Towards linking perception research and image quality

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TOWARDS LINKING PERCEPTION RESEARCH AND IMAGE QUALITY

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Abstract — Image quality as a general notion relates both to elementary and to complex visual functions. In this paper we deal with a few of them, which correspond to some lines of research at our Institute. We start with threshold predictions in time and space domains by means of elementary response functions, which have been recently developed considerably, although full generalization has not yet been achieved. As to suprathreshold stimuli, the responses of subjects usually have to be scaled. Here we deal with some problems connected with scaling techniques. After a brief discussion of the applicability of notions on visual conspicuity and visual search to image quality problems, we finally discuss reading from alphanumeric displays.

I. INTRODUCTION

A. Image Quality: What Does It Mean?

Electronically displayed images are becoming increasingly important as an interface between man and informative or recreative media. Lengthy periods of intense observation of displays are no longer unusual. In professional circles there is a growing awareness that specific demands should be made on displayed images in order to achieve an optimum match with the perceptual properties of the visual system. These demands may vary greatly, depending on the purpose of the display and the environmental conditions. Optimal-image specifications are clearly not the same for home TV, a TV projection system, a radar signal monitor, or a small control display. However, it is not always easy to specify demands explicitly. This is expressed in a characteristic way by Biberman[1]: "It is a truism that a good picture is better than a bad picture, but it has not been abundantly clear, especially to designers of most electro-optical imaging systems, what criteria must be used to decide if the picture is good or bad."

"Image quality" is the term usually used to refer to the way the parameters of the display fulfill the requirements for optimal perception. Its meaning, however, can easily be interpreted differently in different contexts. First, subjective image quality determined by physical parameters on purely perceptual grounds is not always distinguished clearly from purely physical parameters without subjective correlates. Second, subjective quality is sometimes thought of in terms of performance[2-4] (for example, detection or recognition of objects in thermographic, ultrasonic, or radar imaging), in other cases as lack of impairments[5,6,106,107] (for instance, noise interference, vignetting, etc.), and finally in terms of "pleasing the eye" (for example, in the case of TV broadcasting, films, slides, the video telephone, etc.). The latter may be the ability to come close to the impression of the original scene; for instance, by a good choice of the tone reproduction curve,[7-10] but it may equally have to do with the possibility of generating a text that can be read comfortably.[11,12]

In this article we primarily direct our attention to subjective image quality in the sense of "the ability to please the eye," i.e., through the proper image characteristics and by the absence of image degradation. In a way it is expressed by one definition of the word "quality" as given by the Concise Oxford Dictionary,[13] "the degree of excellence of the image." This definition is too vague to be practical. However, while feeling unable to make the general definition more explicit, we shall make part of it operational in the examples to be given further on.

B. Multiple Determiners of Image Quality

On one hand, the subjective image quality of displayed images is determined by the apparatus, and, on the other, by the properties of the visual system. However, the latter can be influenced by the former. It is well known that many properties of the visual system depend on the mean level of retinal illuminance, and consequently on screen luminance.

With respect to the desired degree of quality, a first remark would be that the display should be matched to the eye but need not be better than that. Unfortunately, this does not get us very far. The different faculties of the visual system have different demands. For example, good visibility of details is neither sufficient for good subjective reproduction nor for comfortable vision. A typical example of the latter is displayed text. Although it may be perfectly visible, it may also be unacceptably tiring to read, irrespective of its actual contents. Here we are probably coming close to the underlying principles of layout.[14,15] Generally speaking, comfort or discomfort in perception is significantly determined by higher faculties of the visual system. Although it is a different and rather vague field, we feel that it deserves attention in view of the straining effect of discomfort. Jones[16] characterized the problem pithily by asking: "What does the eye really see? To what extent is the eye capable of seeing? What does the eye like to see?"

C. The Approach in Image Quality Research

There is a considerable amount of practical empirical knowledge about the techniques of displaying images acceptably for the eye. Literature on this is predominantly to be found in engineering journals. There is also a great deal of basic knowledge about the visual system spread over the scientific literature of several disciplines. Yet we experience a gap between the explicit practical needs of the engineer and the possible application of the available fundamental knowledge. For example, in most cases psychophysics cannot predict the answer to the engineer's question as to whether or not some spatial or temporal interference pattern will remain invisible. Psychometrics cannot easily answer topical questions[17] such as: How does (subjective) sharpness of still and moving images vary as a function of screen size and viewing distance? As a result, many engineering problems in which perception is involved have to be solved by ad hoc research. However, we have the impression that in many cases it is difficult to use the results in analogous but somewhat different problems. Although it seems unlikely that this type of approach to engineering problems can be missed, particularly in the short term, the lack of generalization is very unsatisfactory to us. This is especially so since perception experiments in this field are usually tedious and expensive.[18] We feel that attempts to direct research efforts to a more generally applicable direction is worthwhile in spite of the high initial costs. For instance, quantitative modeling with respect to prediction and evaluation of the perception of images is known as one way to promote generalization. This naturally entails a certain amount of risk since, unlike the ad-hoc approach, it takes a considerable initial effort without any guarantee of getting a satisfactory model for the problem involved.

However, a simple way to further the cause of generalization we advocate would be to choose conditions and specify stimuli in such a way that a link with other investigations can be made. A certain amount of uniformity of methods and conditions is already being stimulated in the field of application.[19] Fortunately, experimental designs, permitting an insight to be gained on the basis of more general viewpoints, are becoming more numerous. As an example, we recall that the use of the spatial modulation transfer function concept for the eye has improved our understanding of the limits of contrast and detail vision and their interrelation, although, as a result of a number of complications, the predictive possibilities are felt unsatisfactory.

D. *Factors of Image Quality*

As pointed out above, quality factors may be studied in terms of performance impairment and pleasure or comfort. Hunt and Sera[135] introduced a bisection of the problem by distinguishing between performance- and nonperformance-oriented environments. The latter are understood to be involved with cosmetic or aesthetic considerations and are directed towards broadcast TV, photography, motion pictures, and so on. It is this observer's "internal image" oriented part we would like to emphasize here. However, such a description is still too wide to be practical. We have arranged our choice of subjects we wish to deal with in this article more or less according to the complexity of the perceptual processing involved. We start our serendipity with threshold experiments, followed by scaling and judgement, conspicuity, and problems relating to such aspects as displayed text information. Psychophysics, psychometrics, and cognitive psychology are successively involved. This arrangement of the subjects is by no means obvious. On the contrary, one could very well argue that the determination of the psychological dimensions of image quality (e.g., sharpness, contrast, size, color, etc.) and their relative importance should be looked at first,[20-23] followed by the scaling of the underlying sensorial attributes with respect to the physical parameters, and ending with a discussion of thresholds. Yet, for practical reasons we have opted for the first-mentioned arrangement. Several subjects relevant to image quality are disregarded here, of which color is one. It should be emphasized that the following does not pretend to be anything more than an attempt to look at subjective image quality from a psychophysical point of view, motivated by our desire to narrow a gap between disciplines.

II. THRESHOLDS OF SIMPLE PERCEPTS AS ELEMENTARY FACTORS IN IMAGE QUALITY

A. *Thresholds as Limits of Perception*

In many problems concerning image quality, visual thresholds for the physical parameters of the displayed image are the relevant factors. Some thresholds relate to upper admissible limits, i.e., it is preferable to keep the perceptual attributes connected with the physical parameters below the threshold. Frame flicker, the line structure of frames, interference patterns, vignetting of brightness, etc., are well-known examples of such unwanted percepts. Other thresholds are required as information about lower limits of desirable percepts; for instance, the smallest luminance step that produces a perceptible brightness contour, the minimum size of digits to permit their recognition, etc.

Although thresholds of all kinds have been measured extensively for many decades, it is still barely possible to predict a particular threshold in some practical situation with sufficient precision. Generalization is still rather poor. However, much theoretical and experimental work has been done recently in various laboratories which is beginning to show reasonably good prospects.

B. *Some Considerations on Modelling*

Current models are obviously constructed from different starting points. Some are based predominantly on physiological knowledge, while others are founded on a systems analyses approach, leaving out physiological details of actual processing. In practical image-quality problems, the latter approach seems to be somewhat more applicable, although basic physiological properties should be regarded. We want to restrict ourselves here to problems concerning luminance distribution in time and space. The quantity of interest is frequently the threshold of a luminance change, given its time and space function. Examples are the upper limits of running interference patterns and dynamic noise dots. Models handling luminance processing in space and time simultaneously are being worked on in various laboratories[24-28] but do not yet seem to have achieved sufficient general acceptance and operational simplicity to permit their application in practical problems. As a consequence, in everyday problems one is prepared to relax the requirements of full generality for the time being and look at processing in space and time separately, hoping on this basis to gain sufficient information to be able to work one's way to a more general model eventually. But even when space and time domains are considered separately, prediction is not yet quite satisfactory. We will go into this in more detail later on. There are, of course, other complications that are usually ignored, primarily for the sake of simplicity. One example is the inhomogeneity of the retina.[29-33] Since foveal vision is relatively important, models are frequently restricted to predictions for that area alone (which is then considered to be approximately homogeneous). However, the part played by the periphery in image perception may be grossly underestimated. Before becoming more specific, we would like to make a general remark in relation to the development of adequate quantitative models, which requires a great deal of data. It is no doubt hampered by the fact that different authors often use different experimental conditions so that pooling or even comparison is difficult. Sometimes even the units of the light levels are not given properly. This seems to us an unnecessary waste.

C. Characteristic Functions

An accepted method of comparing the capacity of a display with that of the visual system is to use characteristic functions that reflect the important properties of the system and the state of the variables. The choice of these functions is inevitably connected with one's ideas about the model of the visual system. For instance, temporal or spatial modulation transfer functions (TMTF/SMTF) acquire their full meaning if all the systems in the chain involved in processing the visual information are operating linearly in the range of interest. Indeed, for small signals the eye probably functions approximately linearly and the resulting MTF is found simply by multiplying the transfer functions of the eye and of the apparatus. However, in spite of this obvious advantage of MTF, the interest in the literature for one-shot characteristic functions is gradually growing. Examples are pulse and step responses from which an MTF can easily be derived if the system operates linearly. They give information directly in the space or time domain and have some other advantages that will be made clear below. However, multiplication has to be replaced by convolution in the case of cascaded systems.

D. Spatial Response Functions For Characterization and Prediction

It has long been recognized that the ability of the eye to resolve spatial detail depends both on contrast and on the mean adapting luminance of the scene. Extensive psychophysical studies have yielded a great deal of data giving information about this relation. As an example, we recall Blackwell's work[34] concerning objective contrast thresholds of circular disks on a homogeneous background as a function of background luminance and the diameter of the disk.

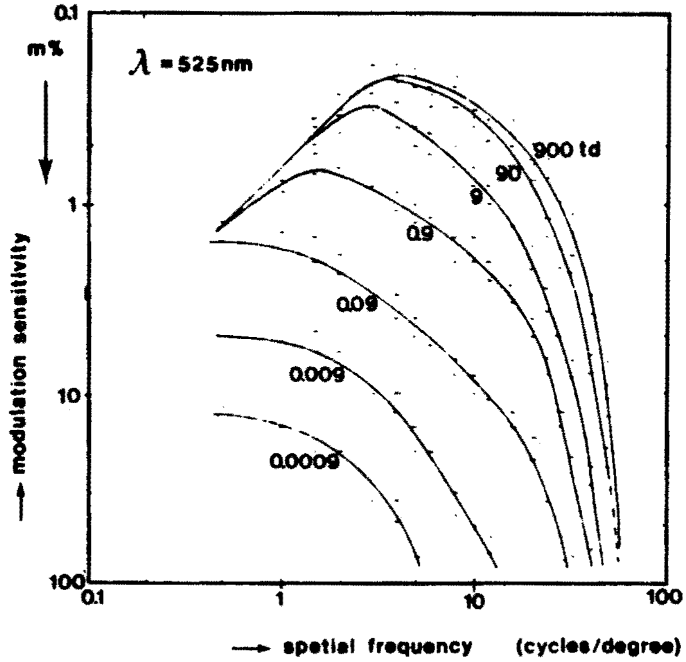

FIG. 1. Example of spatial modulation transfer in a human subject, expressed in the reciprocal of modulation depth at threshold. Monochromatic light (λ = 525 nm) is used. The parameter is the mean level of retinal illumination. The sinusoidally modulated grating spans an angle of 4.5° horizontally and 8.25° in the vertical direction. (Data from Van Nes and M.A. Bouman, Ref. 41.)

Since the introduction of Fourier techniques in optics,[35] followed by electro-optics and vision,[36-40] the modulation transfer function has become a popular means to characterize the transfer of detail in connection with objective contrast (e.g., Fig. 1).[41] In vision, threshold amplitudes favor linearization. If the amplitude of the processed signal of a sinusoidally modulated grating at threshold is assumed constant, the sensitivity, being the reciprocal of threshold modulation amplitude, may be interpreted as the modulation transfer function but for a constant factor. However, predictions made from SMTF, considering the visual system as one linear low-pass filter, did not work out well.[42] It

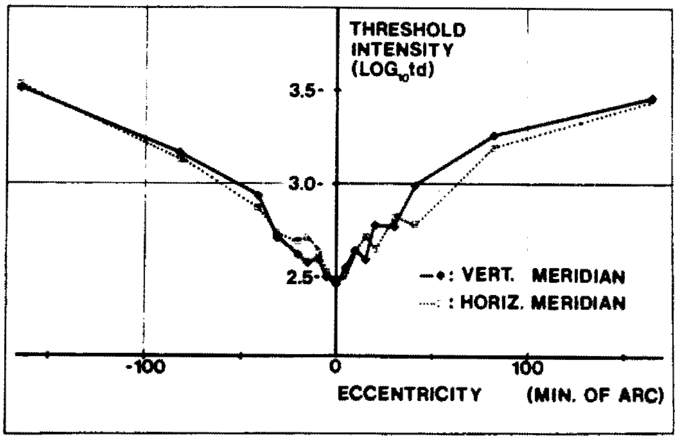

FIG. 2. Demonstration of the inhomogeneous sensitivity distribution of the retina around the fovea. Incremental thresholds of a point-source measured, with a homogeneous background of 1200 td, along the horizontal and vertical meridian. (Courtesy Blommaert, personal communication.)

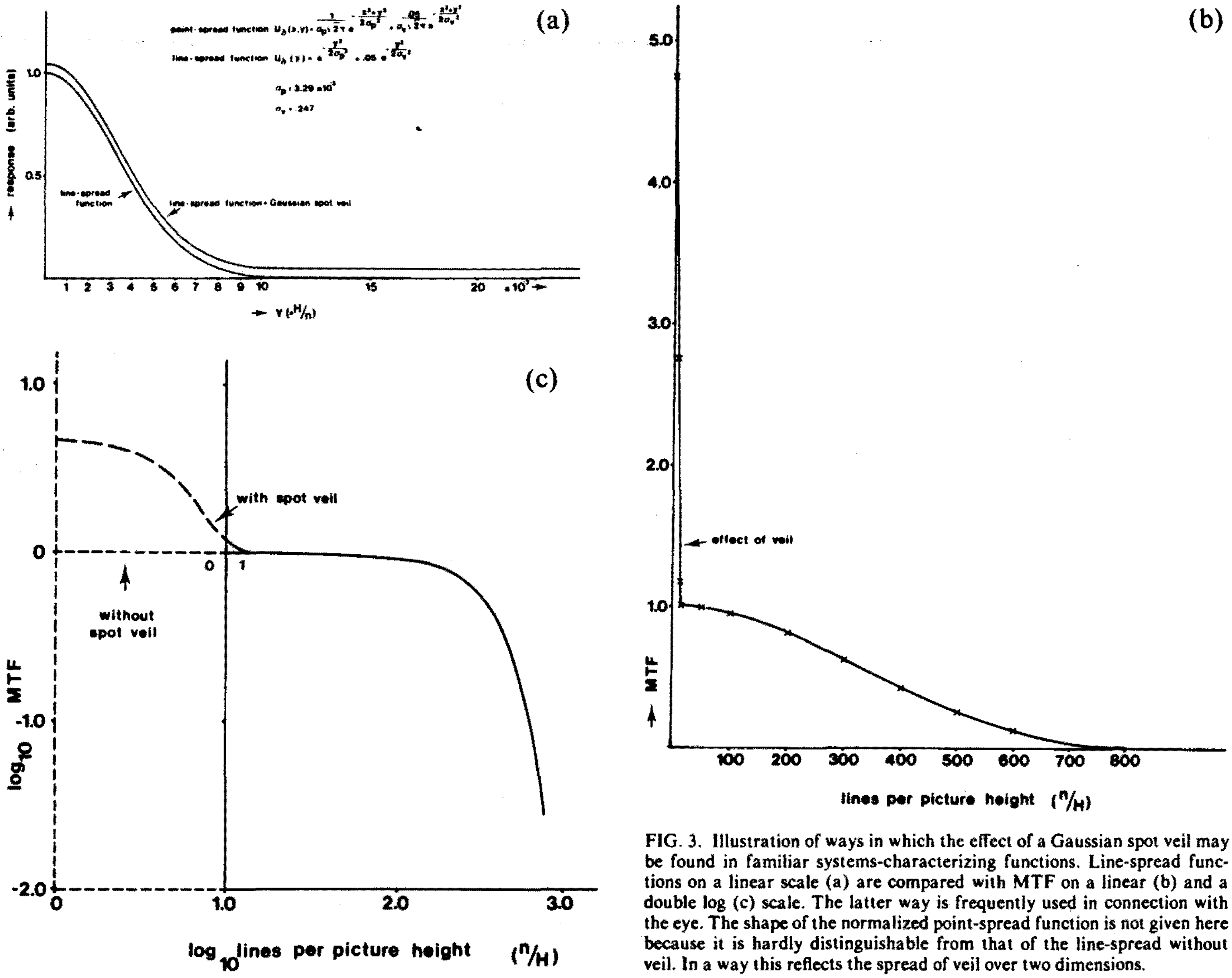

FIG. 3. Illustration of ways in which the effect of a Gaussian spot veil may be found in familiar systems-characterizing functions. Line-spread functions on a linear scale (a) are compared with MTF on a linear (b) and a double log (c) scale. The latter way is frequently used in connection with the eye. The shape of the normalized point-spread function is not given here because it is hardly distinguishable from that of the line-spread without veil. In a way this reflects the spread of veil over two dimensions.

became apparent that this interpretation is too simple. The notion that information is processed in frequency-selective parallel bandpass channels,[43–46] which do not operate independently,[47] is one example of the complications involved. Another is that parameters such as the height of the grating and the number of periods affect the data considerably.[48–50] Since the sensitivity is distributed inhomogeneously (see, e.g., Fig. 2) and since the threshold is influenced by the number of bars, as a result of the stochastic nature of the system, this should be expected. Also, SMTF does not properly reflect the perceptual effect of some peculiarities of the system. For instance, a few percent of veil may be easily overlooked at the log scale of an MTF curve, although it is perceptually a rather annoying phenomenon. On the linear scale of a line-spread function it does not escape attention that easily (Fig. 3).

In conclusion, although we gained much insight with it, SMTF does not seem to be as appropriate a characteristic function as was expected initially. Other possibilities have to be investigated. Point-spread and line-spread functions are gradually receiving more attention from investigators. In order to derive them from thresholds, some system properties also have to be postulated, which implies ample test procedures to justify these.

E. Point-Spread and Line Spread Functions: On Trial

The advantage of working with a point-spread function is its restricted area of action. This makes it easier to cope with the inhomogeneity of the retina, to apply linear theory, and to avoid stochastic complications encountered with extended stimuli. An example of an experimentally determined unit point-spread function $U_\delta(r)/D$ at a background level of 1200 td* is shown in Fig. 4. It is expressed in terms of the internal critical amplitude D, required for detection. It has been derived by Blommaert[51] at thresholds from a combination of a point source (∅ 0.08′) and a thin annulus (width, 0.17′; radius, variable) by a perturbation technique based on local space invariant linearity, homogeneity, radial symmetry, and peak detection. The detection model is illustrated in Fig.

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*The troland (td) is a unit of retinal illumination found by multiplying the luminance of the fixated object (cd m^{-2}) by the pupil area (mm^2).

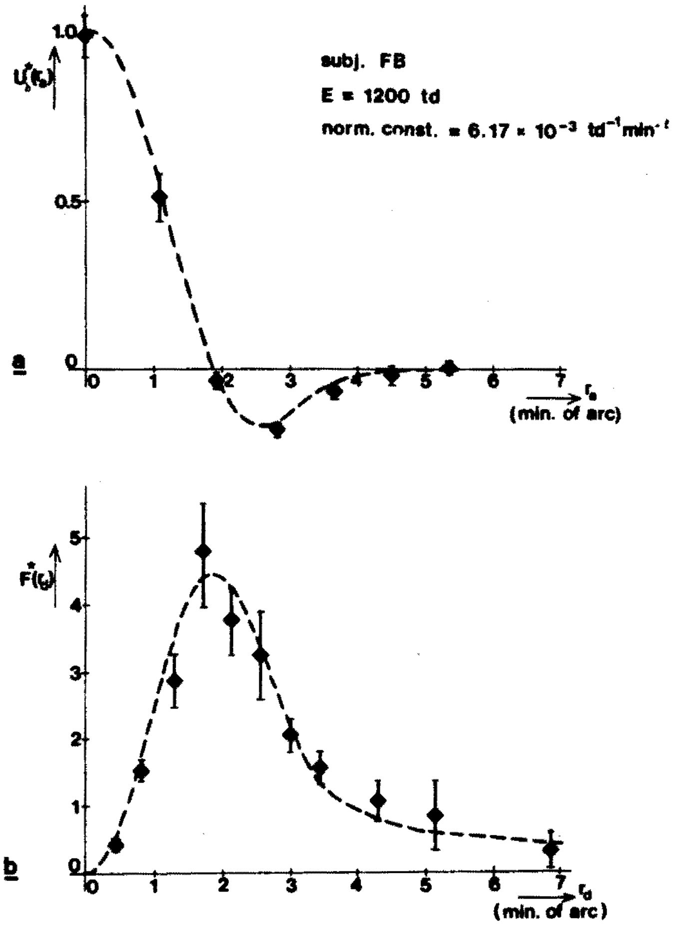

FIG. 4. Top: Experimentally determined foveal point-spread function at a 1200-td background level. The measurements are performed monocularly with an artificial pupil of 2.0 mm. Bottom: The effect of the spread of area elements of a subliminal disk on its center, as probed with a point source (see Appendix A). The dashed curves in the upper and lower figure are simultaneous computer fittings and related according to theory. (Blommaert, Ref. 51.)

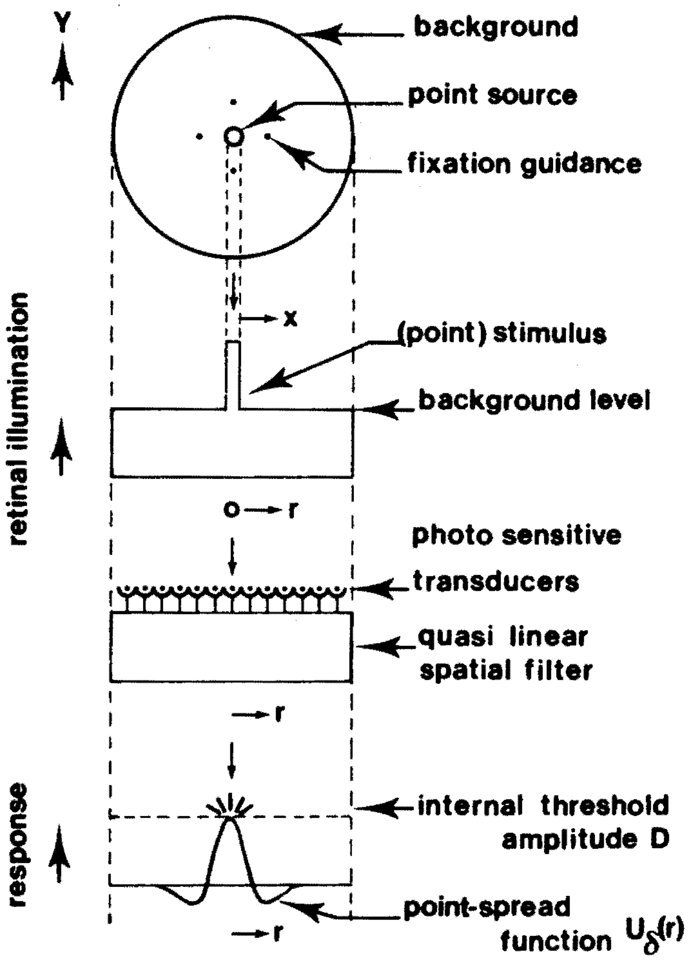

FIG. 5. Visualized detection model as used for the determination of the responses of Fig. 4.

5. Once $U_\delta(r)/D$ is known, the unit response of any stimulus shape can be calculated by convolution, and hence its threshold can be found. Possible size or frequency selective parallel processing have been ignored for these small stimuli. The essentials of the method are given in Appendix A.

Although the determination of the point-spread function by perturbation looks simple and straightforward, within the paradigm it has the disadvantage of being based on small effects; namely, threshold changes. As a consequence, special care has to be taken to prevent camouflaging these effects by sample spread and especially by nonstationary drift effects.[84] As a result, the amount of time to perform an experiment is significant. (This particular curve took about 9000 trials, measured in seven sessions).

The resulting point-spread function looks very much like what is found electrophysiologically in the cat's retina (Rodieck[52]) and can, in this case, also be described fairly well by two Gaussian functions. Furthermore, the shape is consistent with what should be expected in relation with perceptual phenomena like Mach Bands (Ratliff[53]). Nevertheless, its predictive power has still to be thoroughly proven.

Figure 4, lower half, shows the result of one test. A foveal point source is superimposed on a subliminal disk in its center. F* in the lower figure is a measure of the effect of all disk elements on its center and is explained in Appendix A. The points are experimentally determined values. The dashed curves are simultaneous fittings of the theoretical relation (Blommaert[51]). Although the agreement between prediction and experiment seems to validate the model, the next experiment demonstrates the hazards of such a conclusion, based as it is on a rather restricted subset of the parameter domain. Instead of looking at the effect of a subliminal disk on the threshold of a point source, the response of the disk itself can also be used to determine its threshold. Figure 6 gives an example of such a calculated response for a certain diameter. Calculated and measured thresholds of disks as a function of their diameter are shown in Fig. 7.

The discrepancy for diameters larger than about 3 min. of arc is obvious. Incorporation of the effect of inhomogeneity of the retina (see Fig. 2) with linear-space variant theory using circle symmetry[54] and the effect of probability summation does not close the gap. For predictions relating to disks that are larger than a few minutes of arc, the model apparently has to refined. (A possibility at hand is the

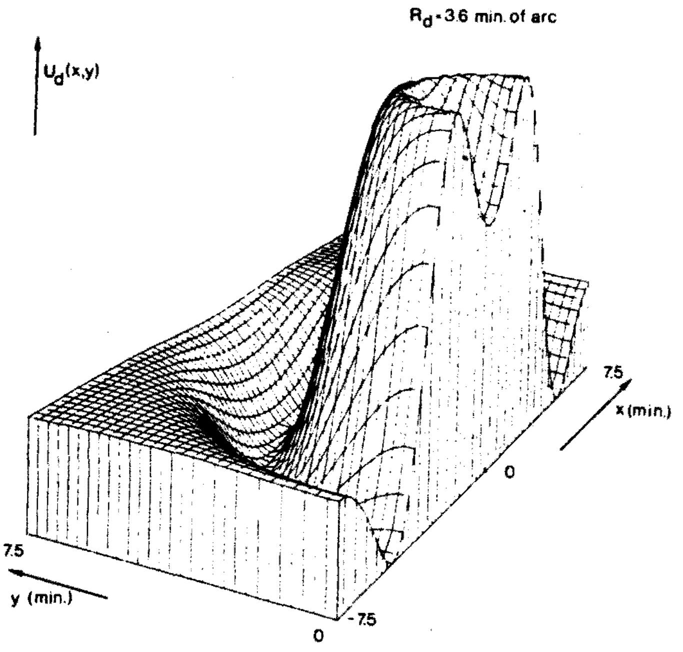

FIG. 6. Calculated visual response of an incremental foveal disk (radius 3.6 min. of arc) on a 1200-td background. (Blommaert personal communication.)

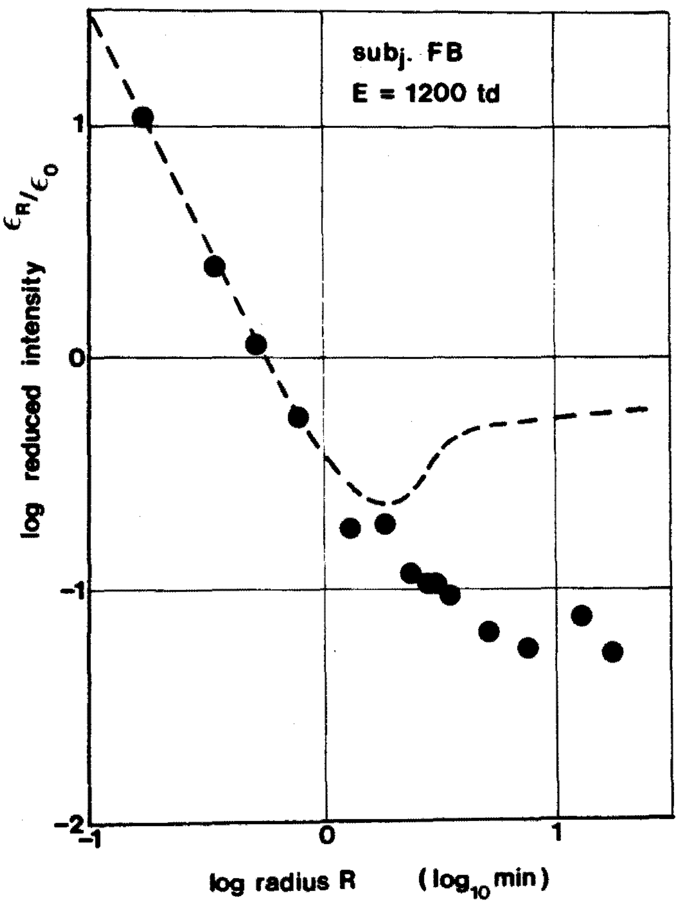

FIG. 7. 50% thresholds of an incremental foveal disk as a function of its radius. The dashed curve is theoretical, being based on convolution of the point spread function of Fig. 4, measured earlier at the same background level. (Courtesy Blommaert, personal communication.)

incorporation of size or frequency selective units, such as suggested by Bagrash *et al.*,[55] Fisher,[56] and Koenderink and Van Doorn.[57] (More time will be required to test this and other refinements quantitatively.) Nevertheless, the measured point-spread function is already of relevance in practical questions connected with electron-beam spot profiles (Biberman,[1] p. 16) and their relation with picture resolution,[36,58] since the half-amplitude-width of the spot usually covers 1–2 min. of arc, which is within the validity range mentioned above. Without going into detail here it might be stated as a sort of general requirement that in any case the spot luminance profile need not be narrower than convolution with the point-spread function of the eye would betray (except for an amplitude scaling factor).

Line-spread functions have been determined from thresholds in analogous ways. In the case of a space-invariant linear system, point-spread, line-spread, and modulation transfer functions are closely related. As regards to the eye, however, local linear space invariancy is only a crude approximation. Therefore, in view of practical TV problems it does make sense to determine line-spread functions, necessarily averaged over the inhomogeneous retina. This has the advantage of not introducing the specific dimension problems of gratings mentioned in Sec. II D. Moreover, the spread of the effect of a TV line in the eye can be measured relatively easily in situ. Figure 8 shows an example, measured in our laboratory with perturbation and using a black-and-white monitor with an average luminance of 200 cd-m^{-2}. Line- and edge-spread functions determined in various laboratories[59-65] have sufficient in common to generate confidence in the techniques, although there are intriguing differences that are partly due to different conditions. The quality of predictions of patterns changing in one dimension is comparable with that of the point-spread function. As Limb and Rubinstein[65] and Wilson[60] have shown, the prediction of bar-type stimuli can be good for bars whose dimensions are not too far from the width of the line-spread function (up to about 6′). Refined models for line- and edge-spread functions are also being constructed in various laboratories.[64,65,67-70] In practice, the line-spread function provides suitable information for problems relating to frame lines. The edge-spread function, which in a space-invariant linear system would simply be the integrated line-spread function, is particularly related to sharpness of contours. It also determines the upper boundary of the frequency response of the circuitry.

The detection of edges is an important quality measure connected with contours in pictures.[66] In that respect it is not only detection as such that is important, but also the noticeability of improvement. Carlson and Cohen[66] found that in such complex perceptual tasks a quadratic detection model is better, which is in line with other findings relating to complex percepts.[108]

F. Temporal Response Functions for Characterization and Prediction

Developments analogous to those described for space have also taken place in the temporal domain—in fact, they

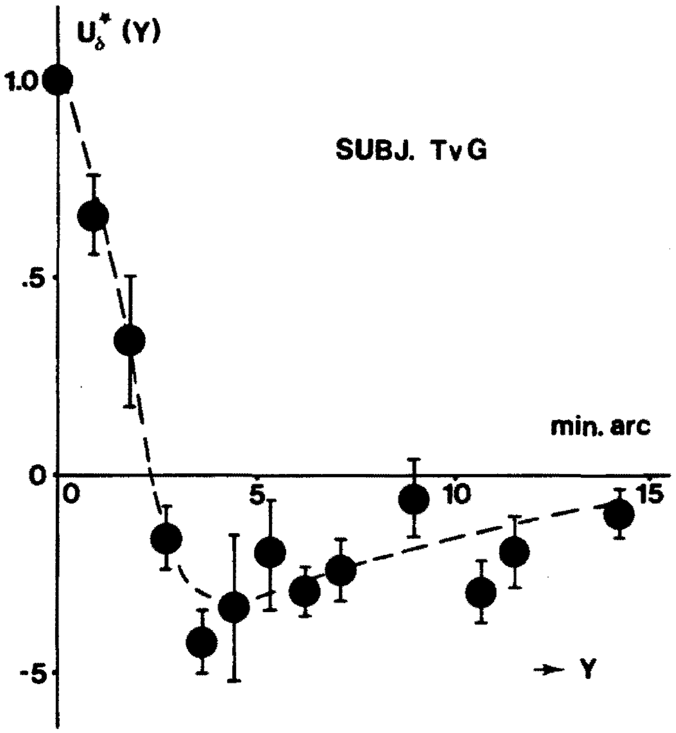

FIG. 8. A line-spread function of the visual system measured with a TV line in situ. The mean luminance level was 200 cd-m^{-2} with binocular viewing, natural pupil, and an average diameter of 4.5 mm. Demonstration of performance of a completely naïve subject. Standard deviations of means are indicated.

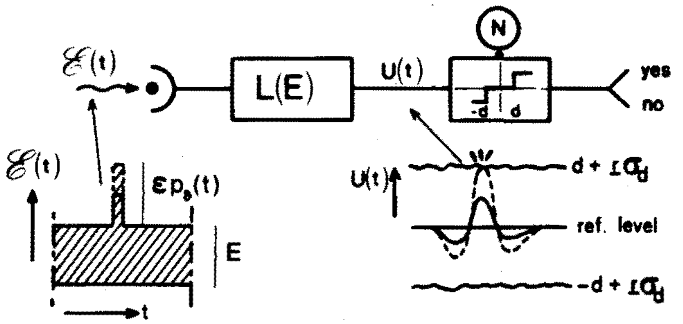

FIG. 9. Visualization of the detection model for temporal stimuli. The light is linearly transduced and the signal is processed in a quasi-linear filter. A temporal response is assumed to be detected if the peak amplitude is *d* (or −d). Photon noise is assumed to be weak compared to the internal noise.

preceded them. Technical inventions like movies, gas discharge lamps, TV, etc., stimulated research on temporal factors in vision. In connection with flicker phenomena alone, Landis[71] compiled a bibliography of about 1500 publications in 1953. De Lange gave the main impetus to a more general approach by using sinusoidally modulated light and keeping the mean background level at a constant value.* He showed that near flicker threshold the system behaves linearly and that the thresholds of arbitrary periodic functions can be predicted by means of Fourier analysis, provided their frequencies are not too low. Later, the link with thresholds of single functions was made by several authors.[73-81] As in space, there are indications that the substitution of one temporal filter for the system is too simple.[78,82,83] Probability summations affect the threshold of periodic stimuli considerably (up to about a factor of 3).[80] Although the effect can be calculated, it nevertheless complicates prediction. This may be one of the reasons for the growing interest in single temporal characteristic functions.

G. Pulse and Step Response: On Trial

a. Responses to Pixels

In the context of images the temporal behavior of a picture element is a natural starting point. Assuming a simple model as shown in Fig. 9, the response of arbitrary functions can be determined by means of perturbation. In Appendix B, this is demonstrated for a particular case; the unit pulse response. The detection process is illustrated in Fig. 10. As in the space domain, the response is expressed in the internal threshold magnitude, in this case "*a*" = *d* or −*d*.

Figure 11 shows an example of an experimental unit pulse response obtained in the way described above with a foveal source $\emptyset$ 0.8′ in diameter and at a 1200-td background.[84] If the assumption of quasilinearity is correct, then the pulse-response is the time derivative of the step response:

$$U_\delta(t) = \frac{\mathrm{d}}{\mathrm{d}t} U_s(t). \tag{1}$$

The result obtained with a step as the perturbation function is shown in the lower half of Fig. 11. The dashed curves are simultaneous fittings, the upper one being the exact derivative of the lower. Figure 12 shows another test, performed by comparing the thresholds of rectangular flashes as a function of duration,. For durations larger than a critical value, the predicted values of the dashed curve have to be corrected by a few tenths of a log unit for "probability summation". The constant value of the dashed curve beyond a certain duration reflects the fact that the peak value of the response to a flash with constant intensity no longer increases with duration. It is only the flat crest of the response that becomes longer when the duration of the test flash increases and, in that way, increases the detection chance of the flash since "*d*" is a stochastic variable. The stars present such a correction. It is based on noise data obtained from the slope of psychometric functions of short flashes[80] and the assumption that the autocorrelation function of the noise is narrow compared to the Shannon time sample of the signal. The intersection point of the asymptotes in Fig. 12 indicates one of the definitions of critical duration, a kind of integration time for the eye, which is a non-ideal integrator. The slope of −1 of the left asymptote demonstrates Bloch's law: intensity times duration determines the threshold. This is a mere reflection of the width of the pulse response (if a short flash is immediately followed by an identical one, amplitudes are

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**A reference list of De Lange's work can be found in Ref. 72.

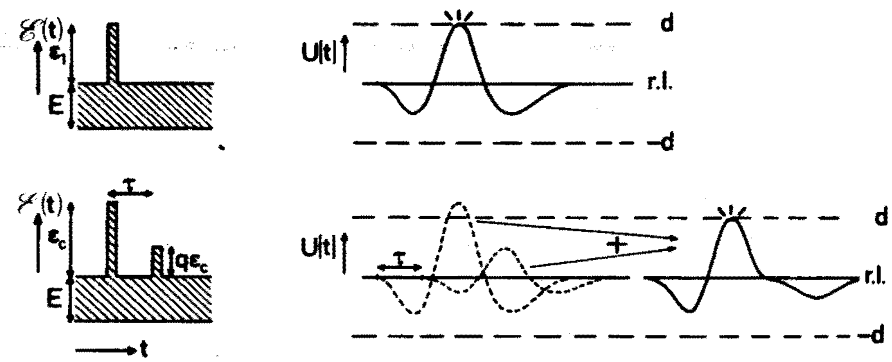

FIG. 10. Demonstration of the essentials of the use of a probe flash, scanning the response of a weak (perturbating) test flash.

scaled up by a factor of 2 and the shape does not change noticeably).

It does not make sense to use phosphors that are faster than the pixel pulse response in order to improve temporal acuity. On the contrary, this is inefficient in view of Bloch's law and it promotes unwanted flicker of larger areas as we shall see below.

b. Visual responses to larger areas

Going from pictures to larger areas, the visual system demonstrates its complex nature. The elements of the extended retinal area that is stimulated interact in a complex way. Near threshold, perceptual attributes change considerably, especially for fast changing stimuli. Incremental flashes are no longer seen as brightness increments but as changes in the visual field that are hard to describe, though they strongly resemble the "agitation" seen with high frequency flicker. It is virtually impossible to distinguish incremental from decremental flashes at 50% threshold level. The pulse and step responses, obtained by the same technique as described above, change drastically in shape as demonstrated in Fig. 13.[85] The responses show more oscillatory behavior: several phases of opposite sign become manifest. In fact, the system acts as a bandpass filter. However, these changes do not invalidate the essential properties we have postulated. The dashed curves are simultaneous computer fittings, the pulse response being the exact derivative of the step response. The prediction of thresholds of arbitrary (not too slowly varying) stimuli is fairly good. Figure 14 illustrates this for rectangular incremental flashes as a function of their duration. The correction for "probability summation" at long durations is small in this case because there is only a significant response at switch-on or switch-off of the stimulus, as a result from the bandpass filtering.

In view of the above-mentioned problems with extended stimuli, the pulse response does not seem a bad candidate for characterizing the system and predicting thresholds in the time domain. Its consequences for other stimulus functions and for the influence of parameters such as the background level on the performance of the system are easily visualized. Nevertheless, a predictor operating simultaneously in the time and space domain will be of considerably more impor-

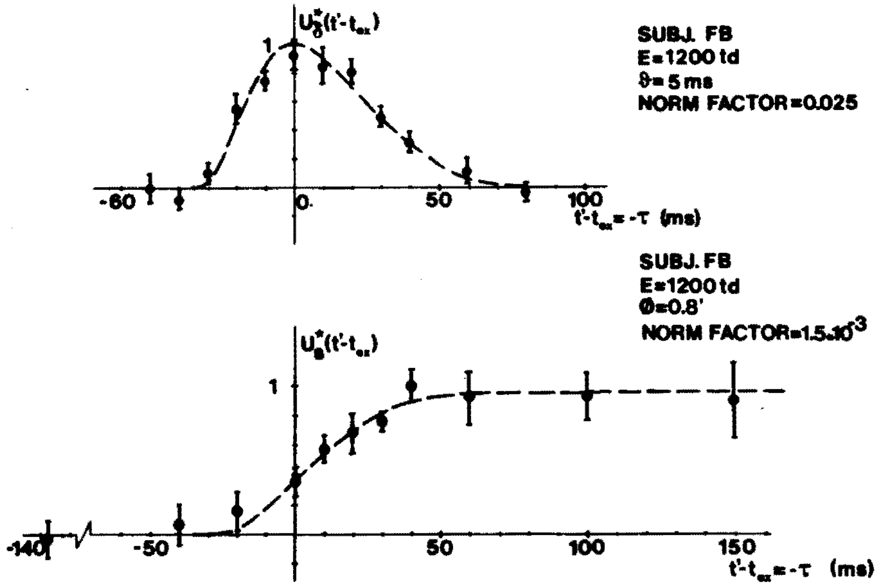

FIG. 11. Upper figure: pulse response of the visual system stimulated by a foveal point source at a level of 1200 td. Lower figure: step response as a result from the same point source. The dashed curves are simultaneous computer fittings, the upper one being the exact derivative of the lower.

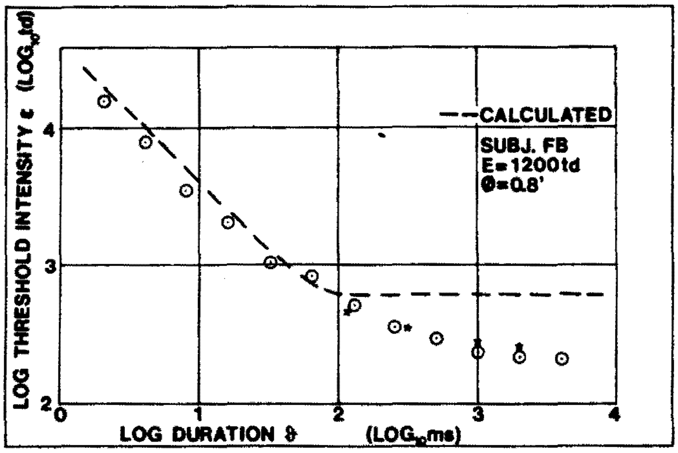

FIG. 12. Open circles: Measured 50% threshold of rectangular flashes of a point source at a level of 1200 td as a function of flash duration. The dashed curve is the predicted value calculated by convolution of the measured pulse response (see Appendix B). For long duration this has to be corrected for "probability summation" (stars).

tance for practical problems. This is especially so in view of the surprisingly large distances over which the fast dynamic interaction of retinal elements carries, compared with the static interaction. In Fig. 15 this is demonstrated for circular centrally fixated stimuli, having a Talbot level*** of 60 td and a dark surround.[86] In plotting thresholds of rectangular increments as a function of duration, or thresholds of sinusoids as a function of frequency for various diameters, it becomes apparent that both sensitivity and time constants change. The sensitivity measures, defined as reciprocals of thresholds for long duration, $F = 1/\epsilon$, or the closely related crests, S, of the De Lange curves,[72,76,86] are shown as a function of stimulus diameter. The diameter at which cooperation between retinal elements ceases to affect sensitivity is much larger, as has been demonstrated for static disks in Fig. 7. This interaction is more complex than a simple addition of signals because the critical duration and the cutoff frequency (the frequency at which aplitude sensitivity has dropped to $S/2$) also change, as shown in Fig. 16.

In practice, frame flicker is a somewhat more-complicated phenomenon as a result of the interlacing of lines. Nevertheless, the large area of summation with respect to flicker and (impairing) transients is an inconvenient factor in relation with image quality. The visibility of one-shot disturbances, in particular, is most adequately predicted on the basis of pulse responses obtained for the same retinal area involved. Thus, complications that occur when flicker sensitivity curves of sinusoidal modulation are used (phase behavior and stochastic aspect of the visual system) are avoided.

III. SCALING METHODS AND IMAGE QUALITY

Thresholds of perceptual attributes are relevant in many problems concerning image quality. However, the strengths of attributes in relation to physical intensities are more directly related to the qualitative experience of subjects.[20-23]

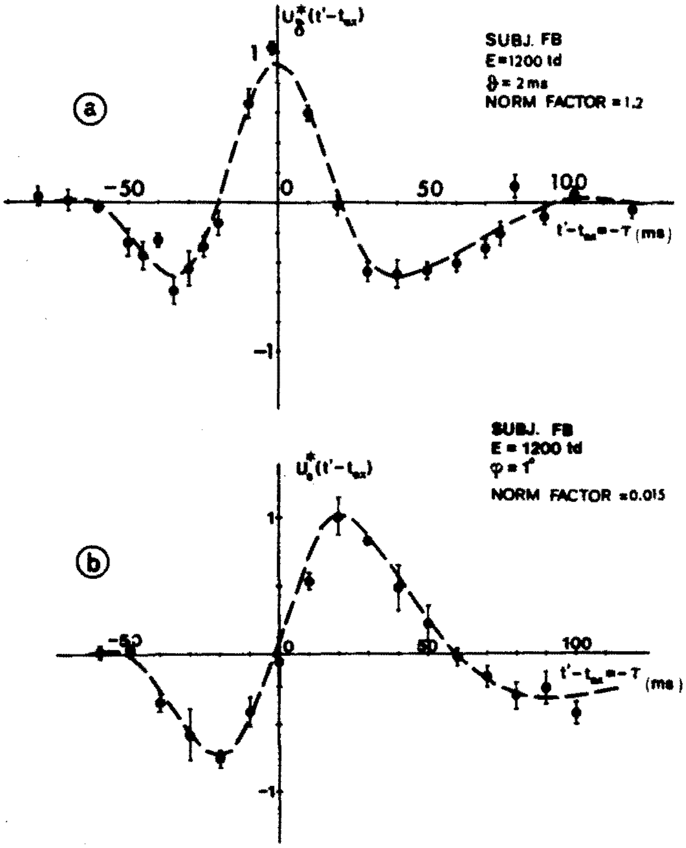

FIG. 13. Upper figure: Pulse response of the visual system, stimulated with a 1° field, having a Talbot luminance of 1200 td and a dark surround. Lower figure: Step response with the same stimulus. The dashed curves are simultaneous computer fittings, the upper one being the exact derivative of the lower.

Consequently, scaling of sensory intensity and of subjective quality is important. Unfortunately, the validity of current scaling methods is somewhat controversial.[87]

With respect to scaling of sensory intensity, magnitude estimation[7-10,88] is frequently used. One of its advantages is

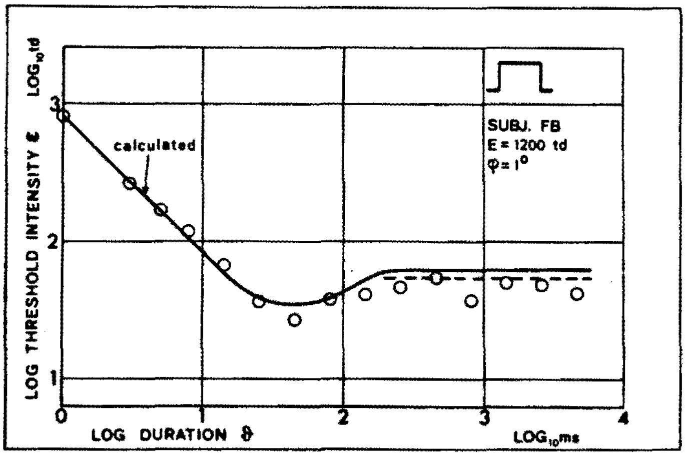

FIG. 14. Open circles: Measured 50% increment thresholds of retinal illumination for a 1° stimulus, having a dark surround and varying rectangularly in time. The solid line shows the predicted threshold. For long durations a small correction for "probability summation" has to be made. The dashed curves show the corrected predicted values. The Talbot level is 1200 td.

***This is the static level equivalent to the local adaptive state.

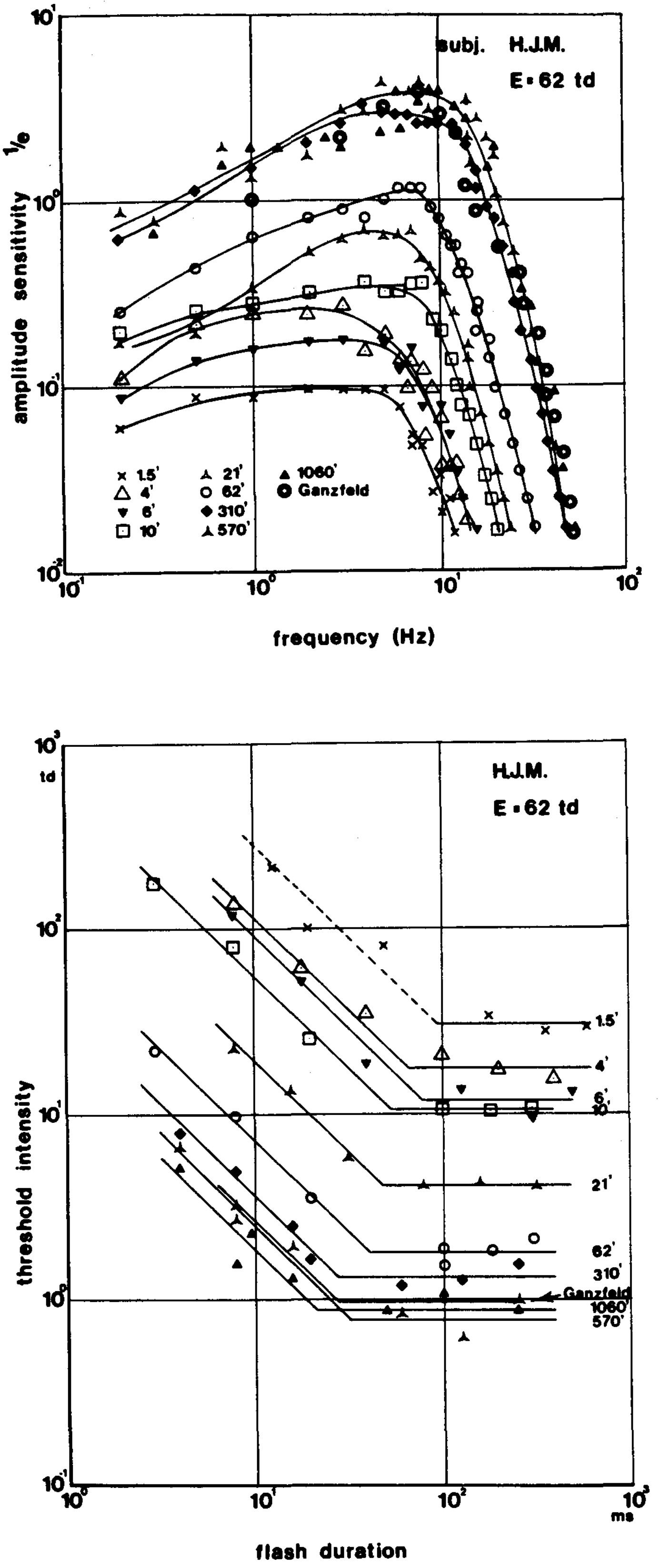

FIG. 15. Upper figure: Temporal modulation transfer as measured by 50% threshold amplitudes "e" of a sinusoidal modulation as a function of frequency. The parameter is the diameter of the foveal circular stimulus (Talbot level, 60 td; dark surround). Lower figure: 50% thresholds ϵ of a rectangular temporal variation, as a function of duration for the same configurations.

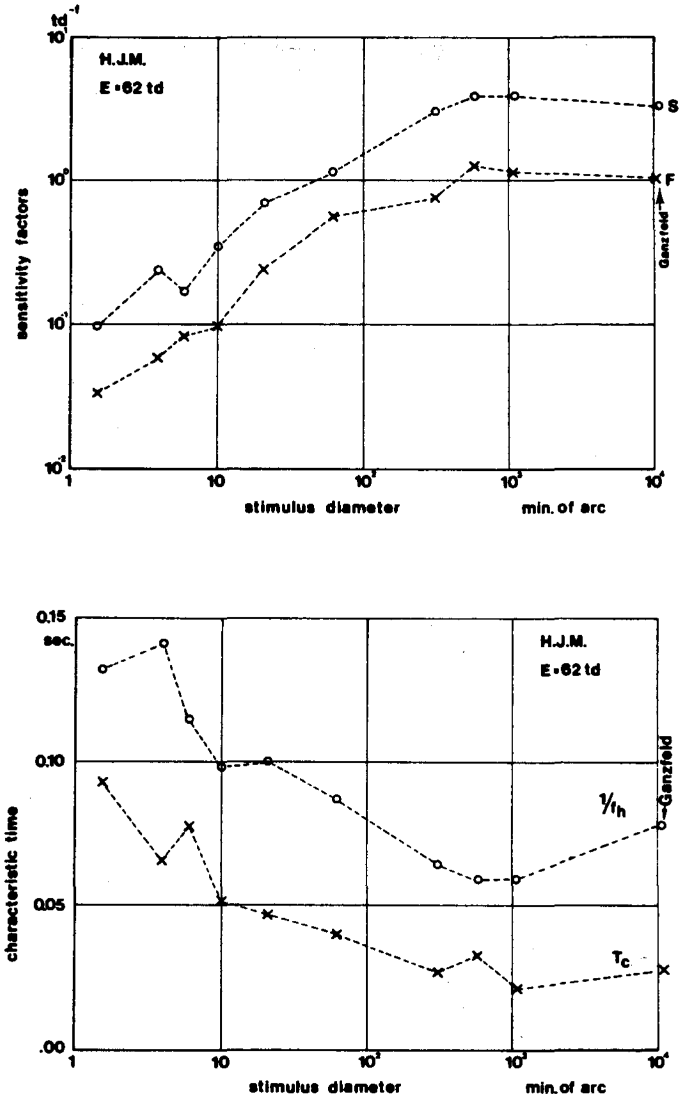

FIG. 16. Upper figure: Sensitivities characterized by the tops, S, of the curves of Fig. 15 (upper half) or by F, the reciprocal of the threshold ϵ of long duration flashes of Fig. 15 (lower half) as a function of stimulus diameter. Sensitivity increases up to diameters of about 5°. Lower figure: The time constants of the visual system characterized by either the reciprocal of the cutoff frequency f_h of the upper curves or the critical duration T_c of the lower curves of Fig. 15.

its relative efficiency. Subjects are supposed to be able to estimate the strength of sensations relative to some standard by assigning corresponding numbers appropriately. On this basis, Stevens et al. found the well-known exponential relation between the magnitude of sensation and the physical parameters. The exponent is believed to be characteristic of the growth of sensation in the mode involved.† The method was given a theoretical foundation by the work of Krantz[91]—still assuming correct handling of numbers by subjects—which in turn is based on length perception. However, there have been several studies revealing difficulties in the interpretation of the results. For instance, the exponent appears to be influenced by the stimulus range used by the experimenter[92]; it may be determined over the range between just perceivable and the maximal applicable

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†Overviews can be found in Marks[89] and Stevens.[90]

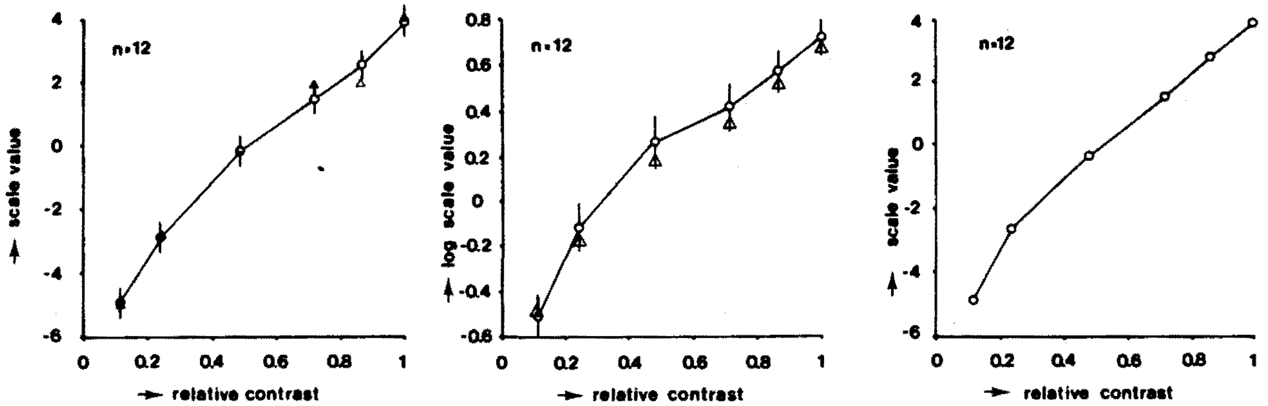

FIG. 17. Comparison of three scales of quality judgement, obtained by three different methods as a function of relative objective contrast of photographic pictures. If objective contrast is defined by $\Delta L/\bar{L}$, where ΔL is some effective measure of deviation from the mean luminance $\bar{L}$, it may be varied by adding L_a according to $\Delta L/\bar{L} \times \bar{L}/(\bar{L} + L_a)$. The decrease in objective contrast is determined by the second factor, which is called "relative contrast" here. In fact, in the actual experiment it is achieved by the photographic copying process. In the left-hand figure, quality is rated on a 10-point scale. Each circle represents the average of 12 subjects. The triangles are the values after a monotonic transform of the judgement in order to obtain optimal fit with respect to differences in quality perception. The middle figure shows the scales obtained from the estimated ratios in image quality between two pictures using all pairs. If the scale values are logarithmized the shape becomes about the same as that of the category of the left figure. This indicates that subjects may obtain ratios by exponentiating differences (circles). The triangles are the values that result after making a monotonic transformation in order to obtain optimal fit with respect to the ratio model. The nearness of circles and triangles indicates that subjects handle ratios quite well. The right-hand figure shows averaged scale values from the same 12 subjects obtained by rank ordering of picture pairs. (Breimer, 1979.)

intensity.[93] These experiments lead to different exponents[89,90] and even to other functional relations.[94] Nevertheless, there is some evidence that subjects who handle numbers quite differently do perceive the same sensations.[95]

Another difficulty is that different scaling methods lead to different results. Scales based on estimated differences in sensations mapped on the sensorial continua, category scaling, appear to deviate from those based on estimated ratios.[90] Stevens, among others, considered the latter to be valid.

Rather than go into the detailed arguments, we prefer to pay some attention to investigations concerning the handling of instructions and numbers by subjects. To this end, Anderson[96-97,105] has suggested a factorial design of the experiments. The sensations evoked by a stimulus are not only compared with those of one standard but essentially with those of every other stimulus involved. This makes it possible to verify the consistency of the numerical judgement of the subjects. (Some essentials of the method will be given below.) This provided information about both the origin of the scaling and its consistency. Birnbaum and others,[98-100] using Anderson's suggestions as a starting point, found in loudness experiments that, at first, subjects use differences in sensations in making their judgements. They claim that if subjects are instructed to estimate ratio's, the results are exponential transforms of subjective differences. This would fit in with Torgerson's[101] earlier observation that a category scale of differences is usually linearly related to the logarithm of the ratio scale, suggesting that "the subject perceives or appreciated but a single quantitative relation between a pair of stimuli." Although these views are not generally accepted,[102] it is clear that the problem is highly relevant for scaling in the field of image quality.

Bremier†† used the Anderson-Birnbaum approach for the rating of subjective quality as a function of objective contrast. Pairs of black-white pictures, having different contrast but the same figural content, were exposed to a group of subjects. Three types of experiments were performed. In the first one, subjects were asked to estimate the difference in the quality of every pair of pictures on a 0-10 points scale. The category ends were labelled as follows: 0 represents no difference and 10 represents a very large difference. In the second experiment the same group of subjects were asked to estimate the ratio of quality of the best of each of two pictures inspected in relation to the worst. In the third experiment the subjects were exposed to two picture pairs and instructed to choose the pair with the greatest quality difference. In the last case a scale was constructed according to the principles of non-metric scaling developed by Shepard.[103]

Since no details can be given here we shall confine ourselves to the remark that the matrices of estimates were consistent with Birnbaum's findings, which means that no matter what instruction is given the estimates are ultimately based on distances in the perceptual continuum. The results of the three methods are compared in Fig. 17. If the scale values of the ratio scale are logarithmized, the same shape is obtained as the one based on differences. Moreover the shape of both curves is very similar to the nonmetric scale based on the rank ordering of pairs. The results show that three different instructions *can* lead to the same scale. Although no firm conclusion can be drawn on the basis of one experiment such as this, the results seem to favor scaling based on differences.

In our opinion, these matters deserve more attention. Moveover, it shows that experiments performed according to Anderson's factorial design do present possibilities for checking subjects behavior and testing the validity of scales even in the case of a rather vague and subjective dimension such as quality.

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††A full account of these experiments is in preparation.

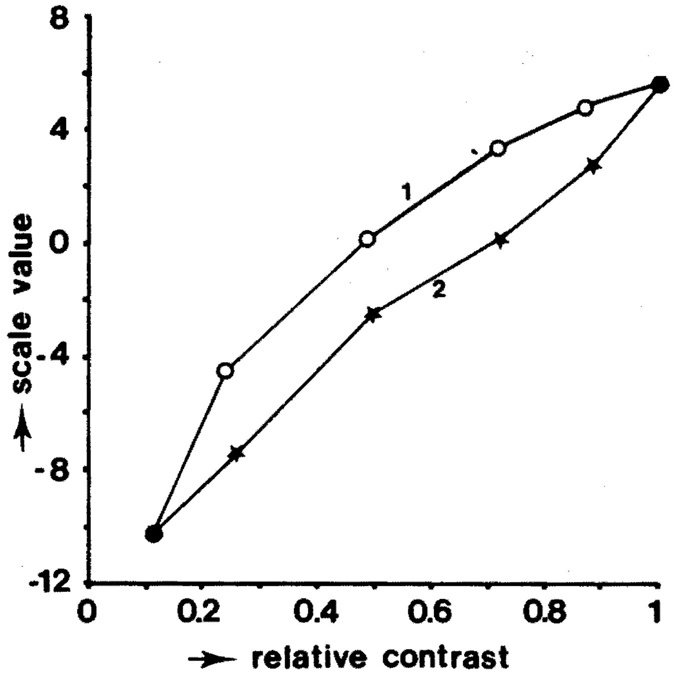


FIG. 18. Two individuals selected from the group who did the rank-order experiments of Fig. 17. Subject 1 displays almost a log scale, whereas subject 2 appears to be quite linear. (Breimer, 1979.)

With respect to image quality application, Breimer also showed how different subjects may interpret such an instruction. In Fig. 18, two subjects are isolated from the group. Subject 1 shows a logarithmic type of scale and in the interview at the end of the experiment he reported that in judging quality he especially looked at the blackness of the dark parts. Subject 2, who behaves linearly, reported that he looked for the visibility of details in connection with quality. People apparently judge quality in terms of different dimensions.

IV. CONSPICUITY AND VISUAL SEARCH

Certain visual objects are more conspicuous than others. Conspicuous objects will be more easily noticed than other objects. A high conspicuity may be of help for vision if the viewer wants or needs to see them. However, a high conspicuity may hamper vision if it distracts the view from more important objects. Also, if unwanted effects in images cannot be made invisible, one should at least wish them to be inconspicuous.

This leads to a search for ways of making the notion "visual conspicuity" amenable, both experimentally and theoretically. In line with Engel,[109–111] we define visual conspicuity as the property of objects in their background, by which they attract visual attention and, consequently, are easily seen. Visual conspicuity should be distinguished from the directing of visual attention to certain objects or situations by internal drives.

If the viewer knows where to find an object, he can direct his eyes toward it and recognize it, inspect it, etc. A measure for the ease of recognition may be the visibility or recognizability of such an object, in terms of the correct score or latency in foveal vision. On the other hand, if a viewer does not know where an object is, he first has to find its position before he can direct his eyes toward it. Now, the fovea covers only a tiny solid angle-in fact about 3 sq. degrees out of the more than 10,000 sq. degrees of our visual space if head movements are left out of account. Thus, the ease of finding an object of unknown position relates to the ease of noticing it in eccentric vision, outside the fovea. Consequently, visual conspicuity may be measured as the correct score or latency in eccentric vision, or the duration of visual search. Thus, unwanted effects such as flicker or visual noise, should also be judged as to their detectability in eccentric vision.

As is generally known, eccentric vision is distinguished from foveal vision by lower visual acuity. In fact, at sufficient luminance the smallest detail of a standard object (Landolt annulus) against a homogeneous background that can be seen is about 1/70 of its eccentricity (both in units of visual angle). It is less generally known that there is a second important difference in that in a non-homogeneous background, adjacent objects interfere substantially with each other in eccentric vision, thus hampering each other's detection. Figure 19 gives an example of geometric objects in a background of lines, where eccentric detectability turns out to depend on differences between the object and background. Engel[112] has shown that a visual search procedure may be described as more or less random eye saccades until the object is sufficiently close to the point of fixation that it can be seen in eccentric vision. A single final eye saccade then brings it into foveal vision.

The question of how the eye is being attracted to wanted or unwanted visual objects can then be translated into the question of detectability in eccentric vision. The primary factor of interest seems to be the difference between the object and its background as to specific visual attributes such as movement, color, brightness, and form. For example, a moving object against a static background, or a red object against a black-and-white background, will easily be seen in eccentric vision, and correspondingly have a high conspicuity. Experiments on detection in eccentric vision might also be applied in image-quality problems. If interferences could be specified for real-world images, explicit form could perhaps be given to notions that experienced photographers and movie directors intuitively use. Displays should then be such that they can produce or reproduce such attributes properly.

Finally, one should be aware of possible unwanted effects of the area surrounding the displays. These should not be so conspicuous that the eyes are automatically drawn from the screen. In addition, if the surround is homogeneous, objects near the edges on the display will have a higher conspicuity because there is no interference from it. This may be compared to the frames of paintings and photographs. For a review, see Bouma.[11]

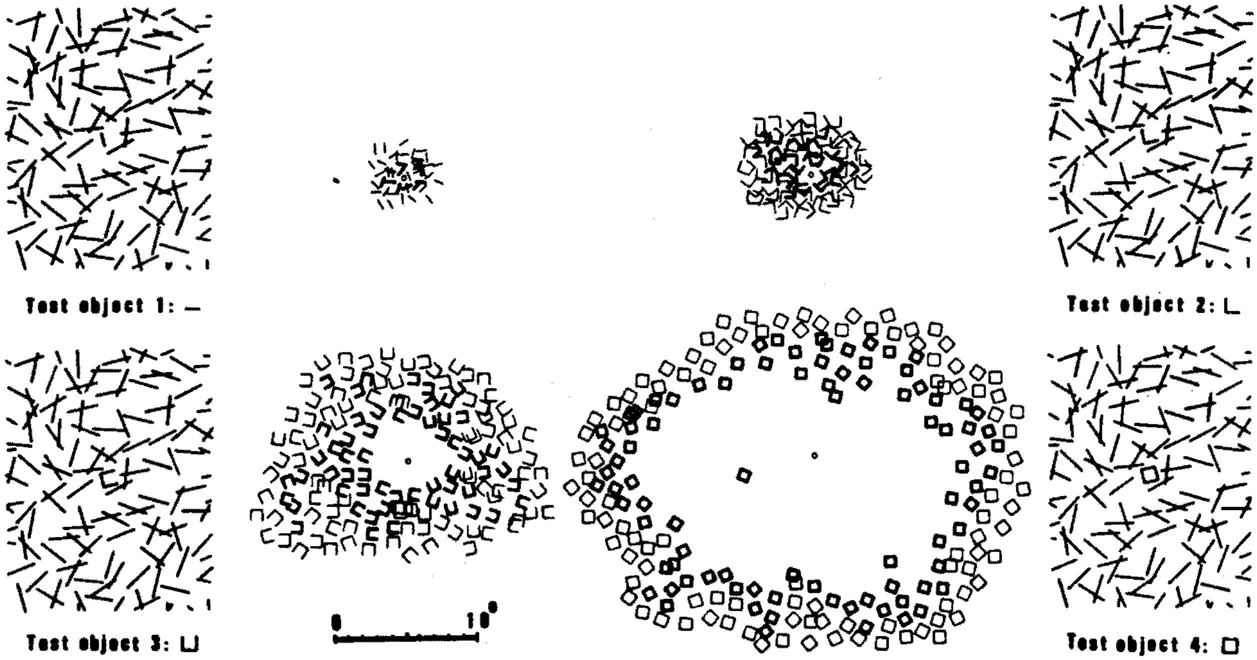


FIG. 19. When each of four different test objects was presented against the same background of straight lines (left picture, test objects in the centers), the functional visual field within which they could be found in a single presentation came out as indicated in the right-hand picture. Test objects drawn in bold lines were reported correctly in a single presentation, those in thin lines were not. Small central circle: fixation spot. (Engel, Ref. 109.)

V. THE QUALITY OF TEXT DISPLAYS

Since text displays are intended for reading, their essential quality is how well users can read text, codes, and numbers on the display. With present-day electronic displays, this is generally far from easy due to a great many factors, which relate to the display itself (size, sharpness, contrast, letter configurations), the formatting of the information (letter density, layout), the location of the display in its actual environment (specular reflections, luminance of the screen relative to the background), and also to ergonomic factors of a non-visual nature. There are many complaints that the prolonged use of many current text displays is very fatiguing and that headaches are common. In a few countries there have already been efforts to restrict by law the periods of time for which subjects are allowed to work with such displays. It seems likely that the complaints find their origin in a non-optimum choice of the above factors.

The term "quality" will be used here to express the degree to which physical factors of the displayed text and its surrounding satisfy the reader. Leaving syntactic and semantic factors out of account, we shall concentrate on the visual quality of the text. Unfortunately, part of what will be proposed here has to be speculative, because we could not find the relevant experiments in the literature. For general surveys of a somewhat more positive tone, the reader might wish to consult Grover[113] and Kraiss.[114] Following the general approach advocated here, we first deal with what is known from visual reading processes in general and then apply it to text displays.

A. Reading Processes

Since reading is a complex task that involves both perceptual and cognitive factors, there are many ways to subdivide the processes involved. The present subdivision is made for research purposes and permits the separate study of the various processes and their mutual relations. Thus, the main purpose is to provide a tool for thinking, experimenting, and modelling visual reading processes. The subdivision is rooted in the observation that in reading normal print the eyes of a reader move in jumps rather than smoothly. Between two jumps or eye saccades, the eyes are at rest during a quarter second or so. During the jumps, the retinal image moves very quickly and no useful information can be picked up. Consequently, the recognition proper has to start from the semistatic images during the eye fixations. Only within the central fovea and at short distances from it, is detail vision sufficient to recognize the information.

We define the visual reading field as the area within which it is possible to recognize useful information during reading. The normal visual reading field is of the order of a few words only. Therefore, many subsequent fixations are necessary before the information contained in units of meaning, such as sentences or parts of sentences can be picked up.

B. Eye Saccades, Eye Fixations, and Their Control

During the reading of connected text, three different types of eye saccade occur (Fig. 20). The most frequent type is forward saccades of 8 ± 4 letter positions. Since forward

FIG. 20. Eye fixations in the silent reading of a paragraph of Dutch text. Three different types of eye saccades are indicated; ●, normal forward jumps; ▲, small backward jumps (regressions); ■, line jumps towards the next lower line. The numbers indicate the order of fixations within each line of print. (Bouma, Ref. 135.)

saccades increase almost proportionally with letter size, it is useful to express them in letter units. For normal print at normal reading distances, there are about five letters in one degree of visual angle. The second type is the large eye saccade from the end of a line of print towards the beginning of the next one. These saccades are leftward directed and also have a small but critical vertical component. They start several letter positions before the end of the line of print and stop a few letter positions within the next line. Consequently, their size is somewhat less than the line length. The third type is a relatively small jump leftward. These jumps occur regularly directly after the large jump towards the next line of print and may also occur at several positions within the line of print. Their usual sizes are about four to six letter positions but occasionally they may be much larger. It is generally held that the frequency of occurrence of these regressive saccades increases with decreasing text quality and with increasing difficulty of the text relative to the reading skill. Thus, one may expect many regressive saccades when poor readers try to read a difficult text.

The duration of fixational pauses is between 150 and 500 ms, a normal average being 200 to 250 ms. These durations are not very dependent on the type of saccade leading to the fixation. In particular, there is little correlation between the size of a certain eye saccade and the duration of the preceding or following eye fixation. The evidence generally indicates that the duration of a certain fixation and the size of a saccade are independently controlled. It is presently a matter of debate as to how individual eye fixations are controlled, both in timing and in extent.[11,115-117] Of course, there may be many different eye-control repertoires, and eye movements will generally follow cognitive processing within memory limits. Both eccentric visual and cognitive processing of text may therefore be reflected in eye movements.

Consequences For Text Quality

Normal forward eye saccades follow the cognitive needs of the reader fairly automatically. Their sizes are derived more or less directly from the effective size of the visual reading field. The same holds for the small regressive movements. However, the large leftward jumps towards the beginning of the next line depend on certain layout factors.

a. Margins

For a proper control of the large leftward jump towards the next line, the left margin of a new line must be visible when the point of fixation is near the right-hand margin of the text. This is therefore a matter of eccentric vision. A suitable way to achieve this is to have a sufficiently wide homogeneous left margin. Also, the beginning of text lines should stand out clearly and must therefore be in a straight line. This enables eccentric vision to plan the size of the leftward jump reasonably accurately. The right-hand end also needs some margin, such that the control mechanism can know in advance where it should stop its normal forward jumps. Requirements for the right-hand margin are not as severe as for the leftward side, because the point of fixation is so much closer to the right-hand margin at the moment where the proper decisions have to be made. It is therefore unnecessary or even disadvantageous in the case of short lines to justify the right-hand margin.[118]

b. Line Distance and Line Length

The line jumps of the eye also need control in a vertical direction such that the eye lands properly on the next lower line. If the vertical component of the eye jump is inaccurate, the eye may mistakenly jump over two or perhaps even three lines. This is clearly inefficient, and in the case of unconnected information, such as code numbers, the reader may not even notice that he has missed one or two lines. The print factor relevant for the proper control of line saccades is line distance over line length. A rough estimate of the minimum admissible value seems to be about 1/40, corresponding to an angle of about 1.5 degrees with line direction. As a consequence, line distance should increase with line length. It follows that for large line lengths, line distance should be large and print density (number of letters per unit area) should be low. Therefore, if a high density is required, line length should be restricted. An example can be found in newspapers, where a high print density is reached by using relatively narrow columns. If only a single column of text is used, it is of advantage to have the page vertically oriented. Most electronic text display units are horizontally oriented (aspect ratio 3:4), probably because they are directly derived from normal television screens. It seems advantageous to use screens vertically oriented (aspect ratio 4:3), thus resembling the standard format of A4 sheets ($\sqrt{2}$:1) or, if oriented horizontally, in a two-column mode, particularly if a high density of letters is required.

C. The Visual Reading Field and Word Recognition

At the point of fixation, i.e., at the center of the retinal fovea, visual acuity is at its maximum. Visual acuity is defined as the reciprocal of the smallest visible detail D of a standard object against a homogeneous background and is measured in units of reciprocal minutes of arc visual angle. At sufficient illumination, normal foveal visual acuity is about 1.0 min. When moving away from the fovea, the smallest visible detail D increases almost proportionally with eccentricity, φ, viz.,

$$D \approx (1/70)\varphi. \qquad (2)$$

In many daily life situations, including reading, the background is not homogeneous. Only recently it has been realized that the concept of visual acuity is not applicable then. Detail vision then turns out to be limited by adverse interactions between adjacent configurations (Fig. 21). The interference has properties quite unlike visual acuity, such as a large working range and an anisotropy since it is stronger towards the fovea than away from it (Fig. 22).

The limits of the momentary visual reading field are determined by eccentric vision. They can be measured by having subjects recognize words, displayed at various distances from the point of fixation for about 100 ms, which is too brief for eliciting an eye saccade toward the stimulus.

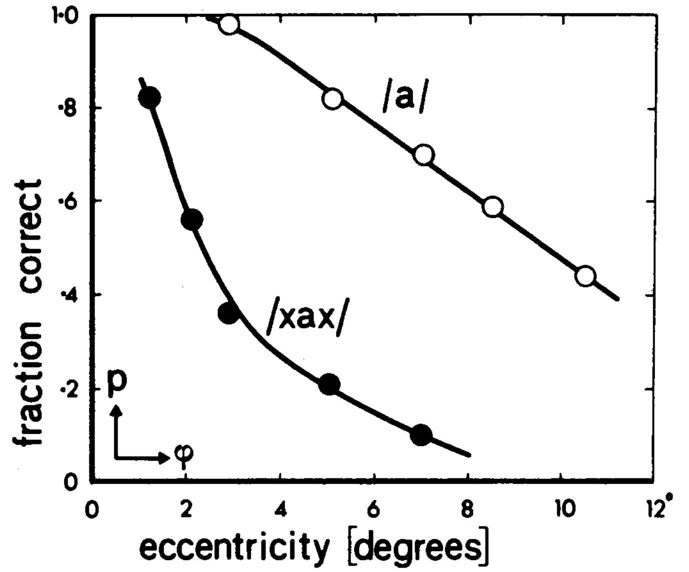
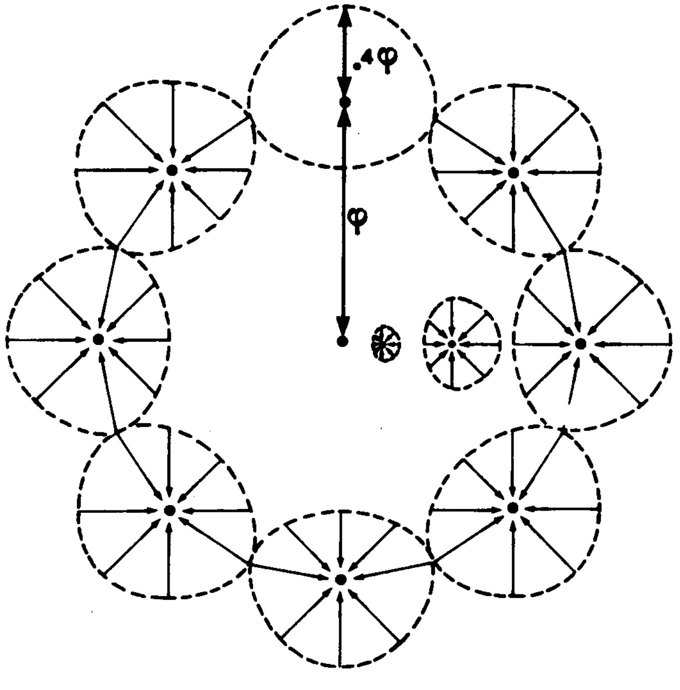


FIG. 21. Embedding randomly chosen target letters between two letters (indicated as /xax/) makes recognition scores in eccentric vision drop sharply as compared with the non-embedded situation (indicated as /a/). The diameter of the corresponding useful visual field shrinks to about 30% of its non-embedded value. One degree of visual angle corresponds to four letter positions. (Bouma, Ref. 132.)

Thus, the visual reading field for words is found to be about 20 letter positions wide, stretching farther to the right of fixation than to the left.[119-120] This is probably because of an asymmetrical interference, visual acuity being strictly symmetrical (Fig. 23). When compared to actual reading



Lateral interference in eccentric vision

FIG. 22. Schematic indication of the extent of lateral visual interference. Recognizability of targets positioned at the centers of the indicated areas is decreased if other stimuli are present within these areas. The central dot is the point of fixation; retinal eccentricity is indicated as φ. (Bouma, Ref. 11.)

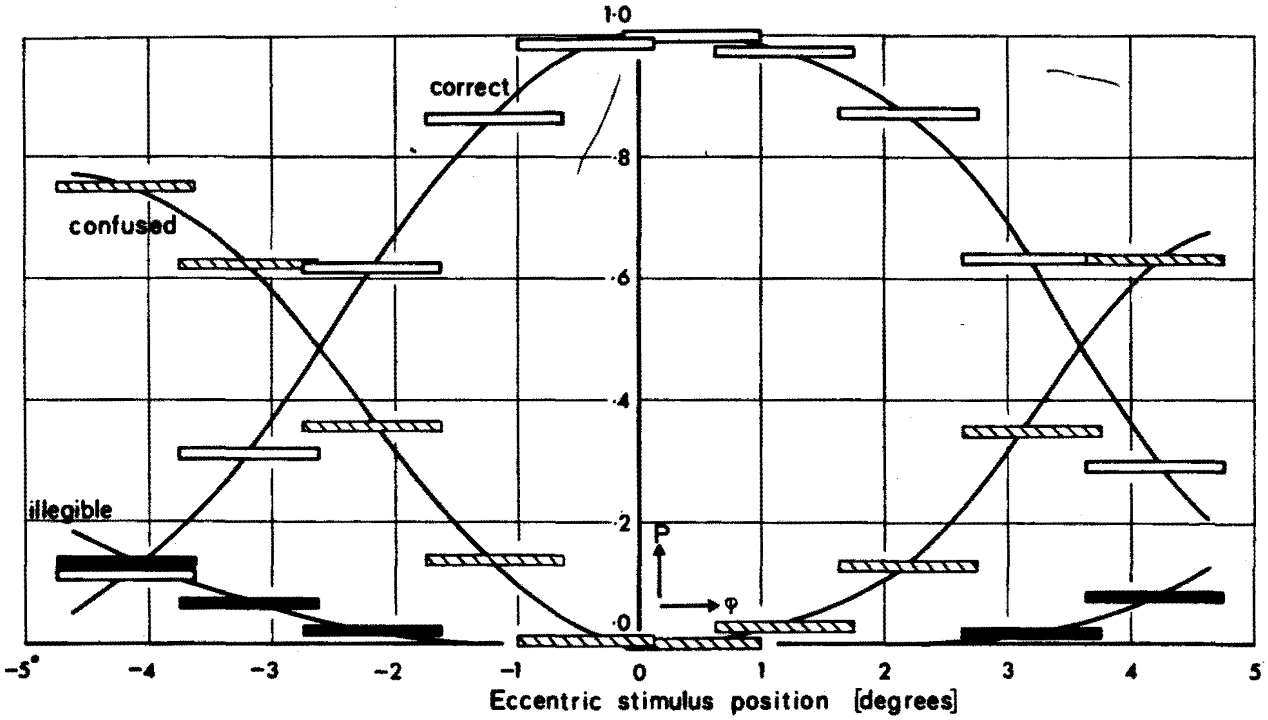


FIG. 23. Average word response fractions as a function of retinal eccentricity of presentation. One degree corresponds to four letter positions. Bar width indicates average word length of 4½ letters. Note the higher correct scores for stimuli right of fixation. (Bouma, Ref. 120.)

situations, the width of the reading field, as determined from single-word recognition, should be corrected in two ways. First, actual text contains many words, and consequently many letters, placed closely together, which causes the interference to be more pronounced. Second, in text, words are connected by grammatical and semantic relations so that less visual information is required for correct recognition. Apparently these two factors roughly balance each other and the estimate found for the reading field in a fairly optimal reading situation comes close to the above mentioned values.[121]

From the above it will also be clear that in eccentric vision initial and final letters of words can be better recognized than embedded letters because the blank spacing limits the amount of visual interference. Also the end of lines can already be noticed far from the actual point of fixation.

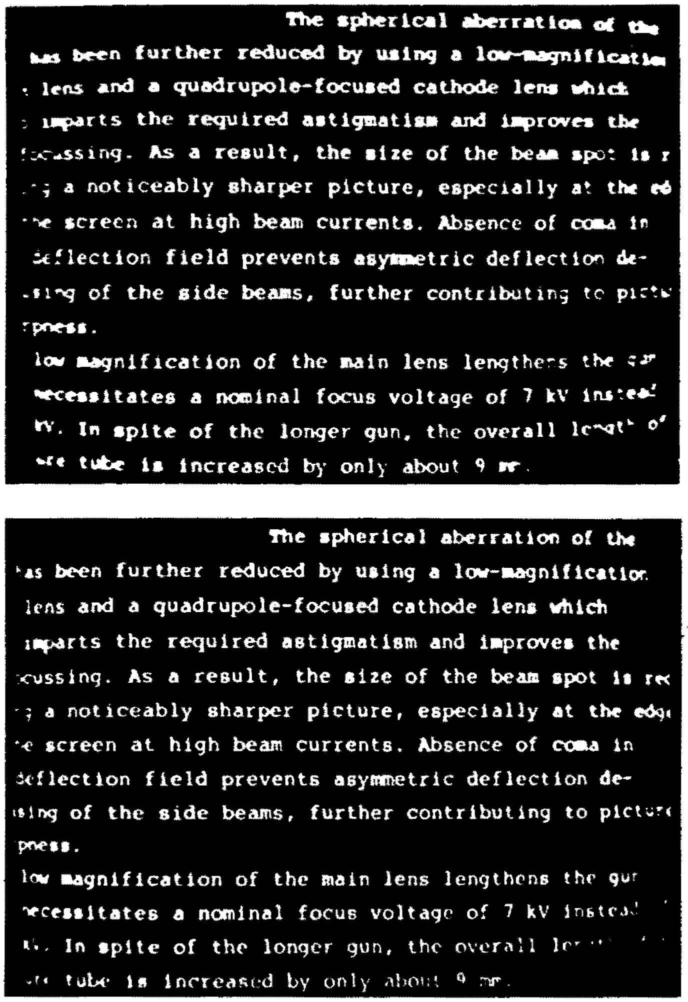
A proper understanding of recognition within the reading field calls for a theory of visual word recognition. Qualitatively speaking, visual word recognition will be easier if more details of the word can be seen. Since all recognition is based on both perceptual information and available knowledge, recognition will also be easier if the words involved are well known or are likely to appear in a particular context.[122] For short words, it has been shown possible to understand both correct and incorrect word recognition scores on the basis of a specification of letter recognition and subjective word availability.[123] If such initial success spreads to longer words, and can also be extended to the dynamics of recognition, the concept of the visual reading field for words will be firmly established.

Consequences for Text Quality

Reading can proceed efficiently if a maximum amount of text information can be picked up in a single eye fixation. In strictly foveal vision, poorly designed letters of low contrast and sharpness can perhaps be recognized although it will take more time than necessary. The width of the reading field, however, depends on eccentric vision and here the requirements are much more strict. In this respect the difference between foveal and parafoveal vision is often not appreciated. At least we can think of no other explanation why the quality of text on commercial displays is often so poor. Text on displays should be such that the visual reading field is maximally wide, and research should be directed at measuring both recognition score and latency in foveal and eccentric vision.

a. Letter Type and Contrast

In the case of print, the requirements of a typeface for easy reading are well known. First of all, displays should provide sharp and undistorted letters (Fig. 24). Letter configurations should be simple, without unnecessary ornamentation. The difference between configurations of letters that resemble each other, such as e versus c, should be maximized. Serifs at the end of line elements may be of restricted help, but they should be short or triangular. For running text, lower case letters are better than upper case letters[124-125] (Fig. 25), but the extensions should be at least 40% of the x height. There are several good letter fonts, and the search for the single best letter configuration seems as



The spherical aberration of the
has been further reduced by using a low-magnification
lens and a quadrupole-focused cathode lens which
imparts the required astigmatism and improves the
focussing. As a result, the size of the beam spot is r
; a noticeably sharper picture, especially at the ed
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necessitates a nominal focus voltage of 7 kV instead
kV. In spite of the longer gun, the overall length of
the tube is increased by only about 9 mm.

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low magnification of the main lens lengthens the gun
necessitates a nominal focus voltage of 7 kV instead
kV. In spite of the longer gun, the overall le
tube is increased by only about 9 mm.

FIG. 24. Effect on text legibility of an improvement in the focusing quality of a shadow-mask color picture tube. The full 26 in. screens type 20 AX (upper) and the improved type 30 AX (lower) is used to display text. (Courtesy of Mr. P.G.J. Barten, N.V. Philips Gloeilampen fabrieken.)

elusive now as it has proved in the past. However, if there are additional restrictions—for example, if letters are designed within a matrix (Fig. 26)—a careful design and a proper experimental check on legibility is necessary. The following three factors should be considered:

Acceptability, i.e., the degree to which the letter configurations suit the notion that subjects have of such letters: There may well be certain cultural differences in these notions, that are, for example, also the case with the usual configurations of digits.

Identifiability of letter details, which should stand out clearly: This is particularly important for the inner details that are surrounded by other elements, for example, in e, a, and s. The line elements should contrast sharply with the background and be homogeneous. Stroke width should be between 10 and 15% of x height. Letter size is probably not very critical but their details should stand out to ensure sufficiently quick recognition.

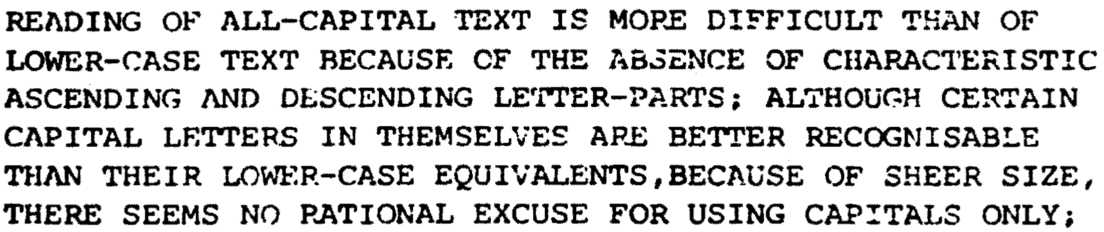
Distinctiveness, i.e., each symbol should stand out from similar symbols: Resemblances between letters depend on the letter font. Figure 27 gives letter similarities for a lower case font. Requirements may be conflicting and an example of this is shown in Fig. 28.

Experimental checks on perceptual quality should involve recognition in eccentric vision. Single letters should be tested both with a homogeneous background and embedded between two other letters. The confusion matrix obtained will indicate the letters that fall behind in legibility and also the reason for this. Particularly in the case of code numbers, which have little redundancy and in which each symbol has to be recognized on its own strength, it is important to have each symbol optimally designed.

The well-known seven-segment digits are not optimal. Confusion between certain digits is common,[129] and depend primarily on the number of segments in which the digits differ (Fig. 29, taken from Bouma and Van Nes[130]). What is probably a better design is proposed in Fig. 30. It seems unfortunate that these digits should have been introduced on a very large scale without proper perceptual testing.

b. Line Distance

The width of the reading field depends on more factors than simply a proper type face displayed in proper contrast. Because of the large-range effect of visual interference in parafoveal vision, there is a danger that recognition is being adversely influenced by the lines of print above and below the one actually read. In order to prevent this, the homogeneous area between the lines should be equal to about three letter spacings. If the interline distance is chosen smaller than this, the width of the reading field will be narrowed by the adjacent lines of print (Fig. 31). This restricts the acceptable text density on the screen. Subjective ratings of character densities demonstrate such an effect (Fig. 32).



READING OF ALL-CAPITAL TEXT IS MORE DIFFICULT THAN OF
LOWER-CASE TEXT BECAUSE OF THE ABSENCE OF CHARACTERISTIC
ASCENDING AND DESCENDING LETTER-PARTS; ALTHOUGH CERTAIN
CAPITAL LETTERS IN THEMSELVES ARE BETTER RECOGNISABLE
THAN THEIR LOWER-CASE EQUIVALENTS,BECAUSE OF SHEER SIZE,
THERE SEEMS NO RATIONAL EXCUSE FOR USING CAPITALS ONLY;

FIG. 25. Reading of all-capital text is the more difficult than of lower-case text because of the absence of characteristic ascending and descending letter elements. Although certain capital letters in themselves are more easily recognizable than their lower-case equivalents, because of sheer size, there seems to be no rationale for using capitals only.

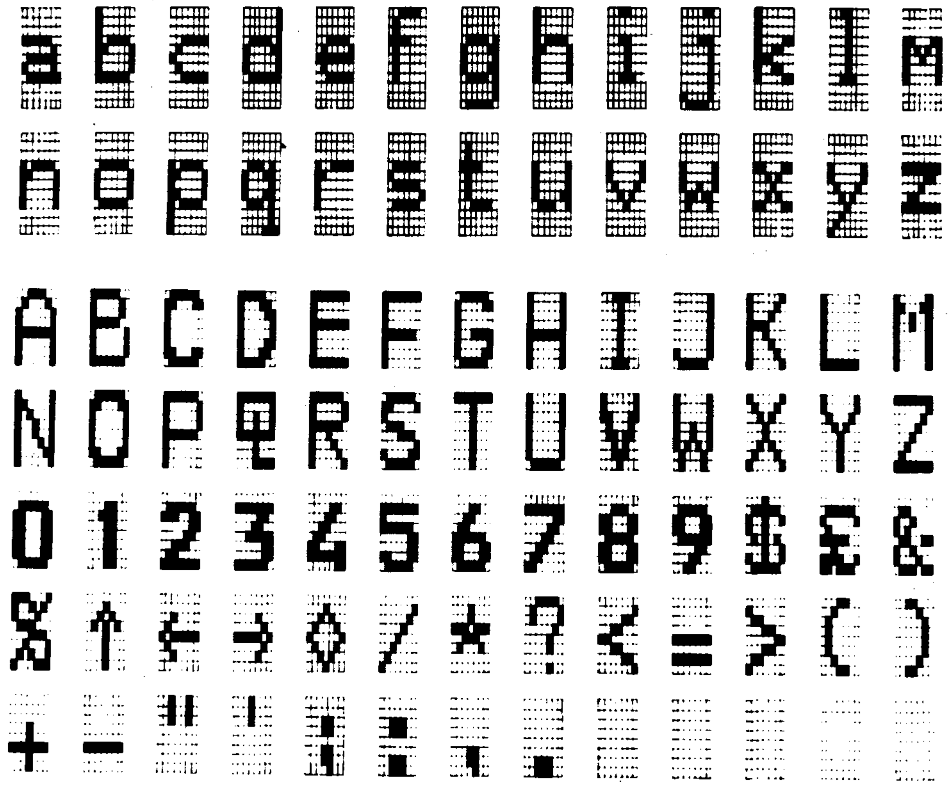


FIG. 26. A set of alphanumeric symbols as designed in a 7 × 11 matrix. Optimum acceptability, identifiability, and distinctiveness were the goals. These have been checked by preference ratings and by analysing confusions from legibility experiments. (Bouma and Leopold, Ref. 126; Bouma and Van Rens, Ref. 127.)

D. Integration of Information From Successive Fixations

From the above discussion it follows that the horizontal width of the reading field is about twice the average eye saccade. It also follows that successive reading fields for words overlap in such a way that each word can be recognized correctly during two successive eye fixations. In actual reading, however, we do not recognize words twice but only once. How can this be explained? Although no definite answer is available, some relevant suggestions have recently been advanced. The basis of these suggestions is the experimental observation that recognition in the parafovea is much slower than in foveal presentation. At a distance of about eight letters from fixation, which is the size of a typical saccade, word recognition is slower by about 200 ms.

Short letters	S_1	a	s	z	x	
	S_2	e	o	c		
	S_3	n	m	u		
	S_4	r	v	w		
Ascenders	A_1	d	h	b	k	
	A_2	t	i	l	f	
Descenders	D_1	g	j	p	y	g

FIG. 27. Letter grouping of lower-case letters, based upon the confusability of letters of the Courier 10 font. (Bouma, Ref. 128.)

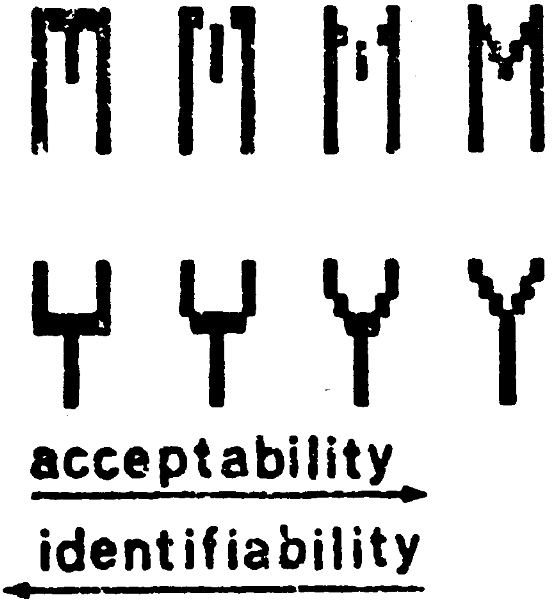


FIG. 28. Two examples of a conflict between acceptability and identifiability. (Bouma and Leopold, Ref. 126.)

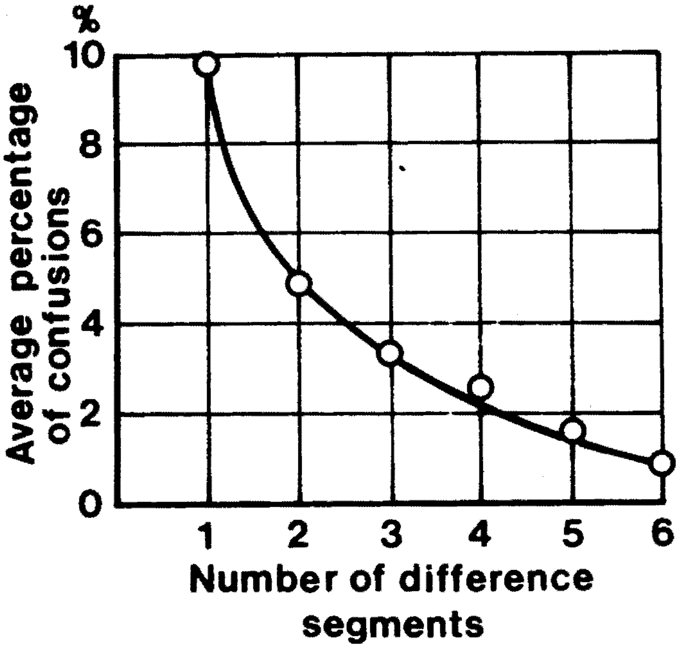


FIG. 29. The percentage of confusions in seven-segment digits as a function of the total number of different segments between the pairs of digits concerned. Data points are averaged over digit pairs and over observation conditions. (Bouma and Van Nes, Ref. 130.)

As a consequence, the two-fold presentation of certain words (first in the right parafoveal field and second, after about 200 ms in foveal fixation) activates the internal word concept at about the same moment, and so can easily operate simultaneously.[11,131]

Consequences for Text Quality

Proper integration of the information requires a sufficiently high speed of recognition. To the first approximation, the running storage of information may be assumed either time limited or content limited. In either case, the adequate units of meaning must be picked up uninterruptedly in sufficiently rapid succession to enable them to be integrated into a meaningful whole. Relevant factors include:

Contrast: black on white versus white on black. The relevant difference here is the state of adaptation of the eye, which is adapted to a higher luminance level in the case of dark letters on a white background than vice versa. A lower level of adaptation corresponds to a somewhat lower resolving power of the eye and, probably more important, a lower rate of processing information. For quick reading, dark print on a light background therefore seems advisable.

Text quality: This should be sufficiently high that recognition time is not prolonged unduly. The requirements are worked out in more detail in the preceding paragraph, but the dependent variable to be investigated is now recognition latency rather than recognition score. Recent pilot experiments in our Institute indicate that eccentric recognition latency is fairly sensitive to a reduction of contrast.[134]

Units of meaning: Since relevant units of meaning have to be picked up within the time span of storage, text should be made up in such a way that these units can be read in connection and not be separated by intervening sentences or parts of sentences. A discussion of this content factor falls outside the scope of this section.

E. Additional Factors

A few factors relevant to text displays did not fit in easily with the context of the last sections and will be mentioned here.

Synchronization and line flicker: For semi-static images, which are usual in text, the horizontal edges of letters will change appearance continually unless frames are synchronized. Flicker between interlaced scanning lines will appear as wobbling horizontal letter strokes, depending on display size and viewing distance.

Frame flicker: In order to avoid the disturbing effects of a flickering image, it is preferable for the image frequency to be above approximately 70 Hz. The increasing quietness of an image when image frequency is raised from 50 to 60 Hz is already quite remarkable. Since flicker perception increases with luminance and with increasing size of luminant parts, bright letters on a dark background have less flicker than a bright background with dark letters, always provided that other factors remain unchanged.

Color and contrast coding: The relevant factor for reading is luminous contrast rather than color contrast. Thus, any color combination of text and background will do as long as the colors are sufficiently bright (on a dark background) or dark (on a bright background). From the viewpoint of perception, color is relevant not for reading itself but rather for grouping and for quick visual search. Only a limited number of colors should be used for this that have sufficiently large subjective differences. About 4% of the population has some color weakness.

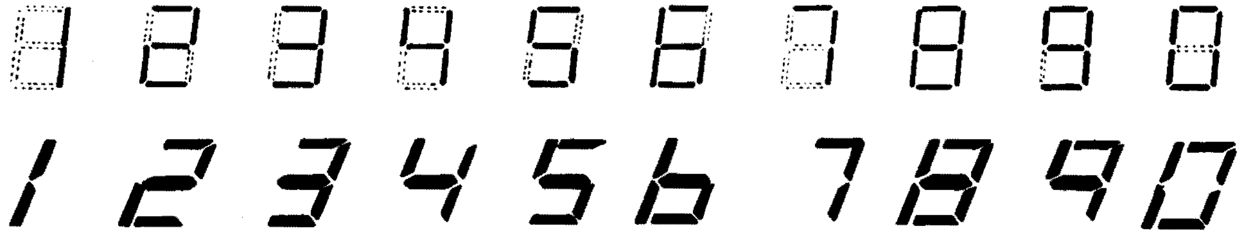
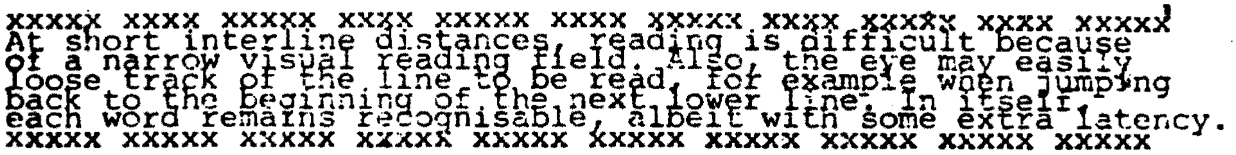


FIG. 30. Configurations of seven-segment digits. Upper row: a commonly used configuration. Lower row: proposed configuration, in which confusability between different digits has been decreased. (Bouma and Van Nes, Ref. 130.)



xxxxx xxxx xxxxx xxxx xxxxx xxxx xxxxx xxxx xxxxx xxxx xxxxx
At short interline distances, reading is difficult because
of a narrow visual reading field. Also, the eye may easily
loose track of the line to be read, for example when jumping
back to the beginning of the next lower line. In itself,
each word remains recognisable, albeit with some extra latency.
xxxxx xxxxx xxxxx xxxxx xxxxx xxxxx xxxxx xxxxx xxxxx xxxxx

FIG. 31. At short interline distances, reading is difficult because of a narrow visual reading field. Also, the eye may easily lose track of the line to be read; for example, when jumping back to the beginning of the next lower line. In itself, each word remains recognizable, albeit with some extra latency.

Screen reflections: Even with adequate luminous contrast in the display itself, actual contrast may be poor because of specular and diffuse reflections from bright windows, walls, and luminaires. There are a number of solutions for protecting the display. In addition, the display should be properly installed in its environment.

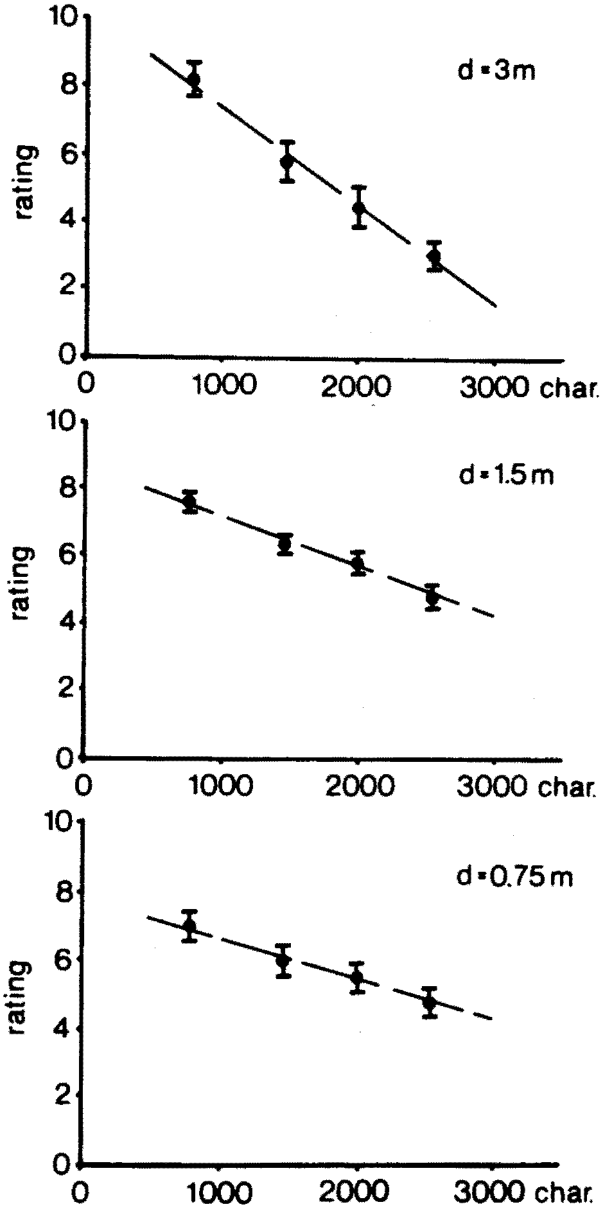


FIG. 32. Judgements by viewers with normal visual acuity of newspaper text on TV screens with different character densities obtained at three different viewing distances, *d*. Results from 12 subjects. (Breimer, Timmers, and Van der Veen; Ref. 12.)

Contrast between the paper or display to be read and its surround: Since the eye shifts continuously over the text, portions of the retina continuously change their state of adaptation from the paper or display to the surround and vice versa. Thus, the general contrast between the text display and its surround should not be too high. For eyes that suffer from internal scatter, which is quite usual for subjects above the age of 50 or so, light letters on a dark background are preferred because they provide a higher retinal contrast.

Reading distance: Reading distance is usually not very critical, if letter size is adequate. However, the need for proper accommodation (focusing) on the text distance should be borne in mind. In particular, subjects above the age of 45 or so will need spectacles specially suited for that particular reading distance. In addition, if two reading distances are involved such as in case of the typing of documents, the original and the display should be at roughly equal reading distances. Adjustment of accommodation is both relatively slow and fatiguing and so should only be required infrequently.

Individual differences: For representative testing, it should be remembered that there are wide individual differences between most perceptual faculties. Thus distributions of the relevant properties should be considered rather than just a few unrepresentative subjects. This is only one reason why critical eyes will distrust what they see.

VI. FINAL REMARKS

The present paper advocates a certain approach rather than either providing answers to the many practical problems that exist or by giving a balanced review of the literature. A proper understanding of image quality requires an understanding of human visual information processing, and thus can only be acquired by dedicated research effort. On the other hand, the design of displays tends to require fast decisions based on many technical and economic considerations as well as perceptual ones. Thus, the two types of activity cannot easily be combined. What can be done is to organize close cooperation between visual researchers and display engineers, to the mutual advantage of both parties. Visual researchers may learn where serious problems lie and where theories offer insufficient insight for understanding vision as it occurs in daily life, of which visual displays have become a part. Display engineers may experience a certain distrust of the representativeness of their own vision, use better methods for subjective rating, and take advantage of the available general insights in the field of human vision. A first requirement for such cooperation is to learn each other's terminologies. Experimental conditions should be chosen carefully and in close connection with the existing literature. It is unfortunate that so much tedious research effort has already lost effectiveness because it proved impossible to relate it to other literature. Of course, one should aim at quantitative theories with well defined, and if possible, wide limits of validation. Furthermore, it seems useful to agree on restricted problem areas that combine practical urgency with theoretical amenability. To suggest just a few of these: What are the limits of visual constancy laws (brightness, color) if display size is increased? How do eye movements depend on display size? How sharp should high definition TV be? What are proper color codes for graphics? What requirements should text displays fulfil in order to permit the easy selection of information by the reader?

We have tried to indicate a number of present gaps between theory and practical problems, each of which may act as a reminder that achieving a real understanding is no easy matter. However, research in the past contains many examples in which a serious concern with practical problems was the basis for an advancement of insights. Vision theory will be incomplete unless it deals with vision as it occurs. Optimum image quality means quality that is maximally suited to vision as it occurs. Consequently, the two problem areas are intrinsically linked and progress will increasingly depend on the ability to make the links explicit.

APPENDIX A

Point-Spread Function Derived by Perturbation

The annulus is always kept below threshold, the point source acting as a probe. Let $A_p\epsilon_p U_\delta(r)$ be the response of the point-source having an area A_p and an increment of retinal illumination ϵ_p. The response in the center of a thin annulus with radius r_a and width Δr_a will be

$$U_a(0) = \epsilon_a 2\pi r_a \Delta r_a U_\delta(r_a) \tag{A.1}$$

$$= \epsilon_a A_a U_\delta(r_a). \tag{A.2}$$

If we keep $\epsilon_p/\epsilon_a \equiv q$ at a constant value and q is sufficiently small to hold the annulus below threshold, than the amplitude of the response of the combination at threshold is given by $\mathrm{extr}[\epsilon_p A_p U_\delta(0) + \epsilon_a A_a U_\delta(r_a)] = D$, where D is the minimum amplitude for (50%) detection. Hence,

$$A_p \frac{U_\delta(0)}{D} + \frac{qA_a U(r_a)}{D} = \frac{1}{\epsilon_p(r_a)}. \tag{A.3}$$

By varying r_a, the point-spread function in D units can be found from the variable part of $1/\epsilon_p(r_a)$. Subtracting the reciprocal of the point source alone leads to the simple formula

$$\frac{U_\delta(r_a)}{D} = \frac{1}{qA_a}\left(\frac{1}{\epsilon_p(r_a)} - \frac{1}{\epsilon_p(0)}\right). \tag{A.4}$$

Within the model the unit response to any stimulus in D units can be calculated by convolution. For example, a circular homogeneous stimulus having a radius r_d and being 1 td above background is

$$\frac{U(r)}{D} = \int_0^{2\pi}\int_0^{rd} \frac{U_\delta(|r - r'|)}{D}\, r'\,\mathrm{d}r'\, d\varphi. \tag{A.5}$$

Hence, ϵ_{thr} at threshold is given by

$$\epsilon_{\mathrm{thr}}\,\mathrm{extr}[U(r)/D] = 1. \tag{A.6}$$

The effect of the response of the area elements of a disk, having a retinal illumination $\epsilon_d = q\epsilon_{p'}$, on the threshold of the point source in its center, is given by

$$\epsilon_{p,d}(r)[A_p U_\delta(0) + 2\pi q \int_0^{r_d} rU_\delta(r)\,\mathrm{dr}] = D. \tag{A.7}$$

The quantity plotted in Fig. 4 is

$$F^* = 2\pi \int_0^{r_d} \frac{rU_\delta^x(r)}{D}\,\mathrm{dr} = \frac{A_p}{q}\left(\frac{\epsilon_p}{\epsilon_{p,d}} - 1\right). \tag{A.8}$$

APPENDIX B

Pulse Response Determined by Perturbation

Two short flashes, having a constant intensity ratio q and equal durations θ are used. The dominant phase of the response to the stronger flash, having an intensity ϵ, is used as a probe for the response to the test flash, having intensity $q\epsilon$ and initiated at an interval τ. In order to be detected, the amplitude of the response to the combination has to be at a threshold level d:

$$\mathrm{extr}[\epsilon_{cp}\theta U_\delta(t) + q\epsilon_{cp}\theta U_\delta(t - \tau)] = a = d \text{ or } -d. \tag{B.1}$$

Since q ≪ 1, the moment at which the extreme value of the combination is the same as that of the crest of the response to the probe flash is given by

$$\frac{U_\delta(t_{e_x})}{a} + q\frac{U_\delta(t_{e_x} - \tau)}{a} = \frac{1}{\epsilon_{cp}(\tau)\theta}. \tag{B.2}$$

The first term is constant, U_δ is expressed in units that can be found from $\epsilon_{cp}(\tau)$.

Using the threshold of the probe flash alone gives

$$\epsilon_p\theta U_\delta(t_{e_x}) = a \tag{B.3}$$

from which we obtain the convenient formula

$$\frac{U_\delta(t_{e_x} - \tau)}{a} = \frac{1}{q\theta}\left(\frac{1}{\epsilon_{cp}(\tau)} - \frac{1}{\epsilon_p}\right). \tag{B.4}$$

Normalizing this gives

$$U_\delta^*(t_{e_s} - \tau) = \left(\frac{U_\delta(t_{ex} - \tau)}{a}\right)\left(\frac{u_\delta(t_{ex})}{a}\right)^{-1}$$

$$= \frac{1}{q\theta}\left(\frac{\epsilon_p - \epsilon_{cp}}{\epsilon_{cp}}\right), \qquad \text{(B.5)}$$

the norm constant being $U_\delta(t_{e_s})/a = 1/\epsilon_p\theta$.

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