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AN ALGORITHM TO ASSESS THE DETECTABILITY OF ACHROMATIC SPATIO-TEMPORAL PATTERNS AT ANY ILLUMINATION

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ABSTRACT

The purpose of this study is to propose a scientifically grounded algorithm to predict the visibility of spatio-temporal patterns at any illumination level. The algorithm incorporates contrast sensitivity data and models from the literature. First, the derivation of the algorithm is presented in general terms, then an applied example is given using data recorded by hand from graphical results available in the literature.

1. INTRODUCTION

Simulation is widely used to build illumination projects. For road traffic, it is essential to predict the conspicuity of targets of various size, form and contrast, for steady or moving objects. There is a need for methods and data to quantify the detectability of complex targets.

For achromatic targets, the key variable for detection is luminance contrast rather than luminance itself. Furthermore, it is known that contrast sensitivity depends on several parameters:

- The spatial contrast of the target
- The temporal pattern of the presentation
- The average luminance at which the observer is adapted
- The eccentricity at which the target is seen

As a whole, visual detection response is characterised by the contrast sensitivity function (CSF) that describes the capability of the visual system to detect elementary structured targets. Contrast sensitivity (CS) G is defined as the inverse of the luminous detection threshold M for a target, the luminance of which varies in time or in space, along a sinusoidal profile, between L_{\min} and L_{\max} .

$$M = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \quad (1)$$

and

$$G = \frac{1}{M} \quad (2)$$

A large amount of data has been collected on contrast sensitivity function and reported in the literature. Results agree between studies. The purpose of this study is to propose a scientifically grounded algorithm to predict the detection of spatio-temporal patterns at any illumination level.

2. METHODS

2.1 The data

An elegant model has been proposed by Kelly (1979) to predict the detection of spatio-temporal patterns at photopic illumination levels. Kelly has shown that the velocity of the target is the key parameter for the detection mechanism. His experiments have allowed deriving a simple function for describing detection vs. velocity. Hence he has built a model in which the contrast detection threshold for a moving target vs. spatial frequency and temporal frequency plots onto a doughnut like shaped surface. Experiments were performed at $3 \text{ cd}\cdot\text{m}^{-2}$. So the analytical function proposed by Kelly is valid for photopic illumination and is likely to vary only little in the photopic range.

Nevertheless, when illumination drops to mesopic levels, acuity and critical flicker frequency severely worsen and the whole contrast sensitivity function (CSF) flattens.

Independent determinations of the spatial CSF and of the temporal CSF have been produced by Van Nes & Bouman (1967) and by De Lange (1958) respectively, which illustrate the decrease of sensitivity in the mesopic range. There, the spatial measurement have been collected with steady tests and the temporal measurements have been collected with uniform tests.

In brief, these data constitute the boundaries of the spatio-temporal contrast sensitivity domain at any illumination.

2.2 Procedure

The procedure consists of entering stationary only CSF data and flicker only CSF data into a unique model for spatio-temporal luminance contrast detection.

The first stage deals with photopic illumination. The unique spatio-temporal contrast detection template proposed by Kelly is accepted. Then a CS surface is derived.

The second stage deals with mesopic illumination. Of interest is the theoretical analysis of CSF by Kelly (1972) who proposes that the variation of the luminance increment threshold with illumination follows three different laws depending upon the values of the spatial and temporal frequencies of the test (Figure 1):

- Weber law applies at low spatial frequency AND low temporal frequency,
- De Vries-Rose law applies at high spatial frequencies,
- linear law applies at high temporal frequencies.

In terms of luminance modulation M , these laws write

at low F_s and low F_t ,

$$\lg M = \text{constant} \quad (3)$$

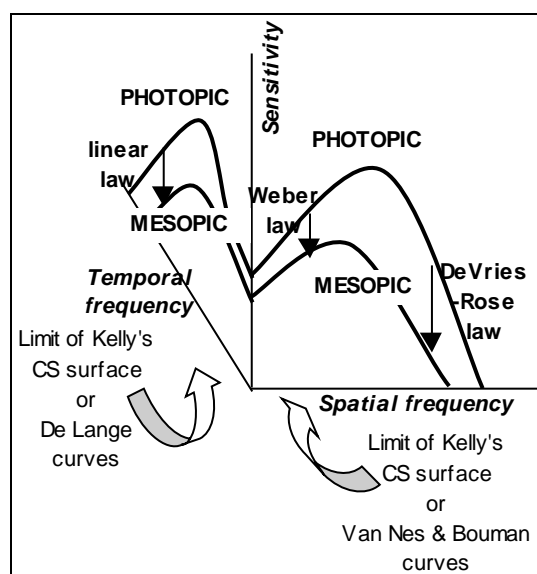


Fig. 1: Laws of contrast sensitivity variation.

at low F_s and high F_t ,

$$\lg M = -\lg B + \text{constant} \quad (4)$$

at high F_s and low F_t ,

$$\lg M = -0.5 \lg B + \text{constant} \quad (5)$$

where B is the retinal illuminance.

The transition between Weber law and De Vries law on the one hand and between Weber law and linear law on the other hand propagates from high frequency to low frequency when illumination decreases. In other words, as retinal illuminance lowers, the Weber law domain shrinks.

The transition between one and another law varies with retinal illuminance and obeys simple laws as shown by Van Nes et al. (1967). This allows determining how much change of CS should apply to any spatio-temporal luminous target.

At this point, it is assumed that the contributions of spatial frequency and temporal frequency to the decrease of CS are independent and can be added.

At the end, mesopic CS surfaces at various illuminations are obtained, applying the appropriate sensitivity reduction law for the spatial frequency and the temporal frequency in sequence.

3. RESULTS

3.1 The photopic CSS

Kelly (1979) proposes a unique analytical band-pass profile for describing the photopic CS G when the velocity v and the angular period α of the luminous sinusoidal target are known

$$G(\alpha, v) = k v \alpha^2 \exp\left(\frac{-2\alpha}{\alpha_{\max}}\right) \quad (6)$$

v is in degree per second, k and α_{\max} are parameters which have been empirically determined by Kelly as

$$k = 6.1 + 7.3 \times |\lg(v/3)|^3 \quad (7)$$

$$\alpha_{\max} / 2\pi = 45.9 (v + 2) \quad (8)$$

The full contrast sensitivity surface (CSS) proposed by Kelly can be derived just by varying the spatial frequency α (in cycle per degree) and the velocity v (in deg/sec). Figure 2 shows a series of band pass CSF calculated at different velocities.

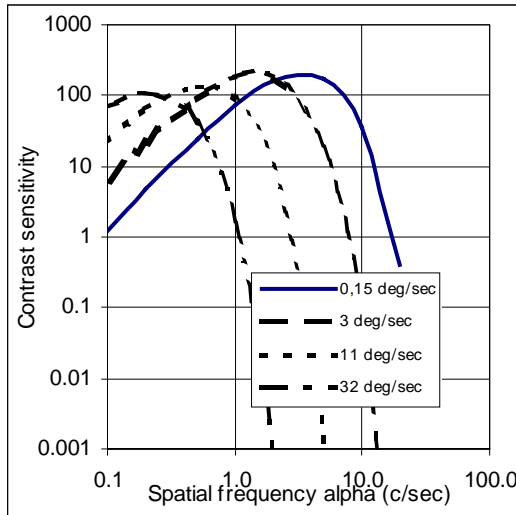


Fig. 2: CSFs at different velocities. Kelly's model.

Let's assume that the domain of useful temporal frequency for vision is [0.1, 100] and that the domain of useful spatial frequency is [0.1, 100]. By definition, velocity is the ratio of temporal frequency to spatial frequency.

$$v = \frac{f_t}{f_s} = \frac{\omega}{\alpha} \tag{9}$$

So equation (6) for G can be written as

$$G(\alpha, \omega) = k \omega \alpha \exp\left(\frac{-2\alpha}{\alpha_{max}}\right) \tag{10}$$

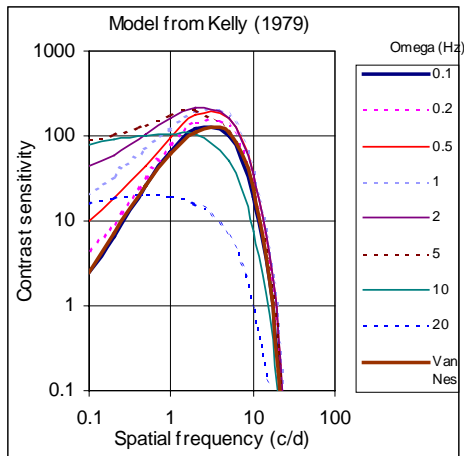


Fig. 3: Spatial CSFs at photopic illuminance.

A table can be constructed with two entries α and ω . The series of curves (Figure 3) drawn with α as a variable and ω as a parameter clearly shows that the stationary condition ($\omega = 0.1$) yields a band-pass CSF

and that slow flicker up to 5 cpd improves the CSF which is reshaped to a low-pass profile. Converse observations can be drawn from figure 4 with ω as a variable and α as a parameter.

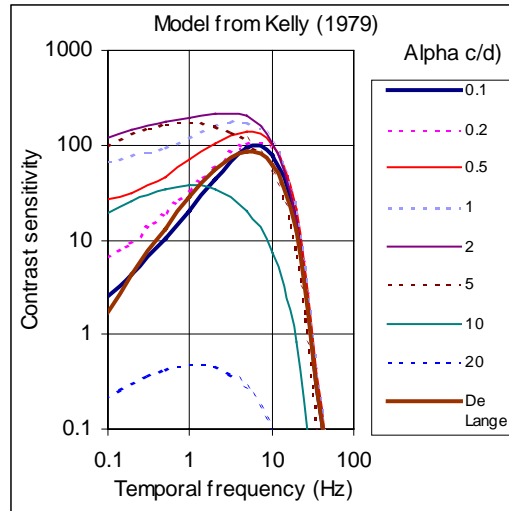


Fig. 4: Temporal CSFs at photopic illuminance.

3.2 The mesopic contrast sensitivity at low spatial frequency or low temporal frequency

3.2.1 Analytical model for the Van Nes and Bouman spatial CSFs

Once we know how to derive the CSS, the question arises whether it is possible to construct a CSS that fits Van Nes & Bouman (1967) results. Because of the band-pass profile of the stationary CSF, we are confident that the whole set of curves derived from the CSS as modelled by Kelly can be matched to Van Nes & Bouman results at the lowest temporal frequency limit. Meanwhile, we need a numerical description of Van Nes & Bouman data.

Van Nes & Bouman have illustrated their results graphically using two kinds of representation, the set of CSFs, i.e. CS versus spatial frequency, alternately, the variation of log contrast threshold versus log retinal illuminance with spatial frequency as a parameter (Van Nes & Bouman, 1967, figure 6). We use the second representation, which shows a remarkable feature: each curve corresponding to a given spatial frequency consists of two branches, as schematically shown in figure 5.

1. At high retinal illumination B , the contrast threshold M remains constant

$$\lg M = a_1 \quad (11)$$

2. At low retinal illumination B , the contrast threshold M varies as

$$\lg M = -0.5 \lg B + a_2 \quad (12)$$

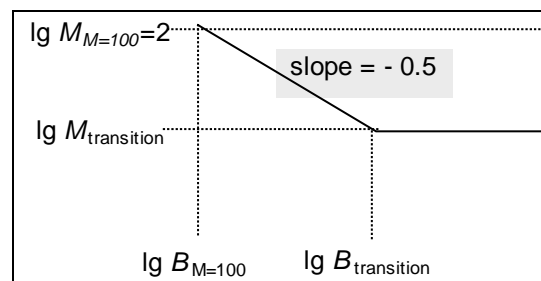


Fig. 5: Variation of spatial contrast threshold.

In order to fully describe the data, we need to determine the constants in equations (11) and (12). The two branches vary along simple rules. The lowest the frequency, the lowest the illumination at transition between the two branches. Precisely, Van Nes et al. (1967, figure 8) have established a linear relationship between log illumination and log frequency at transition (note 1)

$$\lg B_{\text{transition}} = a_3 \lg F_{s,\text{transition}} + a_4 \quad (13)$$

Recording by hand (note 2) the illumination $B_{M=100}$ at which the maximum modulation 100 % is just visible versus the spatial frequency F_s yields a curve that can be approximated by a linear function

$$\lg B_{M=100} = a_5 F_s + a_6 \quad (14)$$

Finally, the two branches can be modelled as a conditional instruction for any spatial frequency F_s .

If

$$\lg B \leq \lg B_{\text{transition}}$$

then

$$\lg M = \lg 100 - 0.5 (\lg B - \lg B_{M=100})$$

else

$$\lg M = \lg 100 - 0.5 (\lg B_{\text{transition}} - \lg B_{M=100}) \quad (\text{equation 15})$$

From this, we can model the Van Nes CSF at any illumination. The similarity with

the original Van Nes results in the mesopic range seems acceptable.

3.2.2 Analytical model of the De Lange data

Next, we need a numerical description of the De Lange data. Kelly (1972) has found temporal CSF similar to De Lange's ones. He has confirmed the Weber law variation at low temporal frequency

$$\lg M = b_1 \quad (16)$$

Furthermore, he has shown that at high temporal frequency, the temporal CSF decreases linearly as the illumination decreases (Figure 3 from Kelly, 1972).

$$\lg M = -\lg B + b_2 \quad (17)$$

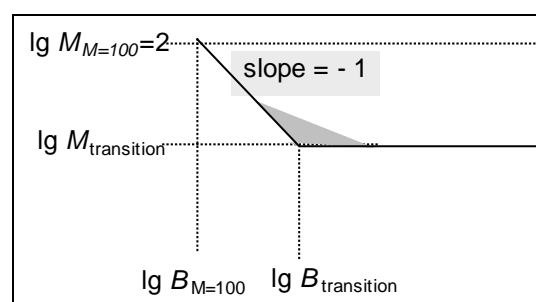


Fig. 6: Variation of temporal contrast threshold.

In the meanwhile, Van Nes et al. (1967) have drawn the De Lange CSF in a similar way as they did for the Van Nes data, i.e. plotting the modulation threshold M versus retinal illuminance B for 7 temporal frequencies and adjusting two branches at every frequency, a line with -0.5 slope and a horizontal line. However, if we transpose the calculation that we have made previously to model the temporal CSF after Van Nes model, we find temporal CSF that are not steep enough at high temporal frequency where they should have a unique asymptote on a log sensitivity versus linear temporal frequency plot (Wyszecki & Stiles, 1982, figure 7 (7.9.3)). Furthermore, it appears on figure 7 from Van Nes et al. (1967) that several points describing the threshold modulation M at low retinal illuminance line along lines with a slope equal to minus 1, as schematically shown in figure 6. So, we have decided to let the modulation vary as the inverse of illumination at high temporal frequency which is equivalent to assert that at high temporal frequencies, the visual system

is sensitive to the absolute modulation rather than to the relative modulation.

We have noted that the transition illuminance, i.e. the abscissa at which each oblique line intercepts the corresponding horizontal branch varies as

$$\lg B_{\text{transition}} = b_3 \lg F_{t,\text{transition}} + b_4 \quad (18)$$

The retinal illuminance at which the maximum modulation ($M=100$) is just visible approximates a straight line, which describes the unique asymptote at fusion (Note 3)

$$\lg B_{M=100} = b_5 F_t + b_6 \quad (19)$$

Finally the two branches can be modelled as a conditional instruction for any temporal frequency F_t :

If

$$\lg B \leq \lg B_{\text{transition}}$$

then

$$\lg M = \lg 100 - (\lg B - \lg B_{M=100})$$

else

$$\lg M = \lg 100 - (\lg B_{\text{transition}} - \lg B_{M=100}) \quad (\text{equations 20})$$

3.3.3 Constructing the CS volume for any retinal illuminance

We hypothesise that the just described rules apply at any spatio-temporal configuration. We apply in succession the laws of variation of CS with illumination and spatial frequency and with illumination and temporal frequency, in order to depress Kelly's CSS and obtain the CS threshold at any illumination for any spatial and temporal frequencies.

This needs a few adjustments, which we will describe now. As a starting point, we aim at reproducing Kelly's CSS at 300 trolands. In a first stage, we optimize the values of the constant factors of the Van Nes model (eqs 13 and 14) in order to minimize the sum of squares of the differences between $\lg G_{\text{Kelly}}$ at retinal illuminance $B = 300$ and temporal frequency $f_t = 0.1$ and $\lg M_{\text{VanNes}}$ for $\lg B = 2.5$. This leads to replace equations (13) and (14) by

$$\lg B_{\text{transition}} = 3,18 \lg F_{s,\text{transition}} - 0,507 \quad (21)$$

and

$$\lg B_{M=100} = 0,428 F_s - 4,51 \quad (22)$$

Then, in order to describe the lowering of the spatial CSF in the mesopic range, we apply the conditional instruction given in equations 15 to Kelly's CSS.

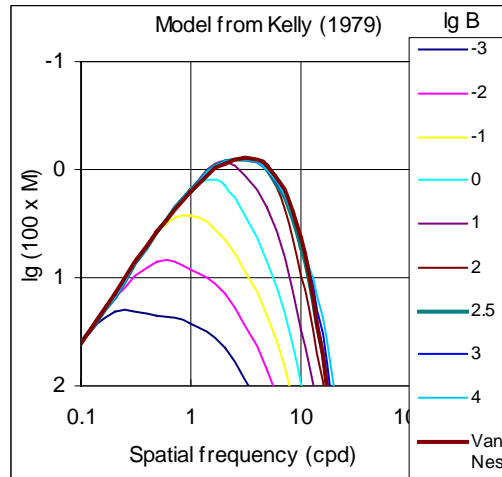


Fig. 7: Mesopic spatial CSFs. $F_t = 0.1$ Hz.

Figure 7 shows the sets of CSFs at various illuminations for $F_t=0.1$, that is the set of mesopic stationary only CSFs which constitutes the "wall" against which the full CS volume leans.

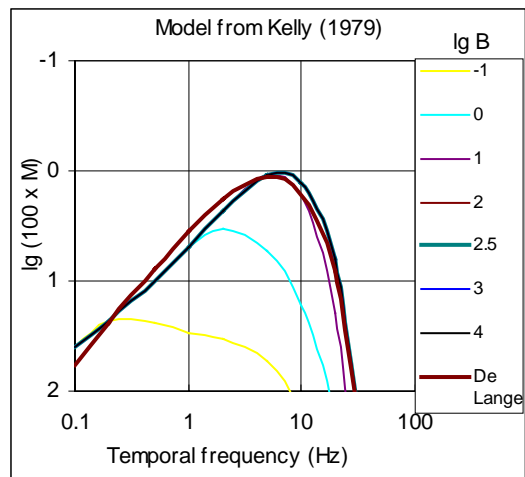


Fig. 8: Mesopic temporal CSFs. $F_s = 0.1$ cpd.

In a second stage, we optimize the values of the constant factors of the De Lange model, in order to minimise the sum of squares of the differences between $\lg G_{\text{Kelly}}$ at retinal illuminance $B = 300$ and spatial frequency $f_s = 0.1$ which represents our aim and $\lg M_{\text{DeLange}}$ for $B = 2.5$.

This leads to replace equations (18) and (19) by

$$\lg B_{\text{transition}} = 1,31 \lg F_{t,\text{transition}} - 0,218 \quad (23)$$

$$\lg B_{M=100} = 0,110 F_{t,\text{transition}} - 1,78 \quad (24)$$

Then in order to derive spatio-temporal CSF in the mesopic range, we apply the conditional instructions given in equations (20) to the previously derived mesopic spatial CSF at every temporal frequency.

Figure 8 shows the set of CSFs at various illumination for $F_s = 0.1$ that is the set of

mesopic uniform flicker only CS curves which constitutes the other "wall" against which the full CS volume leans.

All results can be ordered and summarised to present CS surfaces at any illumination. Figure 9 shows CS surfaces at 316, 10, and 0.1 troland. It appears clearly that the whole CSS collapses at low illuminations, especially for high spatial or temporal frequencies.

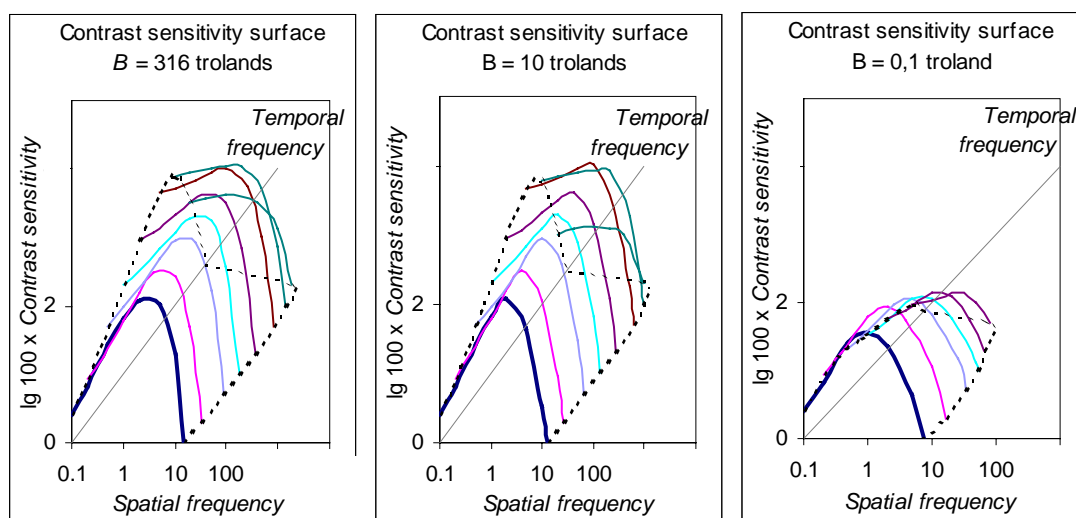


Fig. 9: Contrast sensitivity surfaces at photopic and mesopic retinal illuminance values.

3.4 Algorithm

We have developed an algorithm to predict the contrast detection threshold M at any retinal illuminance B , spatial frequency F_s and temporal frequency F_t .

The steps of the calculation are as follows (Figure 10).

1. Input consists of 3 variables: temporal frequency, spatial frequency and retinal illuminance (in trolands).
2. Velocity is computed and parameters k and α_{max} that control the shape of the contrast sensitivity versus velocity at photopic illumination are derived as proposed by Kelly. Photopic sensitivity is calculated from the velocity, depending upon the spatial frequency.
3. For a given spatial frequency, we look at the adjusted spatial CSF for the illuminance at which 100% modulation is just visible and for the illuminance of the transition between De Vries law and Weber law. Then we lower the sensitivity derived at step 2, applying the law that is valid at the spatial frequency under study.
4. Given the temporal frequency, we look at the adjusted temporal CSF for the illuminance at which 100% modulation is just visible and for the illuminance of the transition between linear law and Weber law. Again we lower the sensitivity derived at step 3 applying the conditional rules that corresponds to the temporal frequency under study.

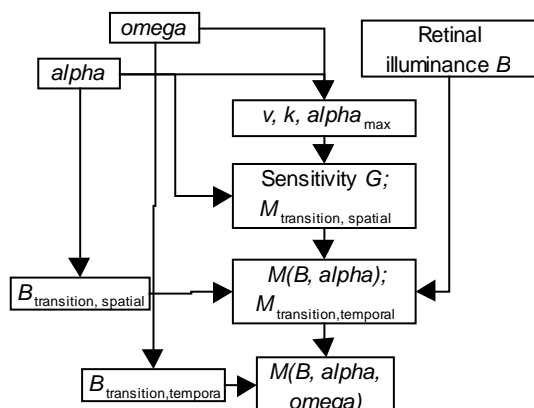


Fig. 10: Schematic algorithm.

Finally, we get CS for any spatio-temporal mesopic target. We have implemented this algorithm in an Excel worksheet.

4. PERSPECTIVE AND CONCLUSION

Using this algorithm, it is possible to predict the contrast at which a test defined by its spatial and temporal components is detected at threshold. The so-determined contrast threshold C_s can serve as a reference to predict the visibility level $V = C/C_s$ as proposed by the CIE (CIE, 1981).

NOTES

Note 1: For the original data of Figure 8 from Van Nes et al. (1967), regression yields $a_3 = 2$; $a_4 = -0.4$. Recording by hand the data in Figure 6 from Van Nes et al. (1967) and fitting a regression yields $a_5 = 0.105$; $a_6 = -4.41$.

Note 2: All linear adjustments were made using the DROITEREG formula from EXCEL and curve fittings were made using the SOLVER package from EXCEL. All decimals were used for the calculation although we have reported in the text a limited number of figures.

Note 3: Recording by hand the data in Figure 7 from Van Nes et al. (1967) and fitting a regression yields $b_3 = 1,48$; $b_4 = -0.271$, $b_5 = 0.0736$; $b_6 = -1.73$.

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