distribution. The arrows indicate the widths measured. Remole[10] has shown that the ratio a/b and the absolute value of b depend on the luminance level.

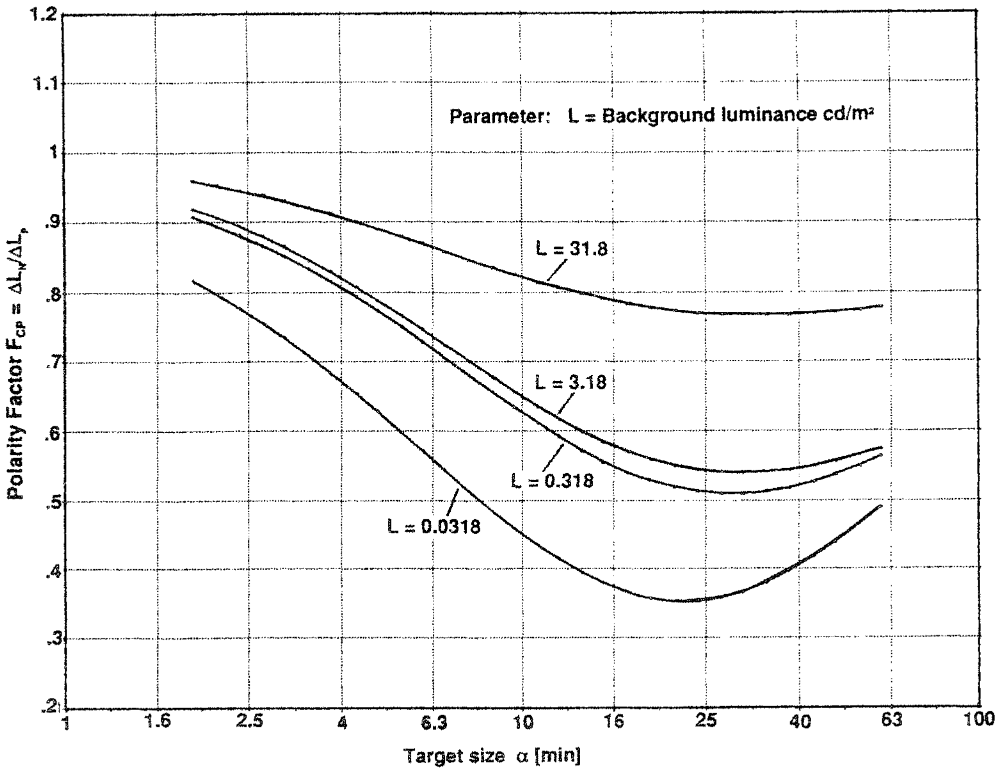

Figure 4 The contrast polarity factor is dependent on target size α and background luminance. The curves display the relationship between positive and negative target contrast. In negative contrast the threshold of a target of a defined size is always lower than in positive contrast at the same background luminance. This explains why darker targets appear to be better perceived than brighter targets at the same luminance difference.

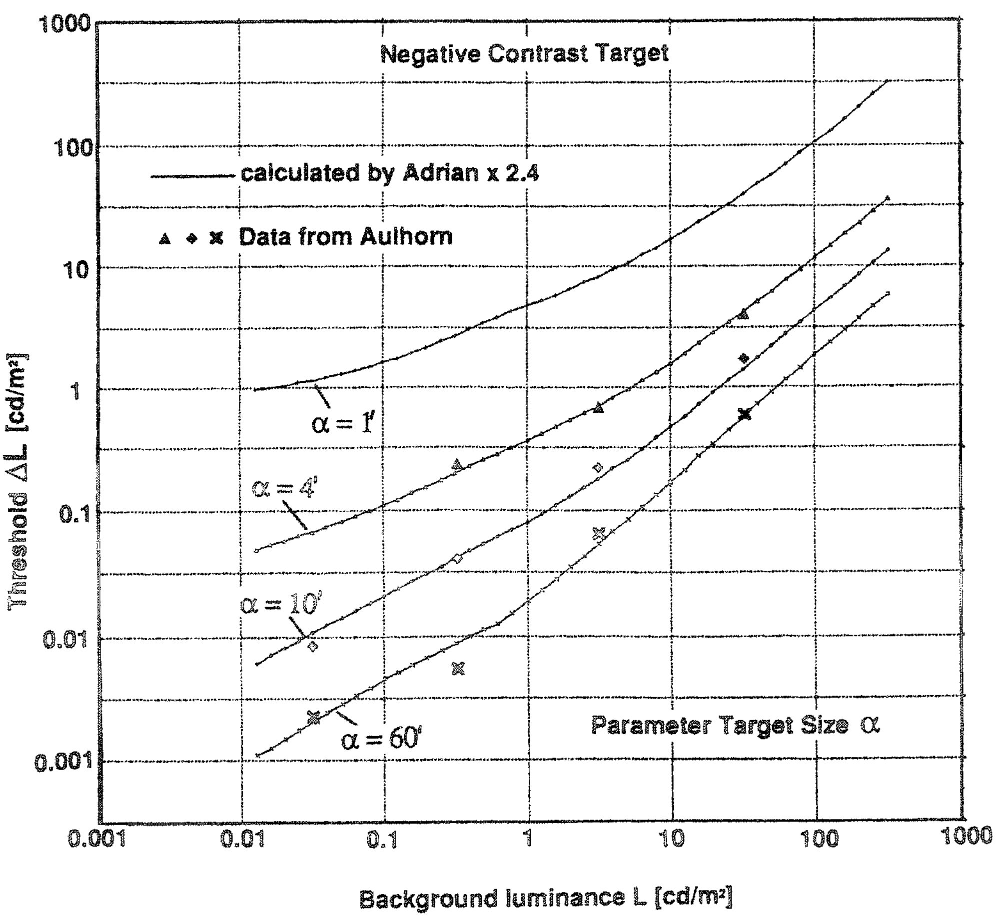

Figure 5 Comparison between Aulhorn's data for negative contrast targets and Adrian's ΔL_{pos} which have been multiplied by F_{cp} to convert to negative contrast. The factor 2.4 had to be applied to account for the monocular observation conditions Aulhorn chose, and the age difference of her subjects.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

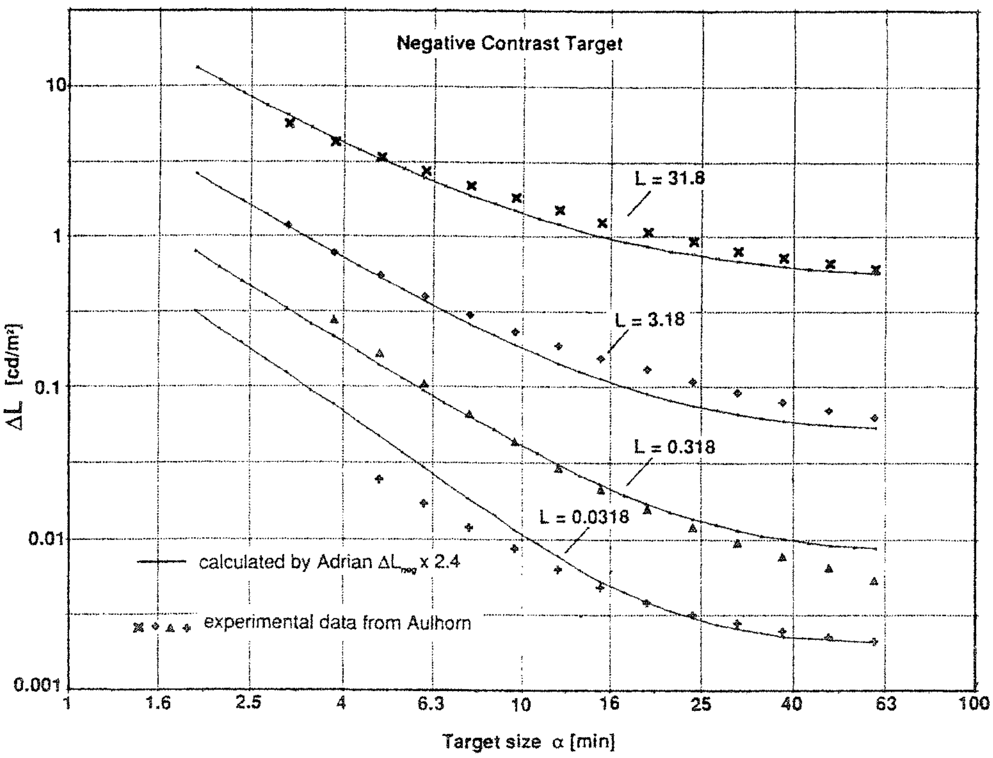

Figure 6 Comparison between calculated curves as in Figure 5 and direct measurements of thresholds for targets in negative contrast. The calculated curves are obtained by using the positive thresholds of Adrian and Blackwell and applying the contrast polarity function F_{cp}.

findings are obtained for positive contrast and it is not unreasonable to assume that they also hold for negative contrast. The relatively good fit of the data for negative contrast with the calculated curves as in Figure 5 also justifies this assumption.

The ΔL for subjects older than 23 years, the age at which the function assumes unity, can be found from the following equation:

$$\Delta L_{\text{Age}} = \Delta L_{23}\,\text{AF} \tag{13}$$

The age factor AF is as follows. For 23 y < Age < 64 y:

$$\text{AF} = \frac{(\text{Age} - 19)^2}{2160} + 0.99$$

For 64 y < Age < 75 y:

$$\text{AF} = \frac{(\text{Age} - 56.6)^2}{116.3} + 1.43$$

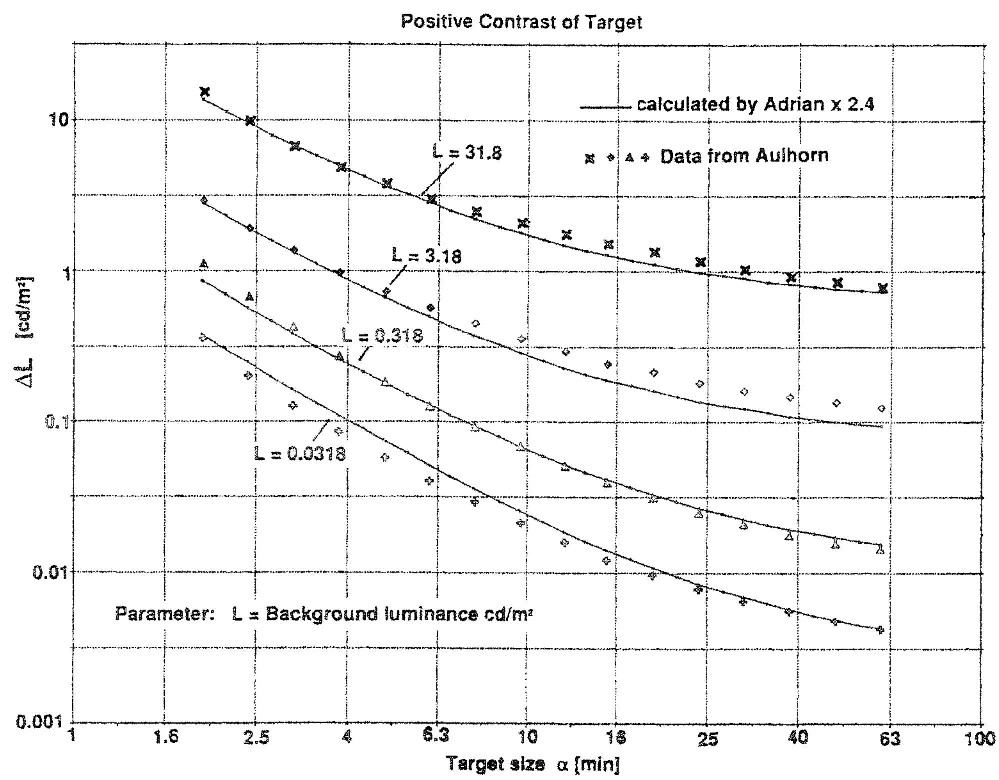

Figure 7 Luminance difference thresholds for ~100% probability of perception for targets of various size and brighter than its background. The curves are calculated and reflect Adrian's and Blackwell's measurements, the symbols are data from Aulhorn. Multiplication by 2.4 was necessary due to different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

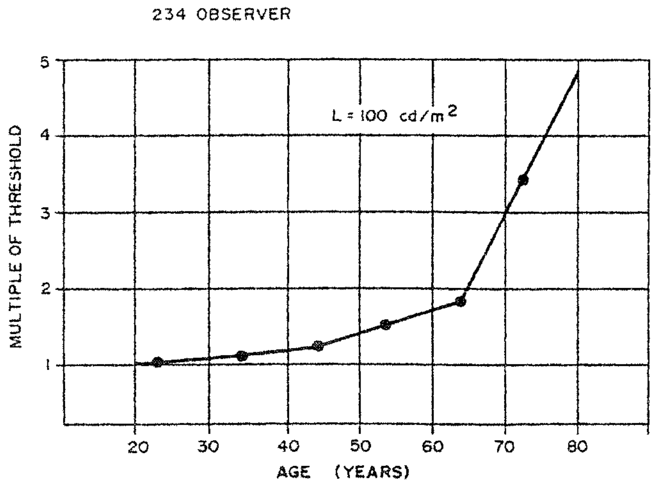

Figure 8 Multiple of the threshold contrast required for observer of higher age in relation to the base group with an average of 23 years.

AF takes account of the age-related threshold increase. ΔL as in equation 4 holds for young persons and has to be multiplied by the age factor AF to obtain the threshold for older subjects ΔL_{Age}.

6 Calculation of ΔL

The final threshold value ΔL for the luminance difference perception, which constitutes one of the basic visual functions, can be calculated from equation 14. It incorporates the factor accounting for the contrast polarity, so that ΔL can be determined for targets, darker and brighter than their background, and the observation time, as we need higher luminance differences with shorter exposure times, and the influence of age on the ΔL-threshold.

$$\Delta L = 2.6\left(\frac{\Phi^{1/2}}{\alpha} + L^{1/2}\right)^2 F_{\mathrm{CP}} \frac{a(L_b, \alpha) + t}{t} \mathrm{AF} \qquad (14)$$

$F_{\mathrm{CP}} = 1$ for positive target contrast; AF $= 1$ for a young observer group with an average age of 23 years; ΔL is practically constant for exposure time $\geqslant 2$ s.

The multiplier of 2.6 accounts for the different experimental condition chosen by Blackwell, Aulhorn and Adrian. In Reference 1 a factor of 3.1 was suggested for the transformation from the mean of 50% probability to nearly ~100% to match earlier data reported by Berek[4]. However I found the thresholds after Berek to be too high.

7 ΔL calculation and disability glare

The presence of glare sources in the visual field impair vision and results in a necessary increase in ΔL to keep targets visible. The reason for this phenomenon is well known and lies in straylight that is produced by the glare sources in the various eye media, especially in the cornea, crystalline lens and in the retinal layers. This straylight superimposes on the retinal image and causes a reduction of the image contrast. The influence of disability glare can be incorporated in a relatively simple way. Holladay[14] has first suggested expressing the effect of the straylight on the target visibility in terms of a uniform luminance that adds to the background luminance L_b. It is called L_{seq}, a veiling luminance equivalent to the glare effect and is given in general form by:

$$L_{\mathrm{seq}} = k \sum_{i=1}^{n} \frac{E_{\mathrm{Gl}_i}}{\theta_i^2} \qquad (\mathrm{cd\,m^{-2}}) \qquad (15)$$

where E_{Gl_i} is the illumination in lux at the eye from glare source i; θ_i is the glare angle in degrees between the centre of the glare source and the fixation line valid for $1.5° < \theta < 30°$; k is an age-dependent constant. For the 20–30 year age group we obtain $k = 9.2$.

The disability glare effect has been redundantly re-examined and the above equation reconfirmed. It is common knowledge that does not need further quotation.

As can be seen, the glare effect increases with smaller angular distance between glare sources and the target and increasing illuminance at the eye due to the glare sources.

In the case of glare the adaptation luminance around the location of the target on the retina is consequently composed of the background luminance L_b and the equivalent veiling luminance L_{seq}. In the calculation of ΔL we have therefore to substitute for L_b by $L_b + L_{\mathrm{seq}}$.

8 Influence of age on the constant k in equation 15

Although the description of the veiling luminance L_{seq} as in equation 15 is well established, only a few studies have been devoted to the influence of age. Weale[15], Aulhorn and Harms[16], Fisher and Christie[17] and Allen and Vos[18] found that the effect of straylight increases with age. This is mainly due to chemical changes which alter the optical clarity and transmittance of the crystalline lens and the cornea. This results in an increased amount of straylight produced in the eye media, that reduces the contrast of the retinal image. From the quoted references I derived a function describing the average of the influence of age on the constant k. This relationship, which shows a considerable spread, can be expressed as:

$$k = (0.0752\ \mathrm{Age} - 1.883)^2 + 9.2 \qquad (16)$$

The equation is applicable within the boundaries $25 < \mathrm{Age} < 80$ y.

Equations 15 and 16 embrace the total influence of disability glare expressed in terms of the equivalent veiling luminance. The contrast reduction of the straylight can be shown in the following way. The contrast is defined as:

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

with

$$\Delta L = L_T - L_b \text{ as in equation 1.} \qquad (17)$$

The straylight superimposes on the retinal image. Thus we obtain for the reduced contrast C_{red}:

$$C_{\mathrm{red}} = \frac{(L_T + L_{\mathrm{seq}}) - (L_b + L_{\mathrm{seq}})}{L_b + L_{\mathrm{seq}}} = \frac{L_T - L_b}{L_b + L_{\mathrm{seq}}} = \frac{\Delta L}{L_b + L_{\mathrm{seq}}} \qquad (18)$$

C_{red} is a hyperbolic function decreasing with higher values of L_{seq}. If for example the equivalent veiling luminance becomes as large as the background luminance $L_b = L_{\mathrm{seq}}$, the glare effect would reduce the contrast C to half of its value: $C_{\mathrm{red}} = C/2$.

9 Visibility level VL

So far the numerical description of the luminance difference threshold ΔL has been dealt with on the basis of experimental data. ΔL indicates a value at which a target of defined size becomes perceptible with near 100% probability under the observation conditions as used in the laboratory experiments. These were free viewing at binocular observation (monocular in Aulhorn's study). The derived functions also fit data reported by Siedentopf[19] very well if the threshold values are reduced by a factor of ~0.84.

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 to render conspicuity to the target. I recall a teacher of mine in the early fifties as terming it 'Suprathreshold-factor'. In the old DIN Standard 5035[20] on signal lights the multiple of the threshold was named 'safety factor' as it renders the target more visible. In the *CIE Report 19.2*[3] Blackwell introduced the very descriptive term visibility level VL:

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

The visibility level is obtained by the ratio of the actual luminance difference the target displays to its threshold value from equation 14. It expresses how much a target is above the level of threshold perception.

The necessary visibility level for different task demands 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 to secure safe traffic conditions has been made that led to values between 10 and 20 for VL in the luminance range of street lighting[21]. It has also been shown that there is a direct relationship between VL and the subjective rating of the visibility in street lighting installation[22]. In a recent paper, Clear and Berman[23] have demonstrated evidence of a connection between VL and visual performance as measured by a criterion consisting of speed and accuracy.

10 Example calculation of VL

The following example demonstrates how to apply the previous formalism to the calculation of the visibility level of a target assumed to be 10′ in size and to display a photometric contrast of $C = 0.3$. It is seen as darker than the background (negative contrast). The target is further assumed to appear on a background luminance $L_b = 1.5$ cd m^{-2}. The example applies to roadway lighting conditions.

What is the visibility level for the target? From the literature we learn[25,26] that a minimal observation time of 0.2 s can be assumed under practical driving conditions. With that we obtain the threshold value for a 25 year old observer from equation 14. The data are given in Table 2.

The threshold contrast for the target is:

$$C_{\text{th}} = \frac{\Delta L}{L_b} = 0.04319$$

The actual value of ΔL of the target follows from the photometric contrast:

$$C = 0.3 = \frac{\Delta L}{L_b}; \qquad \Delta L = 0.3 L_b$$

Table 2

ΔL_{pos}	F_{cp}	L_b (cd m^{-2})	$\alpha(')$	t(s)	ΔL_{Neg}
0.1046	0.6187	1.5	10	0.2	6.476×10^{-2}

The visibility level VL then follows as:

$$\text{VL} = \frac{\Delta L_{\text{actual}}}{\Delta L_{\text{threshold}}} = \frac{1.5 \quad 0.3}{6.476 \times 10^{-2}} = 6.95 \sim 7$$

At luminance levels of $L_b = 1.5$ cd m^{-2} the value of VL ~ 7 is already falling somewhat short to render the target conspicuous under practical conditions[21]. To increase VL either the contrast or the target size has to increase, this means, with given contrast C, we have to get closer to the target to see it.

11 VL calculation in the presence of glare

Let us assume that the lighting installation on that street produces a total glare effect equivalent to:

$$L_{\text{seq}} = 0.217\, k \text{ cd m}^{-2}$$

The reduction of the visibility level VL for a 25 year old observer ($k = 9.2$) is obtained in the following way:

$$L_{\text{seq}} = 2 \text{ cd m}^{-2}$$

This amount has to be added to L_b to arrive at the adaptation luminance L_A, to quantify the effect of the veiling light on the retinal image.

$$L_A = L_b + L_{\text{seq}} = 1.5 + 2$$

$$L_A = 3.5$$

According to equation 14 and substituting L_A for L_b the threshold value for negative contrast will be:

$$\Delta L_{\text{Neg}} = 0.1196$$

This leads to a visibility level of

$$\text{VL} = \frac{\Delta L_{\text{actual}}}{\Delta L_{\text{threshold with glare}}} = \frac{0.3 \times 1.5}{0.1196} = 3.76$$

The calculation shows that under glare of $L_{\text{seq}} = 2$ cd m^{-2} the visibility level is reduced from 6.95 to 3.76, an unacceptably low value for $L_b = 1.5$ cd m^{-2}.

The same calculation can be carried out for older subjects. For a 60 year old person the parameters without glare are as in Table 3.

$$\Delta L_{\text{Neg}}\text{FA} = 0.0647 \times 1.768 = 0.1145$$

$$\text{VL}_{60} = \frac{0.3 \times 1.5}{0.1145} = 3.93$$

and with glare:

$$L_{\text{seq}} = 0.217\, k$$

Table 3

C	$\alpha(')$	L_b (cd m^{-2})	t(s)
0.3	10	1.5	0.2

with $k = 16.11$ from equation 16 for age 60 y:

$$L_{seq} = 3.496 \sim 3.5$$

This causes an adaptation luminance of

$$L_A = L_b + L_{seq}$$

$$L_A = 1.5 + 3.5 = 5 \text{ cd m}^{-2}$$

from equation 14 $\Delta L_{Neg}FA = 0.2808$ for $L_A = 5 \text{ cd m}^{-2}$. From that we arrive at a visibility level of:

$$\text{VL}_{glare,60} = \frac{0.45}{0.2808} = 1.6$$

This result demonstrates that older subjects experience lower VL values which, in this example, border threshold conditions under the influence of glare. Note that age effects the ΔL - threshold in equation 14 and k in the glare formula of equation 15.

The age effect, which can be quantified as shown, is important for consideration and should be incorporated into the recommendations contained in lighting standards. It might also be one of the reasons for the known increased accident rate of older drivers.

12 Transient adaptation

Where the eyes sweep over very different luminances the adaptation has to undergo a transition in which the ΔL threshold will be elevated over its steady-state value. If the difference however does not overstep $\pm$ 2 log units the transition is happening very fast and approaches its steady-state value in approximately 0.2 s. The complete mathematical description of the kinetics of the eye first attempted by Jahn[24] is rather demanding and will be dealt with in a separate publication to follow.

13 Conclusion

This model 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 $C = \Delta L/L$ or the contrast sensitivity CS $= L/\Delta L$ can be derived, applies for binocular, free viewing observations under laboratory conditions.

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 prevailing in lighting installations. The quality of roadway lighting for example will be based, according to the latest draft of the American IES Committee, on VL and recommendations on required visibility levels for different road categories are made.

In order to obtain threshold values ΔL which apply to practical viewing conditions characterised by the visual task demand, a so-called 'field factor' has been used in the past for driving conditions in traffic. An observation time ≤ 0.2 s and a field factor of 4.6 have been suggested, leading to a total of $\sim 10\Delta L$ which Lossagk[27] in 1955 had already applied to obtain practical thresholds to meet the visual task demand in traffic. He spoke of the factor 10 as composed of a conspicuity factor to meet the unexpectedness and ~ 2.5 for the reduced fixation time. The visibility level seems to be an appropriate measure to replace 'field factors' and meet the visual task demands by recommended VL values.

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