



## Letters to the Editor

### The Transition from DeVries–Rose to Weber’s Laws: Comments on Rovamo, Mustonen and Näsänen (1995)

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**Rovamo *et al.* [*Vision Research* (1995), 35, 767–774] measured contrast sensitivity at several frequencies in the fovea and periphery as a function of retinal illuminance, concluding that the critical illuminance for the transition from DeVries–Rose to Weber’s laws is proportional to squared frequency at all retinal locations. Yet, inspection of their data clearly reveals that the DeVries–Rose range was hardly ever followed by a Weber range: either no sign of any second range was apparent or the transition was to a qualitatively different range in which sensitivity decreased with increasing illuminance. The validity of their conclusions is questioned, and the status of the “DeVries–Rose to Weber transition” as a description of the relationship between sensitivity and illuminance is discussed in the light of mounting empirical evidence of a decreasing range in this relationship. © 1997 Elsevier Science Ltd**

Weber’s law    DeVries–Rose law    Contrast sensitivity    Retinal illuminance    Individual differences

#### INTRODUCTION

Conventional wisdom has it that as retinal illuminance increases, contrast sensitivity for sine-wave gratings passes from a linear range to a Weber range through an intermediate DeVries–Rose range, although not all three ranges are found for all frequencies (Graham, 1989, Section 13.9.1). Also, the transition from the DeVries–Rose to the Weber ranges has been reported to occur at higher illuminances as spatial frequency increases (van Nes & Bouman, 1967; Hess & Howell, 1988). Rovamo *et al.* (1995) set out to determine whether the critical illuminance for this transition is independent of visual field location, concluding that this was the case. This letter shows that Rovamo and colleagues’ (1995) data

provide scarce evidence of a transition to the Weber range: for most frequencies, their data either show no sign of any transition whatsoever or they show a transition to a range in which sensitivity decreases with increasing illuminance. Two technical flaws in Rovamo and colleagues’ (1995) analyses are described, and the theoretical implications are discussed of a finding—an eventual drop in sensitivity in the high-illuminance region—that vision scientists have overlooked up to now.

#### RAW DATA

DeVries–Rose and Weber’s laws manifest themselves in the form of log sensitivity increasing as a linear function of log retinal illuminance with a slope of 0.5 (defining the so-called DeVries–Rose range) and then levelling off and remaining constant despite further increases in illuminance (defining the so-called Weber range). When inspected in the absence of the “guiding” fitted curves, Rovamo and colleagues’ (1995) data barely show this characteristic. Indeed, only one out of their 18 data sets§ shows clear signs of a Weber range [see the top curve in their Fig. 2(D), from subject JM]. Conversely, nine of their data sets show a distinctively different transition, with sensitivity increasing (although not quite according to the DeVries–Rose law¶) but then decreasing with increasing illuminance without any traces of an interleaved Weber range [see all curves in their Fig. 1,|| from subject JM, all curves in their Fig. 2(C), from subject SU, and the two lower curves in their Fig. 2(D), from subject JM, the lowest one of which is replotted from their Fig. 1 but with a data point that had not been

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§The set of thresholds collected for the same stimulus at the same eccentricity but at various retinal illuminances are considered here to be a single data set.

¶In Rovamo *et al.*’s (1995) log–log plots, increases in sensitivity with increasing illuminance were hardly ever linear or reasonably close to having a slope of 0.5. However, for simplicity, in the sequel we will refer to these data as describing “DeVries–Rose behavior” or spanning the “DeVries–Rose range”.

||Rovamo *et al.* (1995, p. 771) mentioned the presence of a decreasing range in the data from the experiment leading to their Fig. 1, but they chose to not display the data for the highest illuminances and, thus, the strength of the decrease in sensitivity past the DeVries–Rose range cannot be fully appreciated in their Fig. 1.

displayed in it]. The remaining eight data sets, on the other hand, yield inconclusive evidence that would be consistent with either of these two distinct transitions, since the DeVries–Rose range spans the entire set of illuminances used [see all curves in their Fig. 2(A), from subject KL, and their Fig. 2(B), from subjects JM and TH]. Rovamo *et al.* (1995) acknowledged the presence of a decreasing range that immediately followed the DeVries–Rose range in 50% of their data sets, but they followed all their predecessors (see below) and did not discuss it at all.

### EQUATION FITTING

For each data set, Rovamo *et al.* (1995) fitted a function whose shape accommodates the expected transition from DeVries–Rose to Weber's laws. Even when the wrong transition occurred (in the form of a decreasing range in place of the Weber range) or when no transition was present (by lack of data beyond the DeVries–Rose range), Rovamo *et al.* (1995) reported goodness-of-fit measures indicating that an average 96% (range 88–100%) of the variance of the data was explained by the fitted function. There is a straightforward explanation for this apparent contradiction.

In fitting their equation, Rovamo *et al.* (1995) decided to disregard the decreasing ranges and they reportedly excluded from the analyses all data that pointed in the wrong direction. With this strategy, failure to find a good fit is what would be surprising. It might be argued that since the main goal was to determine the illuminance at the transition point, the behavior of the data past that point was immaterial. However, the rationale behind that search was that there is a transition from DeVries–Rose to Weber's laws, but only one of their 18 data sets actually showed convincing evidence of that particular transition. On the other hand, when no transition whatsoever was observed (i.e., for the eight data sets displaying only DeVries–Rose behavior), fitting by fiat an equation that assumes a subsequent Weber range is not the best way to go about finding whether such transition occurs and at what illuminance, and a good fit will spuriously be obtained.

The best-fitting parameters\* were used by Rovamo *et al.* (1995) to determine whether the critical illuminance  $I_c$  for the transition from the DeVries–Rose to the Weber ranges changes with eccentricity. Obviously, the data should not have been used for that purpose since they did not show evidence of that transition in the first place. However, best-fitting estimates of  $I_c$  were used to test whether critical illuminance is proportional to squared

frequency (see Rovamo *et al.*, 1995, Fig. 3). If these estimates of  $I_c$  were valid—which they are not, for the reason just discussed—one might again argue that the good fit displayed in Fig. 3 of Rovamo *et al.* (1995) proves their point. There are, however, two considerations which invalidate their conclusion. First, testing whether the slope of the (linear) relationship between  $\log I_c$  and  $\log$  frequency is the same at all locations implies fitting a regression line *separately* at each eccentricity and testing for equality of slopes across the fitted functions. Yet, Rovamo *et al.* (1995) pooled their data together with earlier (foveal) data from Rovamo *et al.* (1994) and fitted a single regression line to all of them. Second, the earlier foveal data spanned a broader range of frequencies and had a strong linear trend, and these two factors are responsible for the overall fit obtained when the scarce (and spurious) peripheral data are thrown in. In any case,  $I_c$  estimates from the earlier foveal study were also obtained by fiat, since many of the data sets from which they arose showed only DeVries–Rose behavior [see Fig. 3(A) of Rovamo *et al.* (1994)].

### THEORETICAL IMPLICATIONS

Rovamo and colleagues' (1995) data only provide quite strong evidence that the DeVries–Rose range is sometimes followed by a range that is qualitatively different from the expected Weber range. This extra, decreasing range could be an artifact of some methodological flaw, but we were unable to identify anything in Rovamo and colleagues' (1995) method that could account for this effect. Combined with the fact that only one of their 18 data sets did show convincing evidence of a transition from DeVries–Rose to Weber's laws, the conclusions that Rovamo *et al.* (1995) raised from their spurious estimates of  $I_c$  are not backed up by their actual data.

Moreover, scattered evidence of the existence of a decreasing range is present even in the earliest reports bearing on this issue: both van Nes & Bouman (1967, Figs 5 and 6) and Daitch & Green (1969, Fig. 1) displayed results indicating that the Weber range is sometimes replaced (or preceded) by a decreasing range, although neither of them ever pointed that out when discussing their data. Similarly uncommented evidence of this decreasing range can be found in data displayed by van Meeteren & Vos (1972, Fig. 2), De Valois *et al.* (1974, Fig. 4) and Comerford *et al.* (1987, Figs 1 and 2). Also, Peli *et al.* (1996, Fig. 2) reported a decreasing range that carried over to suprathreshold contrast perception.† Of course, data have also occasionally been reported that show a clear Weber range immediately following the DeVries–Rose range, but the commonest finding is that sensitivity increases over the entire set of illuminances used with no clear sign of any subsequent range whatsoever [Hess & Howell, 1988, Figs 2 and 3; Hess, 1990, Figs 2 and 7; Peli *et al.*, 1991, Figs 2 and 3; Mustonen *et al.*, 1993, Figs 1 and 2; Rovamo *et al.*, 1994, Fig. 3(A); Rovamo *et al.*, 1995, Figs 2(A) and 2(B); Coletta & Sharma, 1995, Fig. 3]. Whenever the latter

\*Incidentally, fitting the equations required the estimation of two parameters, and this was done in many cases using only four or five data points!

†A less surprising report of this decreasing range, either immediately after the DeVries–Rose range or with an interleaved Weber range, has been reported for the rod monochromat by Hess & Nordby (1986, Fig. 1), but this is easily understandable as a result of the lack of functional cones.

result occurred, all authors seem to have assumed that a Weber range would appear afterwards.

When the mixed results arising from all of the reports just mentioned are looked at without molds, the status of the "linear to DeVries–Rose to Weber transition" as a description of the relationship between sine-wave contrast sensitivity and retinal illuminance appears unclear. This "theoretical" expectation—perhaps an unwarranted generalization from results obtained with sharp-edged spots—has filtered the interpretation of sine-wave contrast sensitivity data for years, justifying the fitting of bilinear functions by eye (van Nes & Bouman, 1967; Peli *et al.*, 1996) or the fitting of analytical functions describing a similar shape by numerical methods (Mustonen *et al.*, 1993; Rovamo *et al.*, 1994, 1995). Yet, deviations from a straight line with a slope of 0.5 in the low-illuminance region as well as deviations from a horizontal line in the high-illuminance region are both too strong and too frequent to consider them experimental error any longer. In addition, the three-range description would be meaningful only if the ranges had a broader extent than the transition zones; yet, it seems that the opposite occurs, with transition zones spanning over 4 log units of illuminance [Hess & Howell, 1988, Figs 2 and 3; Hess, 1990, Figs 2 and 7; Peli *et al.*, 1991, Figs 2 and 3; Mustonen *et al.*, 1993, Figs 1 and 2; Rovamo *et al.*, 1994, Fig. 3(A); Rovamo *et al.*, 1995, Figs 2(A) and 2(B)].

It may be time, then, to look at the relationship between sensitivity and illuminance from a different theoretical perspective, one which accommodates the fact that sensitivity *usually* increases asymptotically (but not in a bilinear way) with illuminance, but also acknowledging that there are cases in which sensitivity decreases with further increases in illuminance after reaching a peak. Which perspective that may be (i.e., why this gradual change occurs) is unclear, although the interplay of the rod and cone systems may be responsible for the gradual change found in normal observers. [The change is more abrupt in the rod monochromat; see Hess & Nordby (1986, Fig. 1).] Theoretical developments would be necessary to test this speculation. Also unclear is the cause of the eventual decreasing range in normal observers, but there is some evidence that it is not related to stimulus but to subject characteristics: the two distinct patterns appear only for different subjects (admittedly at different eccentricities and for different stimuli) in Rovamo and colleagues' (1995) data, and Peli *et al.* (1996, Fig. 2) have reported decreasing trends for only two out of four subjects. On the other hand, Hess [1990, Fig. 2(c)] displayed data clearly indicating that the relationship between normalized sensitivity and normalized illuminance is independent of spatial frequency within each of two individual subjects, but the form of the relationship is slightly different across subjects.

Preliminary simulations with a spatial vision model incorporating sensors that explicitly receive both rod-based and cone-based inputs have shown that differences in the balance of these distinct input sources produce differences in the form of the sensitivity vs. illuminance

curve. This simulation work is still in a very early stage, but several results can be advanced. Specifically, if sensors tuned to low spatial frequencies do not receive cone-based inputs, then a decreasing range will occur only at low spatial frequencies as a result of rod saturation and the absence of cone-based inputs that might take over. [None of the empirical reports that we are aware of provide any indication of decreasing ranges at intermediate or high frequencies, although low-frequency data without decreasing ranges have also been reported: e.g., Hess & Howell (1988, Fig. 3).] Also, if rod-based inputs dominate cone-based inputs overall, a decreasing range will also occur over the intermediate range of illuminances where the onset of the cone system cannot make up for the sensitivity drop caused by rod saturation.

García-Pérez & Sierra-Vázquez (1996) have shown that there is ample evidence of individual differences in the functional organization of the visual system across eccentricity, producing the effect that some subjects are more sensitive to low frequencies in the periphery, while others are more sensitive to all frequencies at the fovea. It is not unlikely, then, that the form of the sine-wave contrast sensitivity vs retinal illuminance curve (i.e., whether it includes a decreasing range and at what frequencies) is the consequence of yet another source of individual differences in the functional organization of the visual system, namely, the balance of rod-based and cone-based contributions to contrast sensitivity.

## REFERENCES

- Coletta, N. J. & Sharma, V. (1995). Effects of luminance and spatial noise on interferometric contrast sensitivity. *Journal of the Optical Society of America A*, *12*, 2244–2251.
- Comerford, J. P., Thorn, F. & Corwin, T. R. (1987). Effect of luminance level on contrast sensitivity in myopia. *American Journal of Optometry and Physiological Optics*, *64*, 810–814.
- Daitch, J. M. & Green, D. G. (1969). Contrast sensitivity of the human peripheral retina. *Vision Research*, *9*, 947–952.
- De Valois, R. L., Morgan, H. & Snodderly, D. M. (1974). Psychophysical studies of monkey vision—III. Spatial luminance contrast sensitivity tests of macaque and human observers. *Vision Research*, *14*, 75–81.
- García-Pérez, M. A. & Sierra-Vázquez, V. (1996). Do channels shift their tuning towards lower spatial frequencies in the periphery? *Vision Research*, *36*, 3339–3372.
- Graham, N. V. S. (1989). *Visual pattern analyzers*. Oxford University Press, New York.
- Hess, R. F. (1990). The Edridge–Green lecture. Vision at low light levels: role of spatial, temporal and contrast filters. *Ophthalmic and Physiological Optics*, *10*, 351–359.
- Hess, R. F. & Howell, E. R. (1988). Detection of low spatial frequencies: a single filter or multiple filters? *Ophthalmic and Physiological Optics*, *8*, 378–385.
- Hess, R. F. & Nordby, K. (1986). Spatial and temporal limits of vision in the achromat. *Journal of Physiology*, *371*, 365–385.
- van Meeteren, A. & Vos, J. J. (1972). Resolution and contrast sensitivity at low luminances. *Vision Research*, *12*, 825–833.
- Mustonen, J., Rovamo, J. & Näsänen, R. (1993). The effects of grating area and spatial frequency on contrast sensitivity as a function of light level. *Vision Research*, *33*, 2065–2072.
- van Nes, F. L. & Bouman, M. A. (1967). Spatial modulation transfer of the human eye. *Journal of the Optical Society of America*, *57*, 401–406.

Peli, E., Yang, J., Goldstein, R. & Reeves, A. (1991). Effect of luminance on suprathreshold contrast perception. *Journal of the Optical Society of America A*, 8, 1352–1359.

Peli, E., Arend, L. & Labianca, A. T. (1996). Contrast perception across changes in luminance and spatial frequency. *Journal of the Optical Society of America A*, 13, 1953–1959.

Rovamo, J., Mustonen, J. & Näsänen, R. (1994). Modelling contrast sensitivity as a function of retinal illuminance and grating area. *Vision Research*, 34, 1301–1314.

Rovamo, J., Mustonen, J. & Näsänen, R. (1995). Neural modulation transfer function of the human visual system at various eccentricities. *Vision Research*, 35, 767–774.

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## Transition from DeVries–Rose to Weber’s Law: Reply to García-Pérez and Peli (1997)

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García-Pérez & Peli (1997) claim that a complete transition from the DeVries–Rose to Weber’s law is only rarely observed in the measurements of grating contrast sensitivity as a function of retinal illuminance. According to García-Pérez & Peli (1997), the data plotted on double-logarithmic coordinates most often show either a monotonical increase across the whole luminance range studied or an increase of this type immediately followed by a decrease, without a preceding Weber region. García-Pérez & Peli (1997) suggest that the whole description of sine-wave contrast sensitivity as a function of retinal illuminance by transitions between three main segments—from a linear through DeVries–Rose to Weber range—may be an unwarranted generalization from results obtained with sharp-edged spots. They emphasize that deviations of the log–log data from a straight line with a slope of 0.5 at moderate light levels as well as deviations from a horizontal line at high luminances are too strong and frequent to be neglected, and argue that the three-range description would only be meaningful if the ranges had a broader extent than the transition zones, which, however, span over four logarithmic units of illuminance.

On the above basis, García-Pérez & Peli (1997) question the validity of our estimates (Rovamo *et al.*,

1995) of critical retinal illuminance ( $I_c$ ) marking the transition between DeVries–Rose and Weber’s laws.

First, we would like to commend García-Pérez & Peli (1997) for drawing attention to the generally neglected but important fact that grating contrast sensitivity at high light levels often decreases with increasing retinal illuminance. The phenomenon could indeed be due to rod saturation or rod–cone interactions, as they suggest. However, we would like to offer another possible explanation arising directly from the adaptational properties of cone photoreceptors showing a combined effect of gain decrease and loss of operating range (partial saturation). In bright light, the operating range of (turtle) cones is reduced to half of its dark-adapted range, and much of the loss occurs in a 1–2 log unit range of mean illuminance ( $I$ ) just above the level corresponding to  $10^5$  isomerizations per second per cone (Burkhardt, 1994). It may be important that this is the range where pigment bleaching becomes substantial in human as well as turtle cones (Rushton & Henry, 1968). In the cones of frog and turtle, this range is associated with a stronger-than-Weber decrease in increment sensitivity ( $I^{-1}$ ), indicating that contrast sensitivity also decreases (Baylor & Hodgkin, 1974; Donner *et al.*, 1997). The fact that the decrease of contrast sensitivity is most often revealed in peripheral vision (Rovamo *et al.*, 1995) could result from the increase of cone inner segment size with eccentricity (Curcio *et al.*, 1990) allowing greater quantum catch in peripheral than foveal cones, so that peripheral cones would receive the appropriate isomerization rates at lower retinal illuminances. If this explanation is true, the decrease of contrast sensitivity with increasing retinal illuminance should be followed by a “second” Weber

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