VISUAL MEASUREMENTS AND OPTICAL PERFORMANCE CRITERIA

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This topic calls for a discussion of the correlation between matters of physics as they have to be used for technical hardware and the functioning of the difficult-to-define subject, or object, the human being. We are with this problem at the heart of the task of engineering. Because, whatever we do, even if it is nothing more but sending a fully automated surveyor to Mars, it will finally have to serve human needs. The results will, therefore, have to be in such a form that they can be noticed by human senses, interpreted by the human mind and integrated into his scheme of thinking. Careful considerations of the physiology and psychology of a human being are even more important, if Homo Sapiens is an integral part of a complex technical system such as a training device with an optical display for simulating the visual environment of the trainee.

Immediately, the task becomes imminent to define and to determine how good, in physical terms. a visual simulation has to be in order to fulfill its purpose. This calls for meaningful performance criteria. If we follow the always present temptation to over-specify, the lead time for a project may become much longer than anticipated and the expenditures may skyrocket; we may even hit, after much time and money was spent, the impenetrable wall of an Impossible. If we under-specify, we may have to face the unpleasant fact that our device will not be accepted by the end-customer.

Much work lies still ahead of us in this area. The difficulty we face is that this kind of work is often too basic for the engineer, even for his "applied research," but not basic enough for those responsible for the support of "basic science"; it lies in the gray area between science per se and conventional engineering. Of course, much work has been done already by that branch of engineering science generally known by the name of "human factors engineering," which was developed under the leadership of experimental psychologists. However, the systems engineer is still often disappointed if he does not get as precise answers to pertinent questions as he wants in a certain situation. The reason is that experimental psychologists did have to work out their results, as every scientist does, under idealizing conditions which are rarely present under the practical conditions of the engineer. Often, the practical engineer does not understand this, and the experimental psychologist does not receive the support to expand his knowledge to areas of lesser idealization.

One example: An engineer wants to specify for a system for visual simulation a resolution of one minute of arc because every optics textbook he read says that this is the resolution of the human eye. But, he knows, or a friend tells him, that this is impossible under prevailing circumstances. So he asks: What resolution shall I specify?

First: The one minute of arc is far from being a dogmatic statement even if measured under idealized conditions, that is, with a uniform bright background, and with an idealized high contrast target such as a Landolt ring, see figure 1, an acuity test chart, or the USAF or Bureau of Standard resolution test chart (ref. 1 and 2). The eye resolution in minutes of arc, or its inverse, the acuity, does change considerably even under idealized conditions. Figure 1 demonstrates the change of resolution with two parameters, the specific form of the test target and with the luminance of the background (ref. 3). Available space prohibits to show how resolution changes with the contrast of the test target, with color, time of exposure, size of the test chart and its position in the field of view, with adaptation time, and other parameters.

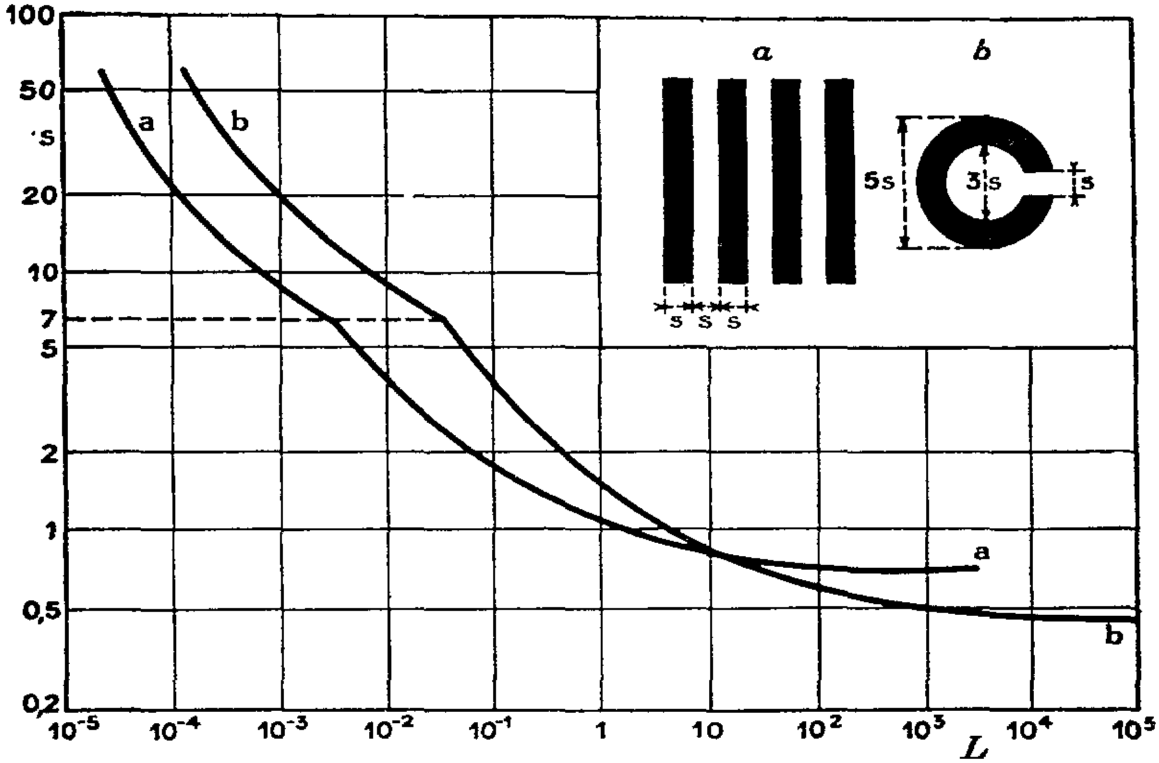

Figure 1. Variation of Eye Resolution

Ordinate: resolution in minutes of arc,
Abscissa: background luminance in cd/m^2,
Curve a: Foucault bar pattern, Curve b: Landolt ring.
Note: resolution for the bar pattern is referenced to bar width; others reference it to bar distance (center to center), which doubles the resolution values.

But, what trainee in a simulator looks ever at a high contrast resolution chart on a uniform bright background? "Resolution" must appear reduced for objects in a complex image because of distractions from the many details in that image. I found no source of reference which would attempt to answer or even mention this obviously important question. The only pertinent remarks which would apply are contained in some German textbooks concerned with optical instrument theory (see ref. 4). They recommend for the design of diffraction limited instruments one minute of arc for best seeing, two minutes for good seeing, and four minutes of arc for convenient seeing. For instance, the so called Abbe's Rule for the upper limit of useful magnification, m, of a microscope (see ref. 5)

$$m = 1000 \times NA$$

NA = numerical aperture

is based on an apparent radius for the Airy disc, or resolution, of 4 min. of arc. This may indicate that resolution in complex imagery will be between two and four minutes of arc under favorable seeing conditions and for objects resembling precise and high contrast details such as resolution targets. On the other hand, it should be remembered that objects may be visible under favorable conditions which subtend much less than one min of arc, such as a telephone wire against a bright sky (a few seconds of arc) or a star in the dark night sky (0.01 sec of arc or less). However, in these cases the diffraction pattern of the image of those objects in the eye approaches one min of arc.

In my last year's presentation (see ref. 6), I made it clear that sharpness of an image, that is presentation of edges, cannot unambiguously be related to resolution. We will then have to resort to acutance. If both are related to the Modulation Transfer Function (MTF) as an expression of physical performance, acutance requires emphasis on the lower frequencies of the MTF and resolution on the higher frequencies (see figure 2 and ref. 7).

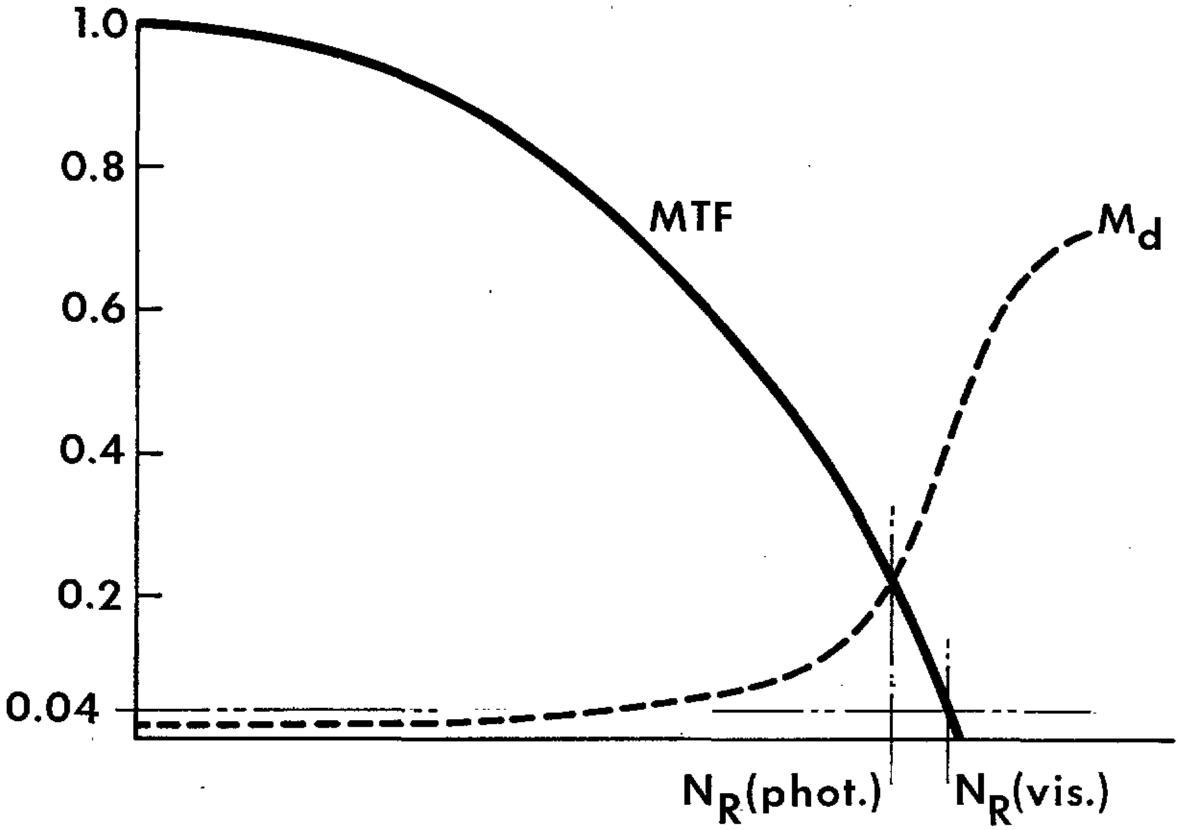

Figure 2. Modulation Transfer Function and Resolution

Abscissae: spatial frequency in (optical) lines per mm; Ordinate: modulation M = $(L_{max} - L_{min})/(L_{max} + L_{min})$; N_R(vis.) = visual resolution in optical lines/mm for a high contrast bar pattern assuming a threshold contrast of 4 percent; N_R(phot) = photographic resolution determined from the intersection point of the MTF-curve (Modulation Transfer Function) of the optical system and the M_d-curve (Modulation Detectivity) of a photographic emulsion.

Investigating how resolution can be related to the MTF, leads to the question of minimum contrast recognition, namely, that minimum contrast between two line images necessary to discern them as two separate lines. Rayleigh's resolution criterion was only conceived intuitively and must not be taken dogmatically.

Berek was the first to point out that the minimum contrast between maxima and secondary minimum is of decisive importance for the discernment of resolution and that it is a physiological constant which cannot be derived from theory alone (see Ref. 8). He wrote for the visual resolution in a microscope:

$$d_R = k \frac{\lambda}{(A_{obj} + A_{ill}}$$

d_R = resolved distance of two points of equal intensity

λ = average wavelength

A_{obj} = numerical aperture of objective lens

A_{ill} = numerical aperture of illumination in the aperture stop of the objective lens

k = physiological constant

He determined from carefully conducted experiments for microscopic observations k = 1.0 instead of Rayleigh's 1.22. This is in agreement with the Dawes-Sparrow criterion for telescope observation (see ref. 9).

Selwyn investigated what the actual contrast between the images of two fine slits produced by an optical instrumentwould have to be in order to discern them as just resolved (figure 3, and ref. 10). He was careful to make the resolution instrument-limited instead of eye-limited and found that, with this condition, the minimum contrast was in the average of 3.5 to 4 percent. It is assumed then that the point of resolution for visual observation and for a high-contrast square bar pattern is represented by that point on the MTF for which the modulation is 4 percent, provided that the resulting angular resolution for the eye is larger than three to four minutes of arc (see figure 4). The difference between a square and a sine wave pattern becomes practically negligible at this point of resolution.

If we are interested in photographic resolution, we must be aware of the fact that discernable minimum contrast for a photographic material depends to a large degree upon the characteristics of the emulsion used, such as its gamma, graininess, and spatial frequency, the so called Modulation Detectability Curve (figure 4, and ref.11). Use of the directly measured M_d-Curve relieves us from the difficulties caused by the non-linearity of photographic emulsions (linearity is a necessary condition for the use of MTF curves).

The situation is again much more complicated if we turn from idealized resolution targets to lively complex imagery. Goldberg reported in a little, hopelessly out-of-print classic (ref. 12) that the discernable minimum contrast is in photographic pictures throughout their dynamic range of reflectance. He found that detail recognition requires a minimum contrast of 4 percent in the bright part of a photographic image, but grows to 25 percent in the dark, deep shadows. We must assume that minimum contrast for detail rendition will follow similar trends in projected and virtual images. However, for the detectability of a spot in an otherwise spotless sky, the minimum contrast can be as low as 1 percent, the same value as for the detectability of a contrast difference in the field of a visual photometer. (Contrast is defined, within this context, as the absolute value of [L(detail) - L(background)] /L(background).

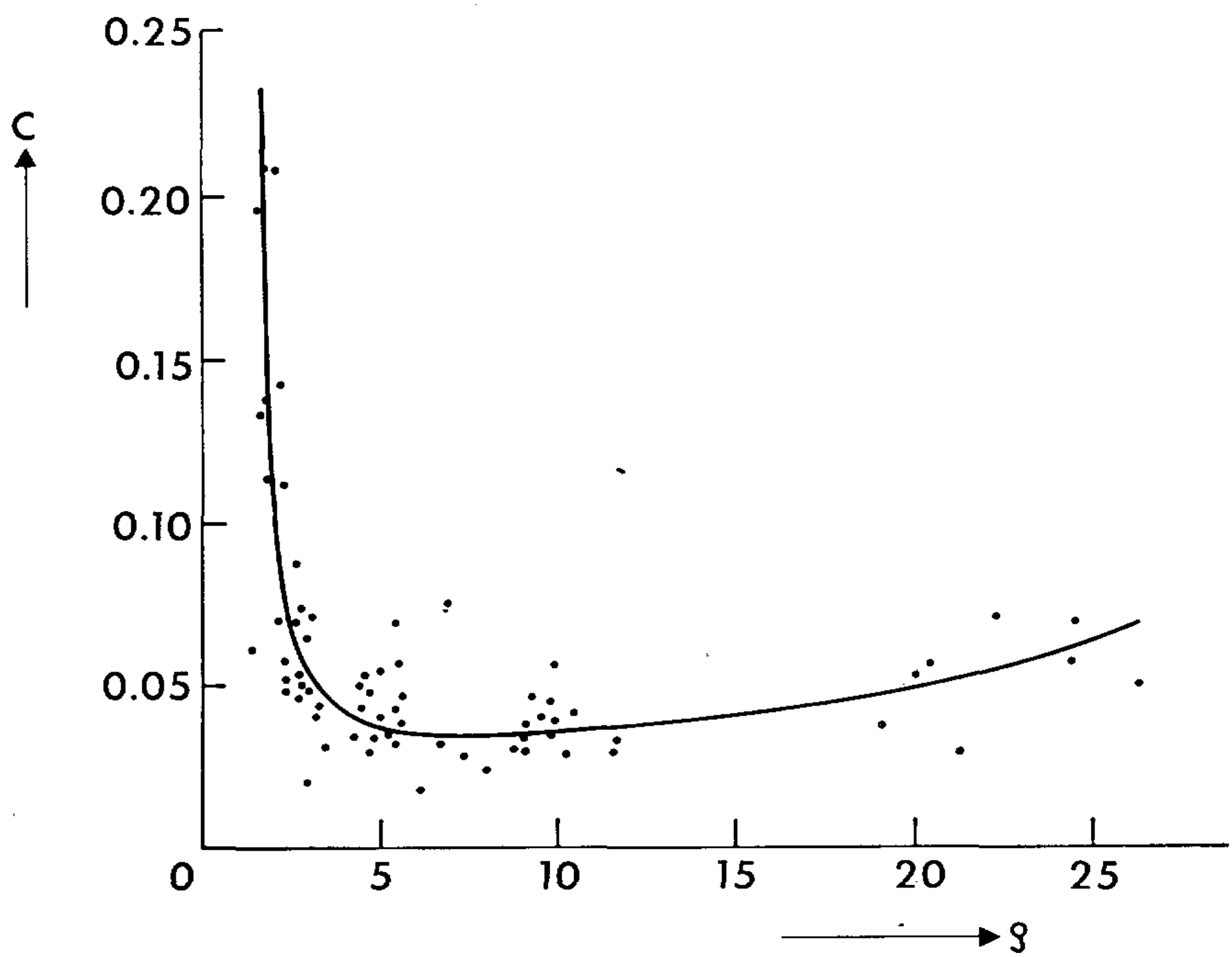

Figure 3. Minimum Contrast for Visual Resolution

Ordinate: contrast between the two maxima of the image of two slits and the minimum between the two maxima, Abscissa: δ = angle in min of arc between the two slits.

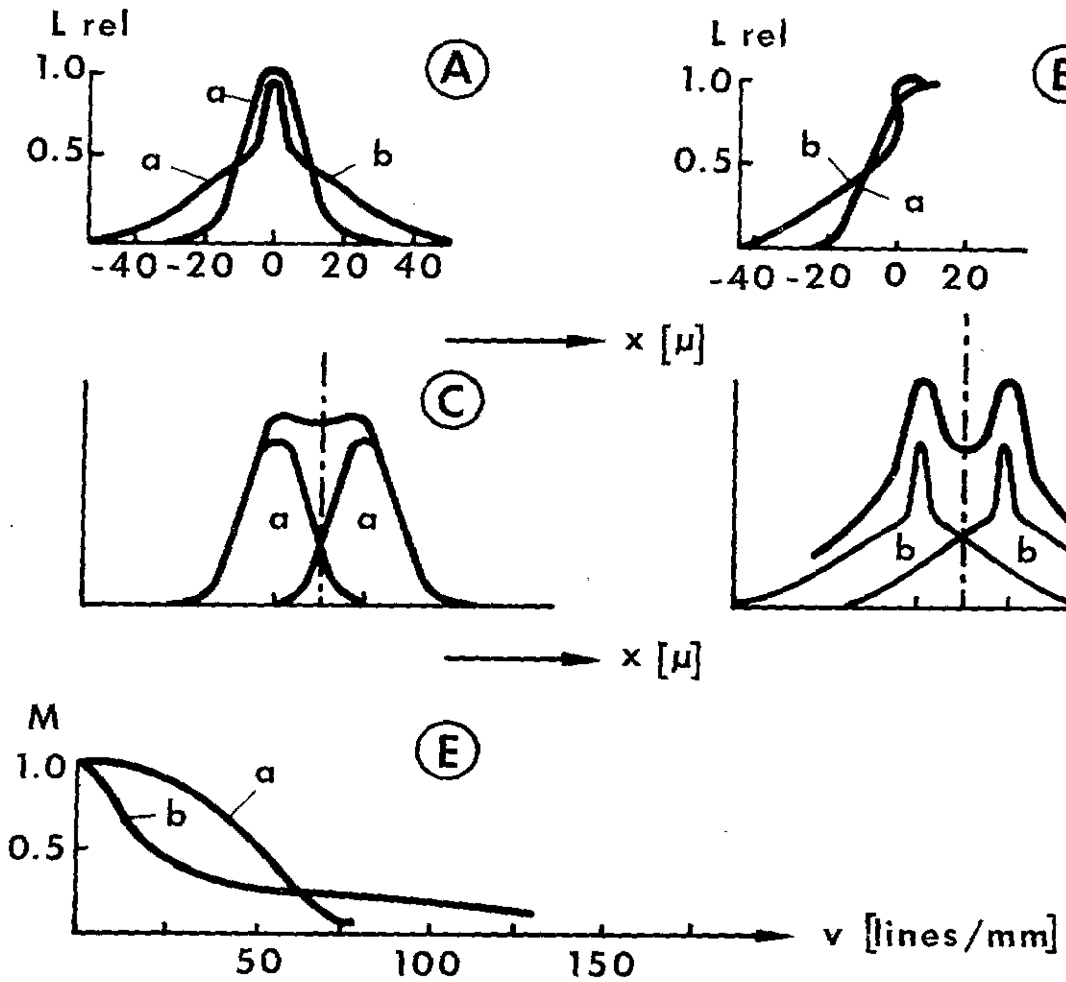

Figure 4. Modulation Transfer Function, Resolution and Edge Sharpness

A. Two line spread functions (LSF), a) Gaussian LSF, b) with widened foot and sharpened tip (a and b are shown separated at the maximum for the sake of clarity; both reach the 1.0 point in reality); B. Edges corresponding to LSF(a) = narrow edge spread and LSF(b) = wider edge spread (curvature of curve b is exaggerated for the sake of clarity; in reality, the upper part of b does not bend over and levels off at 1.0. C. Double line of LSF(a) = low resolution; D. Double line of LSF(b) = high resolution; E. MTF for LSF(a) = emphasis on low frequency and de-emphasis on high frequencies, opposite behavior of MTF for LSF(b).

I hope it will be understood that we have to fill our treasure chest of knowledge with new research results before we can draw from it what we need so dearly for improved designs for visual simulation. It will be wise to be aware of the limitations of the conventional concepts and methods which we have to use meanwhile.

ACKNOWLEDGMENTS

Figure 1 has been taken from ref. 3, figure 3 has been redrawn from ref. 10, and figure 4 from ref. 7.

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