DEPENDENCE OF CONTRAST DETECTION AND INDEPENDENCE OF AM AND FM DETECTION ON RETINAL ILLUMINANCE

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Abstract—Thresholds for the detection of contrast differences ("amplitude modulation", AM) and spatial frequency differences ("frequency modulation", FM) present in suprathreshold sine-wave gratings were measured as a function of mean retinal illuminance. These thresholds are found to be virtually independent of mean retinal illuminance, despite the fact that the threshold contrasts of the gratings do depend significantly on illuminance.

Retinal illuminance   Sine-wave grating   AM   FM   Suprathreshold contrast

INTRODUCTION

In two recent papers (Jamar *et al.* 1982; Jamar and Koenderink, 1983) we reported on experiments in which we measured the detectability of modulations of the contrast and the spatial frequency of suprathreshold sine-wave ("carrier-") gratings. We found that the detectability depends on the spatial frequency of the modulation (our 1982 paper) and on the number of bars in the carrier grating but not on its spatial frequency (the 1983 paper). The latter means that almost the same modulation thresholds are found for gratings that have different spatial frequencies but equal numbers of grating bars (this phenomenon we termed "scale invariance"). All these experiments were done at about the same mean retinal illuminance (20 and 16 td). However, it may be necessary to check whether the results would have been the same for other retinal illuminances. The subject's task in modulation detection is to compare contrast or spatial frequency across different retinal positions. He has to compare the responses of contrast-detecting mechanisms (encoding contrast-information and spatial-frequency-information) at different retinal positions. It is commonly accepted that at any retinal position a number of such mechanisms, different in size and tuned to different ranges of spatial frequencies, operate simultaneously. The spatial weighting function (receptive field profile) of mechanisms is likely to change with the illuminance level (van Nes, 1968; van Meeteren and Vos, 1972; Enroth-Cugell and Lennie, 1975; Srinivasan *et al.*, 1982). So it is conceivable that the contrast-information and spatial-frequency-information passed on by these mechanisms to the higher stages of the visual system also varies with retinal illuminance (and thus the modulation thresholds vary with illuminance).

Several experimental studies demonstrate the importance of flux (rather than illuminance) received within a receptive field. Koenderink *et al.* (1978) showed that for contrast detection of gratings the transition from de Vries–Rose to Weber behaviour occurs at a lower illuminance (but at about the same flux within a receptive field) in the periphery (where average receptive field size is large) than at the fovea (where receptive fields are small). Enroth-Cugell and Shapley (1973) found that the transition in the impulse/quantum curve of cat retinal ganglion cells occurs at a fixed flux within the effective central summing area. In line with this is the fact that for grating contrast thresholds the transition from de Vries–Rose to Weber behaviour occurs at a higher illuminance for high spatial frequencies (which presumably are detected by small receptive fields) than for low spatial frequencies (detected by large receptive fields) (van Nes and Bouman, 1967; Kelly, 1972).

Thus it may be that, when we compare our modulation detection results for different spatial frequencies, we should make the comparison between a low spatial frequency at a lower illuminance and a high spatial frequency at a higher illuminance. This could be of importance for the scale-invariance results given in Jamar and Koenderink (1983).

To check the influence of mean retinal illuminance we repeated some of our experiments at a number of illuminance levels, spanning a range of more than 3 decades. With gratings adjusted to contrasts equal to eight times the threshold contrast, we find that modulation thresholds are not affected by changes of the mean illuminance, although the threshold contrasts do of course depend on illuminance. It follows that (1) our previous results can be generalized because they are not affected by the choice of a fixed illuminance level, and (2) the processing of spatial information, although strongly dependent on illuminance for patterns at threshold contrast, is remarkably constant over a large range of illuminance for

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patterns presented at suprathreshold contrast. As the latter are the patterns most frequently encountered in natural vision, this phenomenon is of obvious practical importance.

METHODS

The apparatus and experimental procedure have been fully described in Jamar et al. (1982) and Jamar and Koenderink (1983). Here we shall only summarize the essentials.

The stimuli are stationary vertical sine-wave gratings displayed on the screen of a black-and-white monitor. The linearity of the monitor's intensity control has been carefully checked (see Jamar et al., 1982 for details). The stimuli subtend an angle of 4×4 deg^2. The surround is dark. A small black fixation dot is placed on the centre of the screen. The subjects are instructed to fixate this dot as carefully as possible. Viewing is monocular. The mean retinal illuminance is determined by the screen luminance (fixed), the diameter of the artificial pupil (2.8 mm) and neutral density filters placed in front of the subject's eye.

In order to produce changes in contrast or spatial frequency the brightness signal for the monitor's intensity channel can be modulated (sinusoidally) in amplitude or frequency. We thus obtain "amplitude-modulated" (AM) or "frequency-modulated" (FM) gratings. The spatial frequency of the modulation will be called the modulation frequency (f_m), the spatial frequency of the carrier grating is called the carrier frequency (f_c). For a complete mathematical description and a photograph of these stimuli the reader is referred to Jamar et al. (1982).

The contrast for each stimulus pattern is set at eight times its threshold contrast. Thus the contrast varies with illuminance, because the threshold contrast varies with illuminance. However, we have good reason to believe that the results would have been the same for any other choice of contrast provided the contrast is never lower than about eight times threshold: we showed before that in this contrast range modulation thresholds hardly vary with contrast (see Fig. 6, reproduced from Jamar et al., 1982) (Fig. 6 gives FM-results, but AM-results were very similar).

The subjects set modulation thresholds by the method of limits. In each case sufficient time is allowed for the subject to adapt to the mean retinal illuminance (up to 20 min for the lowest illuminance).

All results presented are means of at least 4 threshold settings, made on different days. Standard errors of the mean were about 0.05–0.10 log unit.

Experiments were carried out for carrier frequencies of 1, 4 and 16 cycles per degree (c/deg). At each carrier frequency mean retinal illuminances were used down to the lowest illuminance that allowed the contrast to be set at eight times threshold and still be kept within the range of linearity of the monitor.
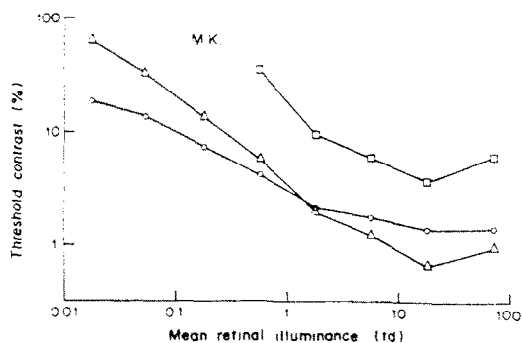

Fig. 1. Dependence of threshold contrast on mean retinal illuminance for spatial frequencies of 1 (circles), 4 (triangles) and 16 (squares) c/deg. Stimulus size 4*4 deg.^{2} Subject M.K.

RESULTS

Figure 1 shows the threshold contrast for sine-wave gratings of 1, 4 and 16 c/deg as a function of mean retinal illuminance. The 1 c/deg results show the classical de Vries–Rose and Weber behaviour, with the transition at about 5 td. Below 5 td the threshold contrast decreases as the inverse of the square root of the retinal illuminance (de Vries–Rose law; slope of the curves $-1/2$ on the double logarithmic coordinates). The 4 and 16 c/deg results do not conform to the classical "laws" (slopes -0.74 and -0.85 at 4 c/deg for M.K. and F.K. respectively), although they do show a gradual flattening of the curves towards higher illuminances.

Figure 2 shows amplitude-modulation and frequency-modulation thresholds (plotted as a function of the modulation frequency f_m) for a 4 c/deg carrier and the highest (72 td) and lowest (0.72 td) retinal illuminance used with this carrier. It is clear that modulation detection is performed equally well at both illuminances.

In Figs 3–5 AM and FM thresholds are plotted against mean retinal illuminance for all three carrier frequencies and for a number of modulation frequencies for each carrier. It can be seen from these figures that in all cases changes in mean retinal illuminance hardly affect modulation thresholds.
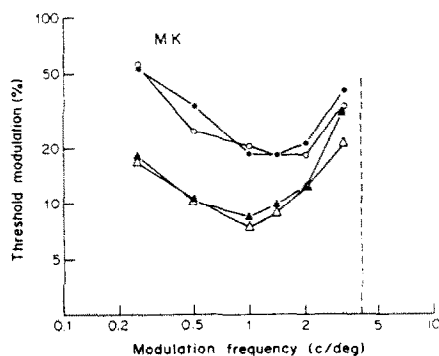

Fig. 2. AM- and FM-thresholds as a function of modulation frequency for a 4 c/deg carrier frequency. Circles and triangles indicate AM- and FM-thresholds respectively. Open symbols: retinal illuminance 0.72 td; solid symbols: 72 td. Subject M.K.
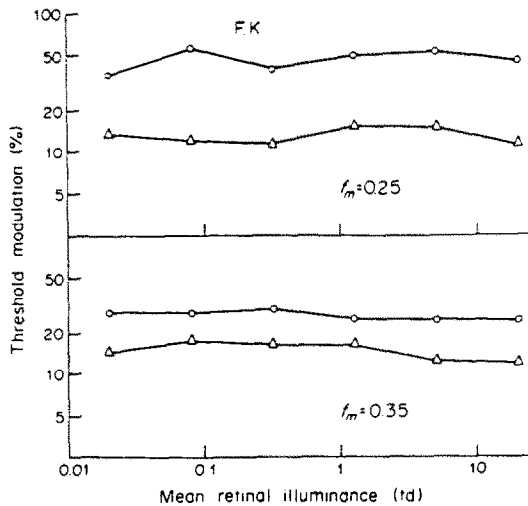
Fig. 3. Thresholds for AM (circles) and FM (triangles) as a function of mean retinal illuminance for a 1 c/deg carrier frequency. Modulation frequencies of 0.25 and 0.35 c/deg as indicated in the figure. Subject F.K.

Fig. 5. Thresholds for AM (circles) and FM (triangles) as a function of mean retinal illuminance for a 16 c/deg carrier frequency. Modulation frequencies (c/deg) are indicated in the figure. Subject F.K.

Some of the curves in Figs 4 and 5 seem to show a slight tendency for the modulation thresholds to increase with illuminance. In a few cases the difference in modulation threshold between the lowest and the highest illuminance is statistically significant. However, the modulation thresholds for subject M.K. were even less dependent on illuminance than those for F.K. For M.K. there were a few cases where the thresholds showed a slight decrease with illuminance. Whether the slight dependencies on illuminance represent a real and reliable effect cannot be judged from the available data.

DISCUSSION

The threshold contrast results shown in Fig. 1 do not conform very well to the classical de Vries–Rose and Weber laws. However, similar deviations from these "laws" have been found by other investigators (van Nes and Bouman, 1967; Kelly, 1972). Some possible explanations were given by Kelly (1972). The
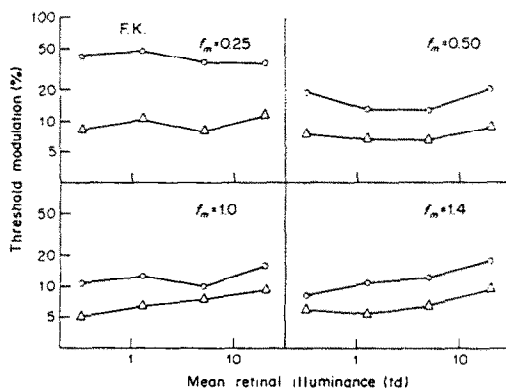

Fig. 4. Thresholds for AM (circles) and FM (triangles) as a function of mean retinal illuminance for a 4 c/deg carrier frequency. Modulation frequencies (c/deg) are indicated in the figure. Subject F.K.
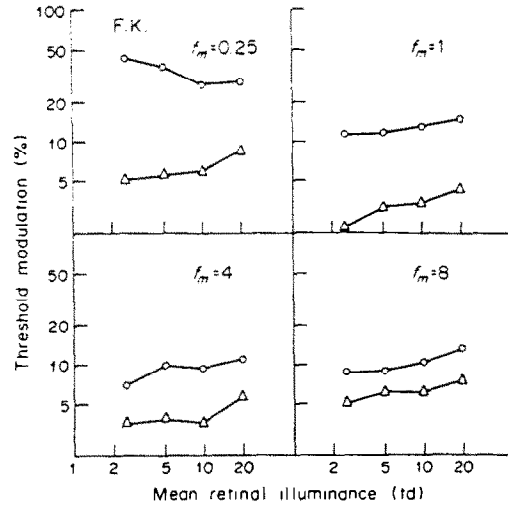
data presented by Kelly suggest that the steeper slopes at higher spatial frequencies (4 and 16 c/deg) may arise from the influence of involuntary eye movements, which in effect may introduce rather high temporal frequencies into the stimulus. Kelly (1972) presents results demonstrating this "linear" behaviour at high temporal frequencies. The results shown in Figs 2–5 demonstrate a constant performance in the task of contrast- or spatial-frequency-discrimination with changing mean retinal illuminance. This means that the results of our previous experiments were not influenced by the choice of one fixed luminance level, and that their validity is extended to a fairly large range of mean retinal illuminance.

The fact that the modulation thresholds are constant over a range of retinal illuminance cannot be explained by the assumption that modulation detection is limited either by quantum noise or by an internal noise source whose noise amplitude is proportional to threshold contrast. Both mechanisms predict that modulation thresholds will be inversely proportional to grating contrast. Experimental results (Fig. 6, reproduced from Jamar et al., 1982) show that this is not the case at the contrast levels used in this study.

The modulation detection threshold at highly suprathreshold contrast for a particular stimulus pattern generally is invariant when the threshold contrast of the pattern is varied. This holds true when the threshold contrast is changed either by presenting the stimulus at a different retinal illuminance level or by presenting it at a different scale (different spatial frequency) (Jamar and Koenderink, 1983). A hypothesis that accounts for this behaviour is that it is a consequence of the very weak dependence of modulation thresholds on contrast at contrasts above about eight times threshold (Fig. 6).
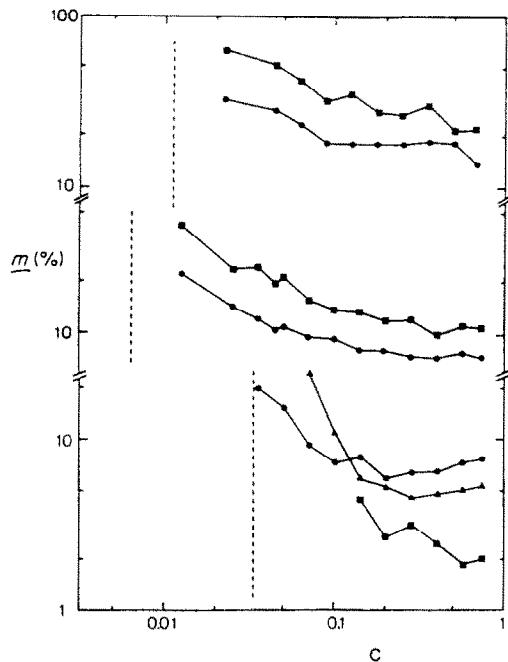
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Fig. 6. Dependence of FM-thresholds on the contrast of the carrier grating for carrier frequencies of 1, 4 and 16 c/deg. Upper set of curves: $f_c = 1$ c/deg and $f_m = 0.25$ c/deg (circles) and 0.8 c/deg (squares). Middle set: $f_c = 4$ c/deg and $f_m = 0.25$ c/deg (circles) and 3.2 c/deg (squares). Lower set: $f_c = 16$ c/deg and $f_m = 0.25$ c/deg (circles), 4 c/deg (triangles) and 12.8 c/deg (squares). The dashed lines indicate the threshold contrast for each of the carrier frequencies. Subject J.C.

If the curve describing the dependence of the modulation threshold on contrast for a particular pattern (a curve like the curves of Fig. 6) is shifted horizontally (but not vertically) with changing illuminance or scale, we would expect to find the constancy of the modulation threshold. Such a horizontal shift is a natural inference from several recent models for suprathreshold vision (Legge and Foley, 1980; Wilson, 1980). These models postulate a nonlinear transducer stage after the initial spatial filtering stage.

In the model of Wilson (1980) a contrast difference is at threshold if the lower and higher contrasts produce outputs from the nonlinear transducer which differ by a fixed amount. Thus, given the transducer function, the model can predict contrast-discrimination-/amplitude-modulation-thresholds.

The shapes of the transducer functions used by Wilson (1980) and by Legge and Foley (1980) are such they correctly predict the shape of our AM-curves (which have the same shape as the FM-curves in Fig. 6). If a change in illuminance or scale leaves the hypothetical transducer function unchanged, except for a shift along the (logarithmic) contrast axis to account for the change in threshold contrast, then the effect on the predicted AM-curves is also a horizontal shift along the (log) contrast axis, and AM-thresholds are predicted to be virtually independent of contrast.

FM-thresholds show the same (in-)dependence on contrast, retinal illuminance and scale as AM-thresholds. A possible explanation is that AM and FM are detected by the same mechanism. This hypothesis is supported by the fact that the subjects in our experiments reported that at the modulation threshold an AM-grating and an FM-grating look alike: both look like a sine-wave grating that is "in some way" irregular. Only at modulation depths above threshold does it seem possible to identify the kind of modulation.

The following detection mechanism is compatible with this hypothesis: suppose that both FM-detection and AM-detection are based on differences in the output amplitude of spatial mechanisms at different retinal positions but with the same spatial frequency tuning (i.e. modulation is detected within one "spatial frequency channel"). Differences in output amplitude can be produced either by contrast-differences (AM) or by spatial frequency differences (FM). Subsequent nonlinear transduction processes then affect AM and FM in the same way, and one expects AM- and FM-thresholds to behave in a similar way.

The results presented in this paper indicate a remarkable constancy of suprathreshold spatial information processing under illuminance changes. Both this phenomenon and the scale invariance (Jamar and Koenderink, 1983) are obviously advantageous for vision under natural conditions. Together they provide the visual system with the possibility of maintaining an almost constant perception under large changes of illuminance level and scale.

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