# Cut-off frequencies along cardinal axes for gratings in different orientations II

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## INTRODUCTION

In this report, we present measurements for one subject on the sensitivities of the luminance and color pathways for gratings in two different orientations. We refer the reader to the IPO report no. 794 by the present authors to gain insight in the rationale behind the experiments. Here, we give an account of how the experimental set up, as conceived in the aforementioned report, was modified in order to do the measurements. We want to stress that even though the data presented in this report are in good agreement with data found in the literature, further verification of the results on an additional subject is necessary.

### MAJOR MODIFICATIONS

The experimental set up described in the previous report has been changed most notably with respect to the waveforms used in the five experimental conditions (see Table 1).

Table 1: Synopsis of the five conditions

| Condition | Attribute |
|---|---|
| 1 | Luminance |
| 2 | S = constant ' color only' |
| 3 | Tritanopic ' color only' |
| 4 | S = constant 'with chromatic aberration' |
| 5 | Tritanopic 'with chromatic aberration' |

For conditions 1, 4, and 5, we have used square waves instead of sinusoidal waves in order to measure the thresholds. The use of square waves has the advantage that the full resolution of the display system is used. The minimum contrast[1] that may be displayed with square wave gratings is 1/140. Moreover, for sinusoidal waves the waveform is distorted at low contrasts due to quantisation errors. The relation between contrast thresholds measured with different waveforms is discussed in v.d. Horst (1969). He shows that the sensitivity ratio for square wave to sine wave gratings is 1.27, which v.d. Horst confirmed experimentally. For conditions two and three sine waves were used because full resolution of the display system was not necessary.

A second modification is that in order to reduce the number of conditions, only 0 and 45 degrees orientations have been measured.

A third modification is that different viewing distances have been used to vary the spatial frequencies within the desired range.

A fourth modification is that different chromaticity coordinates have been used. The chromaticity coordinates are chosen in such a way that, given the chromaticity coordinates of the phosphors of the monitor, maximum stimulation of the tritanopic pathway is obtained. The S=constant pathway is stimulated at 73 % of the maximum stimulation that may be obtained with the monitor (see Figure A).

## METHOD

Two alternative forced choice (2AFC) contrast sensitivity measurements were made for five conditions at two different orientations. For each condition, several spatial frequencies were tested.

### Equipment

Stimuli were presented on a Barco CTVM 2/51 color monitor coupled to a Gould Inc. Imaging and graphics system with 8 bits wide R, G, and B lookup tables. A homebuild front mirror image rotator in front of the subject's left eye was used to present the stimuli at the various orientations.

### Stimuli

Sinusoidal gratings were presented in a rectangular field (width x height = 17.4 cm x 13.6 cm) at the center of a dark surround field of 45 cm x 45 cm. Outside the surround field, the

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[1] The contrast of a waveform is defined as $(L_{max}-L_{min})/(L_{max}+L_{min})$, where $L_{max}$ and $L_{min}$ are the maximum and minimum luminances of the grating.

average background luminance was 13.5 cd/$m^2$. The viewing distance was usually at 7.4 m unless explicitly mentioned otherwise. For this viewing distance, the grating subtended 1.34° x 1.05°.

Stimuli in the luminance condition 1 (see Table 1) were square wave luminance gratings with CIE (x,y) chromaticity coordinates of (.33,.33). The mean luminance level was 20 cd/$m^2$. For the spatial frequency of 28 c/dg, the viewing distance was 8.75 m. In condition four, the S=constant grating consisted of two square wave luminance gratings with chromaticity coordinates of (.53,.35)[2] and (.28,.55) added in counterphase. In condition five, the tritanopic grating consisted of two square wave gratings with chromaticity coordinates of (.185,.08) and (.28,.59) added in counterphase.

For the color gratings, the color modulation depth was varied through a variation of the yoked luminance modulation of the two constituent gratings. In condition four, the grating appeared as red/ green at low spatial frequencies and as achromatic yellow luminance grating at the higher spatial frequencies. The mean luminance of the grating was 15 cd/$m^2$. In condition five, the grating appeared as green/blue at low spatial frequencies and as a blue luminance grating at higher frequencies. The mean luminance of the grating was 5.6 cd/$m^2$. The catch trial stimulus for conditions four and five was an uniform field with zero color modulation. For the spatial frequencies of 16 and 21.33 c/dg in conditions four and five, a viewing distance of 10 m. was used.

In conditions two and three, a luminance grating of 90 degrees out of phase was added to the color gratings. This luminance grating had a mean luminance of 0.6 cd/$m^2$ with 100 % modulation depth. The mean luminance of the combined grating (color plus luminance grating) was 15.6 cd/$m^2$ for the S=constant grating with a modulation depth of 3.85 %. For the tritanopic grating, the mean luminance was 6.2 cd/$m^2$ with a modulation depth of 9.7 %. In conditions two and three, we used the combined grating with zero color modulation as catch trials, that is, the catch trial consisted of a luminance grating with modulation depths of 3.85 % and 9.7 % for conditions two and three, respectively.

The stimuli were presented at two different orientations of zero and 45 degrees counter clockwise rotation. We denote a sinusoidal grating with vertical bars as a zero degree grating.

Procedure

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In retrospect, a better choice for the red chromaticity would have been (.61,.33) to obtain maximum stimulation along the S=constant direction.

The subject looked at the color monitor with his left eye in front of the rotator. The rear end of the rotator served as a field stop with a diameter of 6.34 degrees. The subject's head was held in position by a headrest. Upon a signal from the computer, the subject positioned the image rotator in one of the two possible orientations and adapted for 5 seconds to the catch trial stimulus for that particular condition. Starting with a full contrast stimulus, thresholds were varied until two reversals had occurred (no catch trials were present in the starting phase). Next, the detection threshold was measured in a 2AFC staircase procedure consisting of 40 trials. The threshold in the staircase was increased following any error in the judgements and decreased following three correct judgements (not necessarily in a row). The average of the 40 trials was taken as the threshold value for that staircase. The catch and test trials were alternated at random.

One session consisted of 20 staircases. The threshold was estimated as the mean of 6 staircases. Stimuli were presented in a semibalanced order. Furthermore, the stimuli were presented continuously in order to keep the temporal transients small. Subjects had to look to the stimulus for at least one second before the response was registered.

In order to compare these monocular data with free viewing conditions, the contrast sensitivity for free binocular viewing was also measured for a luminance grating of 28 c/dg.

Subject

One subject (the first author, 34, male, corrected myope and normal color vision according to the Farnsworth-Munsell 100 hue test and a battery of other color tests) participated in these experiments.

## RESULTS AND DISCUSSION

Figures 1,2a,2b,3,4,and 5 contain respectively the data for the five conditions described in Table 1. Along the vertical axis, the inverse modulation depths or contrast sensitivities are shown on a logarithmic scale. Along the horizontal axis, the spatial frequency is plotted. Square and diamond symbols correspond respectively to grating orientations of zero or 45 degrees. Bars represent one standard error of the mean. Figure 2b contains the same data as Figure 2a but plotted on a larger scale.

------ insert Figures 1,2a,2b,3,4, and 5 about here ------

A quick inspection of Figures 1,2a,3,4, and 5 shows that for most conditions the spatial frequency decreases linearly with the logarithm of the contrast sensitivity for high spatial frequencies.

This is in accordance with results of Campbell *et al.* (1966). Straight lines were fitted through the data points by eye in order to determine the cut-off frequencies at 100 %. Table 2 summarises the results. Note that the results in this table are based upon one subject and may vary for different extrapolation methods. For condition two, extrapolation has been done using Figure 2b.

Table 2: Cut-off frequencies (in c/dg) at 100 % modulation depth for all conditions.

| | Orientation | | |
|---|---|---|---|
| | 0 degrees | 45 degrees | correction |
| Condition | | | |
| 1 | 36 | 34 | -0.5 |
| 2 | 13 | 12 | +2 |
| 3 | 5 | 4.5 | +1 |
| 4 | 33 | 25 | -0.5 |
| 5 | 24 | 23 | -0.5 |

Three correction factors have to applied to these cut-off frequencies.
1) For all conditions, sensitivity should be raised because one is more sensitive when free binocular viewing is permitted. The ratio of the binocular to monocular threshold equals 1.2.
2) For conditions 1, 4, and 5 sensitivity should be lowered by a factor 1.27 because the relative contrast modulation required for a sine wave versus a square wave is 1.27:1 (v.d. Horst, 1969).
3) The S=constant grating has been displayed at only 73 % of the maximum attainable color modulation. For condition two, the sensitivity curves should therefore be raised with a factor 1.37. For condition four, where we assume that the threshold is based on luminance artifacts, no correction is necessary. The resulting correction for the cut-off frequencies for these three factors is given in the third column of Table 2.

The cut-off frequencies listed in this table are in good agreement with the estimates given in the previous report and with data in the literature (Campbell *et al*, 1966, Kelly, 1974; Mullen, 1985; see also the discussion in the previous report)

In Table 3, we have estimated the slopes s of the lines for the different conditions for the equation f = s*(log(1/m) - c) where f is the frequency, m is the modulation depth at threshold, and c is a constant.

Table 3: Slopes s of interpolated data for all conditions.

| | Orientation | |
|---|---|---|
| | 0 degrees | 45 degrees |
| Condition | | |
| 1 | - 14 | - 14 |
| 2 | - 8 | - 9 |
| 3 | - 3.7 | - 3.8 |
| 4 | - 27 | - 30 |
| 5 | - 16 | - 19 |

A closer inspection of the Figures 1 through 5 reveals some unexpected deviations from the linear relation on semi-logarithmic coordinates at the high frequency end. For the luminance condition for an orientation of 0 degrees (Figure 1) the curve appears to be concave. For the S=constant, 'color only' condition 2 (Figure 2b) for both orientations a concave section around 4 c/dg is present, which upon closer inspection is also present in Mullen's data (1985, her Figure 6). Concavity is also present in condition 4 for the S=constant 'with chromatic aberration' data at the 45 degrees orientation in Figure 4. These observations need to be checked with additional subjects.

The color gratings have been chosen in such a way that (almost) maximum stimulation of the color pathways is achieved, given the chromaticity coordinates of the phosphors of the color monitor. Therefore, the corrected cut-off frequencies of Table 2 are valid for current display technologies such as color monitors and liquid cristal displays. Cut-off frequencies for spectral colors may be higher because spectral colors allow for a stronger stimulation of the color pathways. The presented contrast modulations along the S=constant and tritanopic axes are respectively 36 % and 19 % of the maximum contrasts, obtainable with spectral colors, as calculated with the Vos-Walraven primaries (Vos, 1978).

## CONCLUSION

The cut-off frequencies listed in Table 2 are in good agreement with those found in the literature. The additional luminance mask appears to give valid sensitivity measurements for the 'color only' condition. This is important because tedious achromatising procedures, which are for instance too cumbersome for clinical applications, are avoided. Finally, we conclude that more subjects are needed to confirm the data presented in this paper.

## ACKNOWLEDGEMENTS

The first author wishes to thank Martin Boschman, Huib de Ridder and Jean-Bernard Martens for their stimulating interest and assistance.

Figure A: Location on the CIE x,y color diagram of the colors (closed points) used in this experiment. T is the tritanopic confusion point. The line passing through T is a tritanopic confusion line. The line passing through (1,0) is a line along which the S-cone stimulation is constant. Open circles indicate the phosphor chromaticity coordinates. Filled squares denote the chromaticities of the constituting gratings.

Figure 1: Luminance contrast sensitivity as a function of spatial frequency.

Figures 2a & 2b: Chrominance contrast sensitivity as a function of spatial frequency for the S=constant 'color only' grating.

Figure 3: Chrominance contrast sensitivity as a function of spatial frequency for the tritanopic 'color only' grating.

Figure 4: Contrast sensitivity as a function of spatial frequency for the S=constant 'with chromatic aberration' grating.

Figure 5: Contrast sensitivity as a function of spatial frequency for the tritanopic 'with chromatic aberration' grating.

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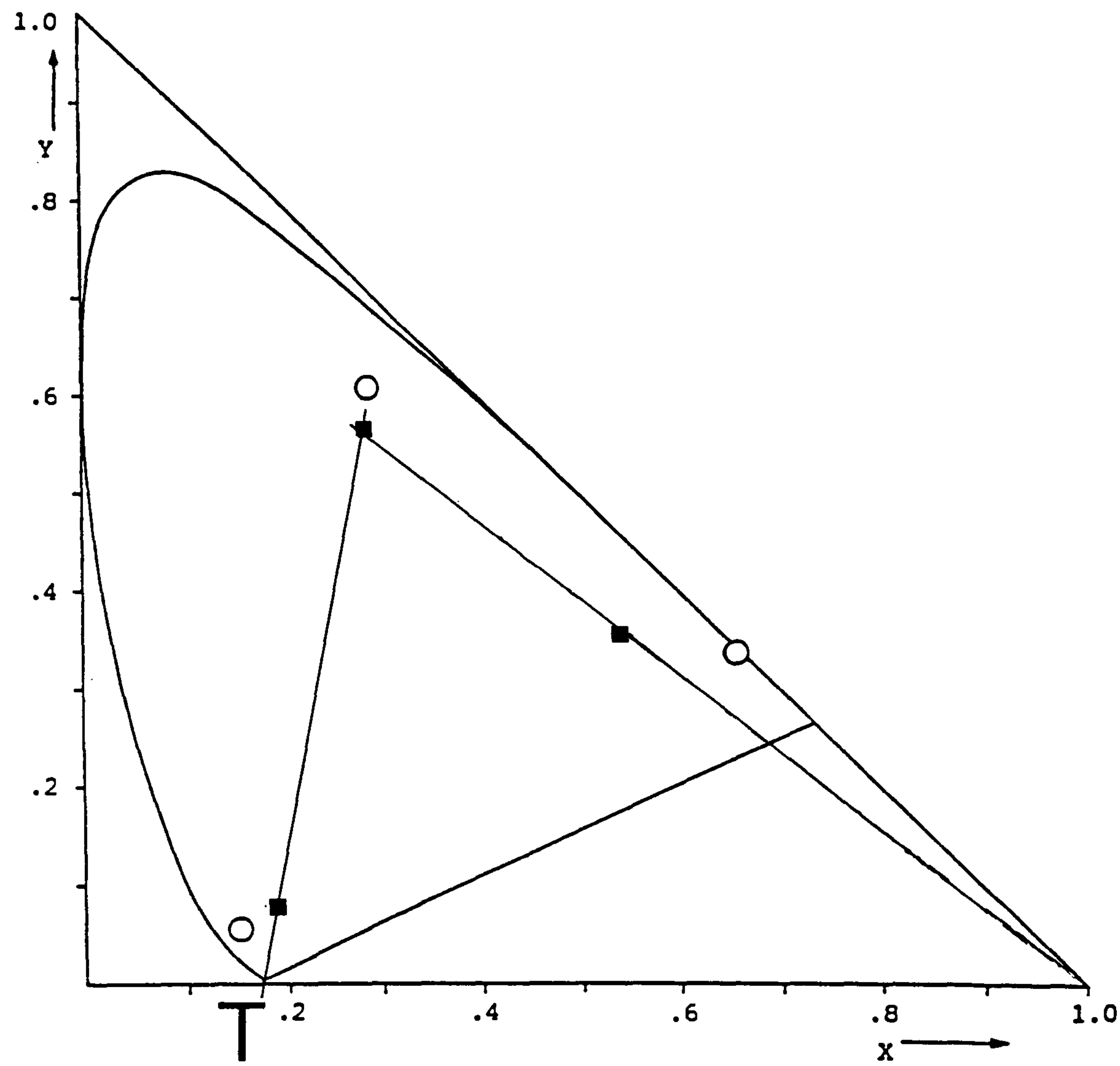
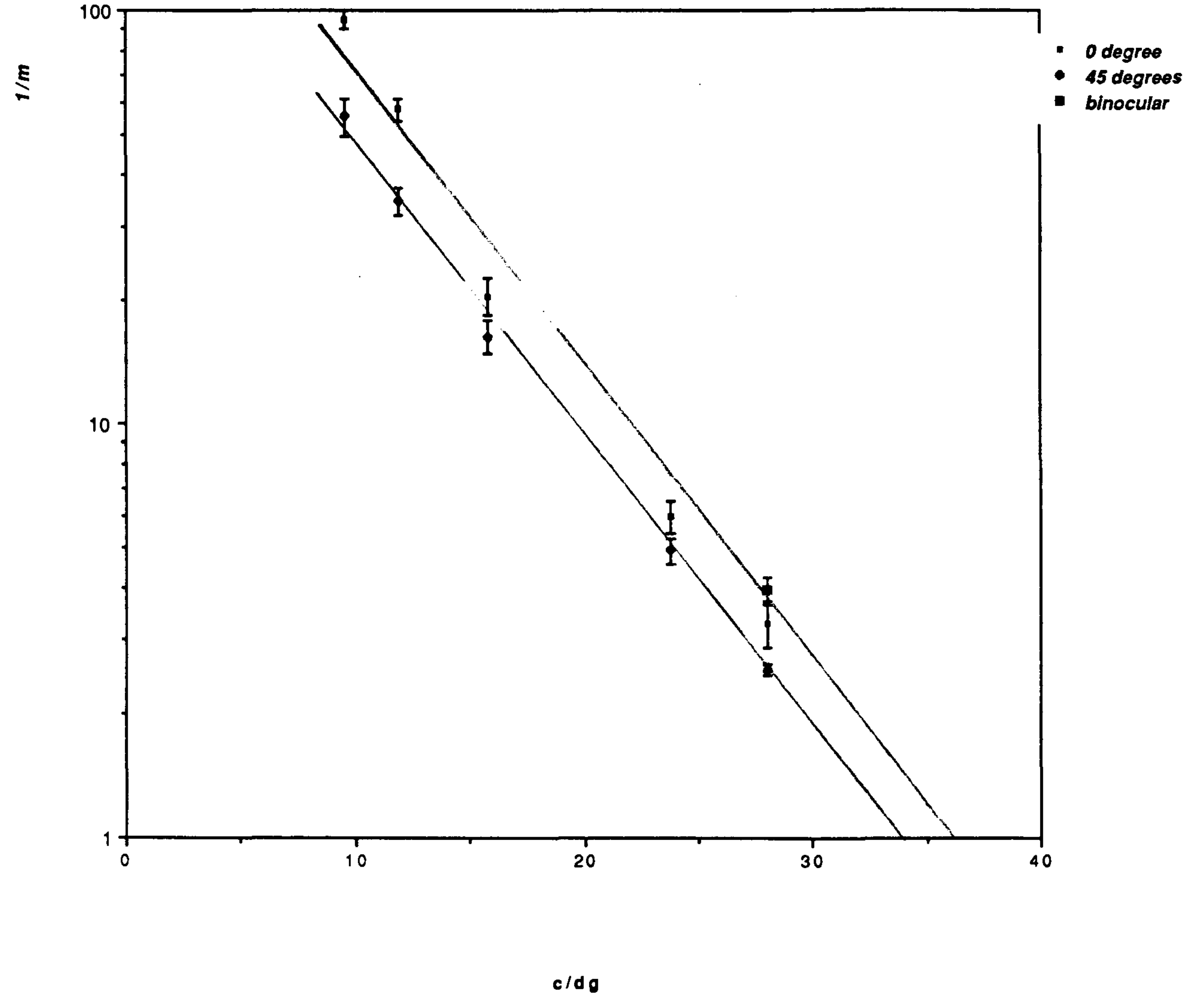


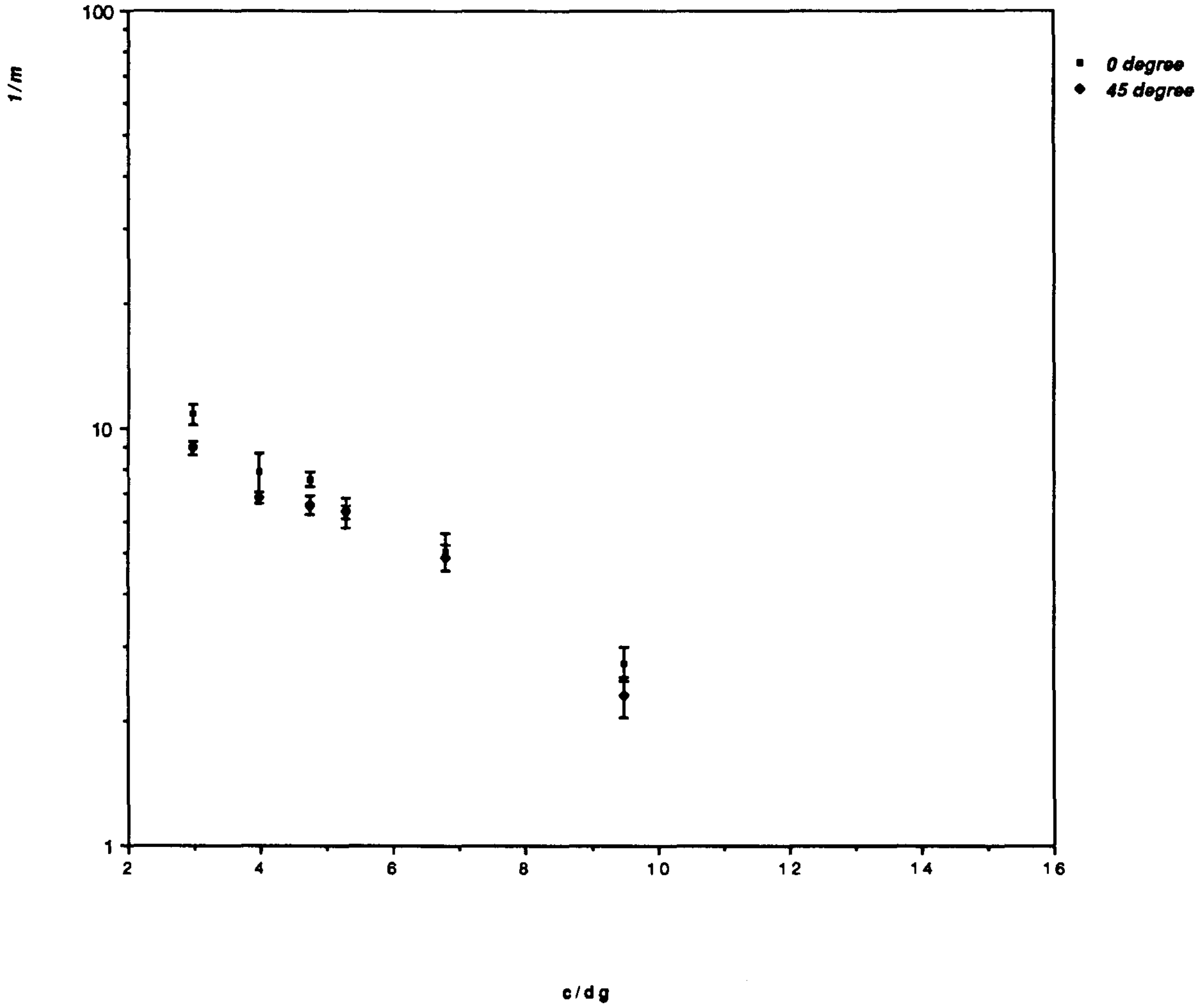

Figuur A

Data from "csflum.data"



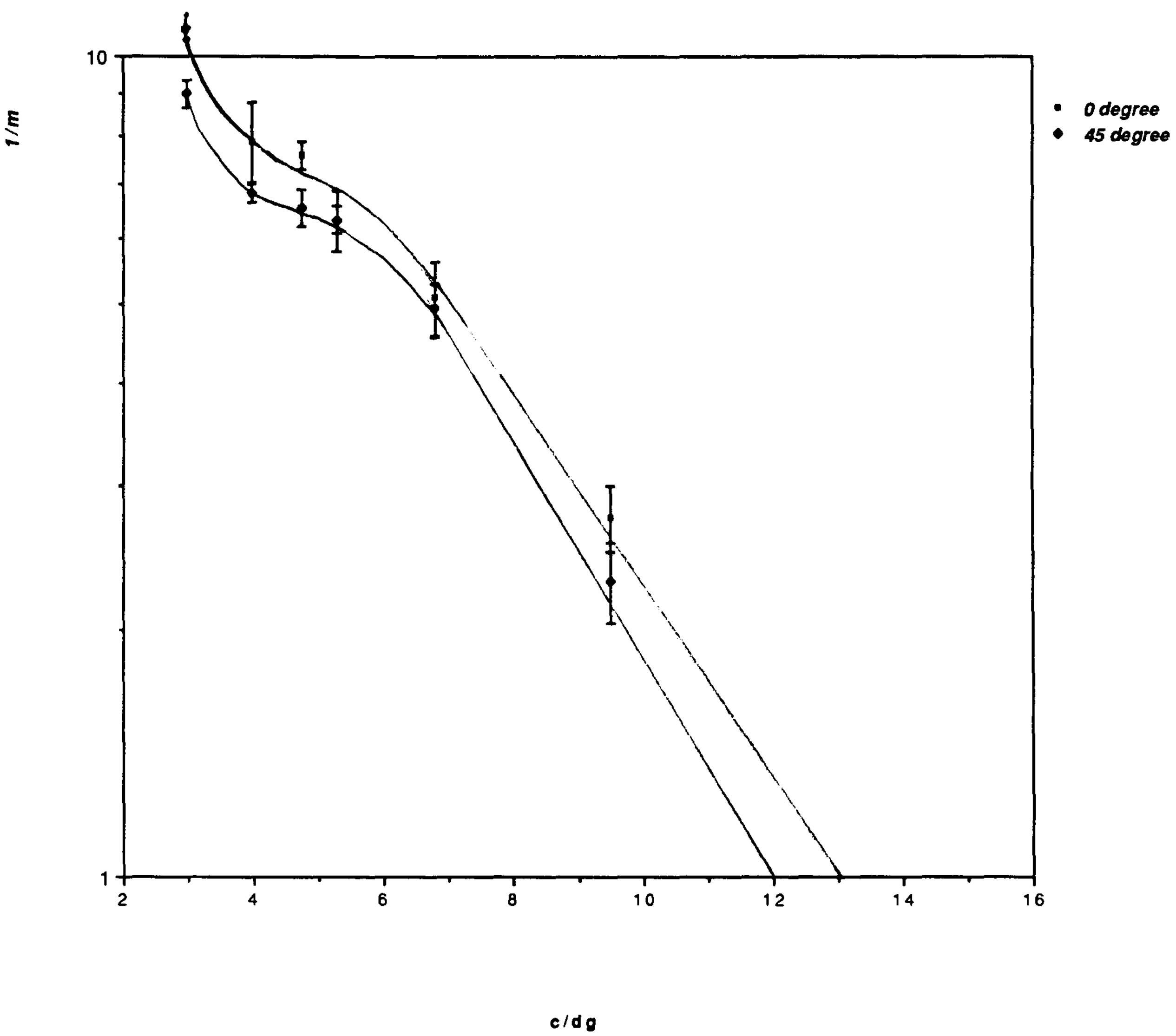

Figuur 1

Data from "csfrg.data"

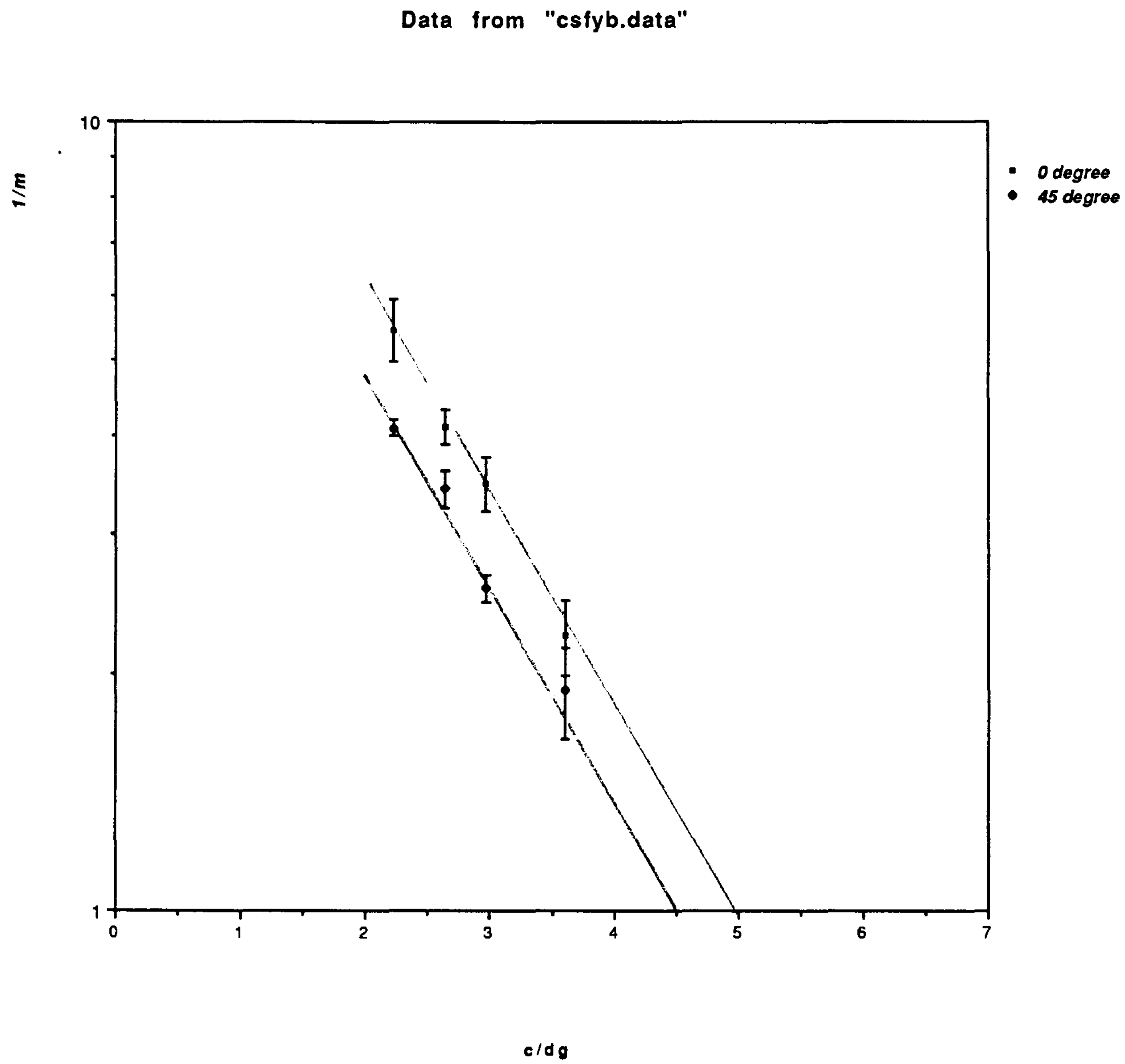



Figuur 2A

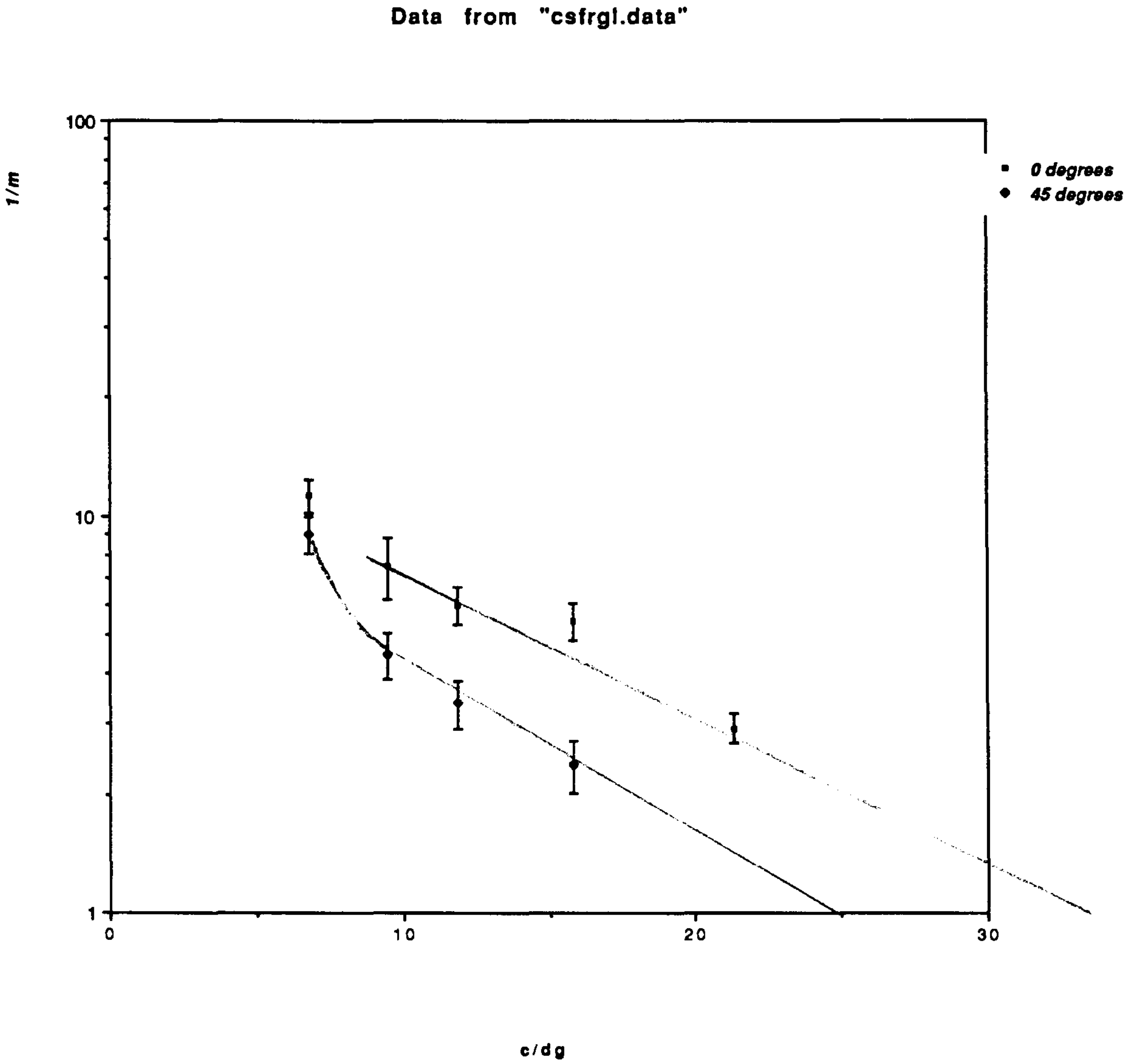
Data from "csfrg.data"



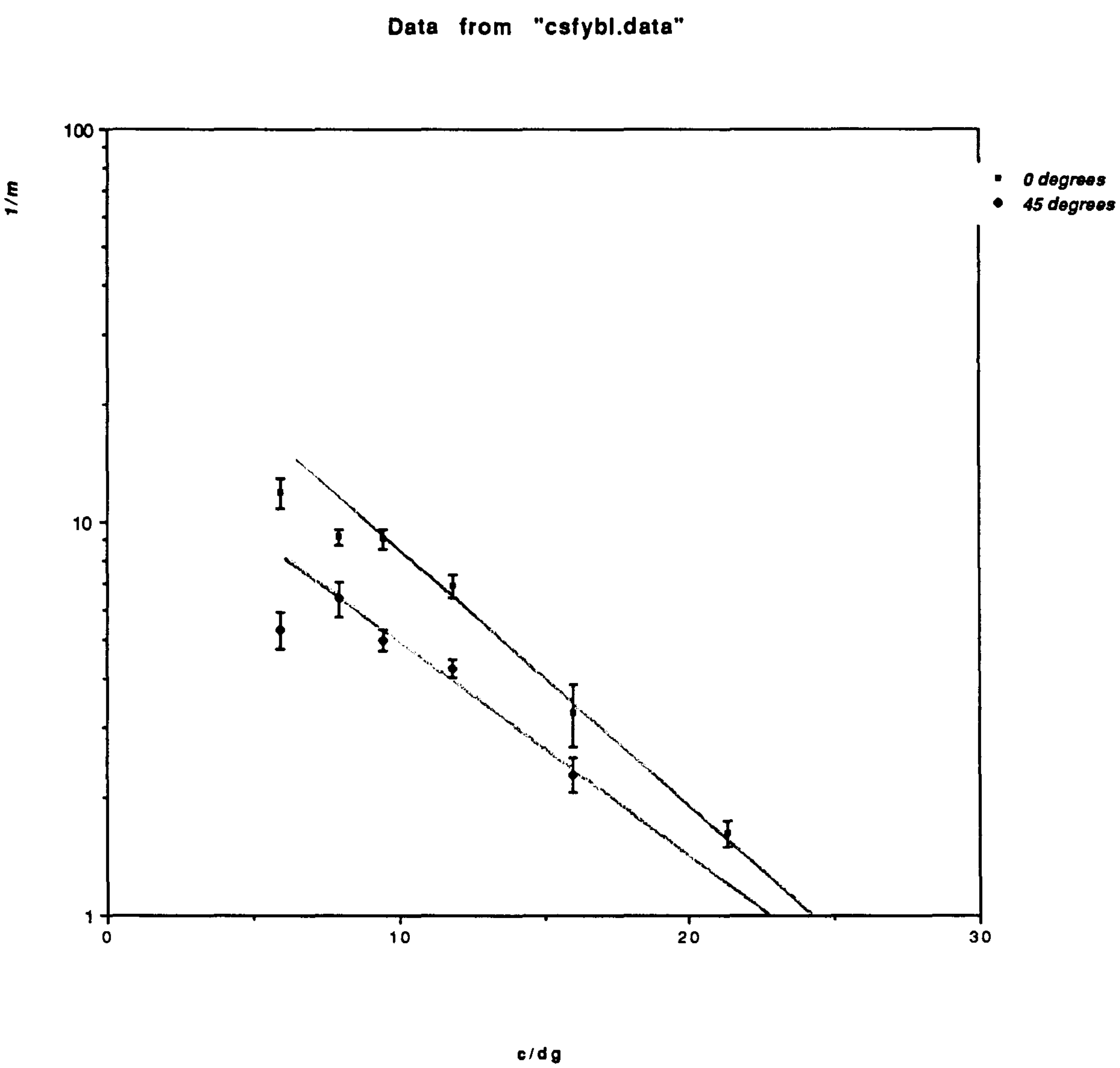

Figuur 2B




Figuur 3


Data from "csfrgl.data"
100
10
1
1/m
0
10
20
30
c/dg
0 degrees
45 degrees

Figuur 4


Data from "csfybl.data"
100
10
1
1/m
0
10
20
30
c/dg
0 degrees
45 degrees

Figuur 5