10 Assessment of Image Quality

The need to be able to measure optical quality was recognised many centuries ago, but no really adequate concept was put forward until the 19th century, when several scientists progressively refined the concept of resolving power – the limit of ability to detect that two adjacent objects were present as the separation between them was reduced. This 19th century work culminated in the classical papers of Lord Rayleigh, which defined the limit of resolution for a perfect optical system to be the angular separation of two point objects when the first dark ring of the Airy disc produced by one object coincided with the peak of the Airy disc formed by the other. This concept was later extended by Rayleigh's followers to the case of two line objects, and later again became a general concept for specification of performance of most optical systems. Useful discussions of the concepts of resolution and resolving power are to be found in Ronchi,[1] Brock[2] and Perrin.[3]

Since the 1930's there has been an increasing awareness that this simple concept was other than satisfactory, because of the dependence of its value on numerous factors. As a result of this, other more adequate and universal measures have been sought. Some 35 years ago a concept already widely used in the fields of electronics and control systems was 'borrowed' by optical scientists – that of frequency of response.[4] From this grew the concept of Optical Transfer Function (OTF) which, in theory, was a complete measure of the degradation in sharpness due to an optical system.[5–7] Many methods have been developed for the instrumental measurement of the OTF of optical systems (see Section 10.2.2). If used in conjunction with some measure of gross change of scene contrast (e.g. veiling glare – see Section 9.1.6) such a measure should be capable of completely specifying an optical image. However, it soon became apparent that there was no obvious, direct relationship between OTF and visual performance in normal viewing, partly due to the unknown effects of coupling between the optical component and the eye, and partly due to an incomplete understanding of the relationships between visual performance when looking at periodic functions and when looking at isolated objects.

In recent years there has thus been a considerable effort made to find a figure of merit related to OTF which can define visual performance. Several possible empirically derived figures of merit have been investigated. These will be discussed later in this chapter (Section 10.3). Finally, from the modelling described in Chapter 7 it has been possible to propose a physically-based figure of merit (visual efficiency) which may be used as a starting point for the prediction of visual performance for many simple and definable viewing situations. This will also be discussed later in the chapter (Section 10.3.5).

Whilst progress was being made in the development of methods of measuring frequency response, attention was also being given to the possible forms of veiling glare. This has resulted in the definition of a Veiling Glare Index (VGI) as a standard for specifying general loss of contrast, and other glare functions applicable to ghost images and local glare. These will be discussed in Section 10.4.

10.1 LIMITATIONS OF RESOLUTION

As intimated earlier, the concept of resolution was originally applied to the minimum detectable separation between two point objects. This had some value

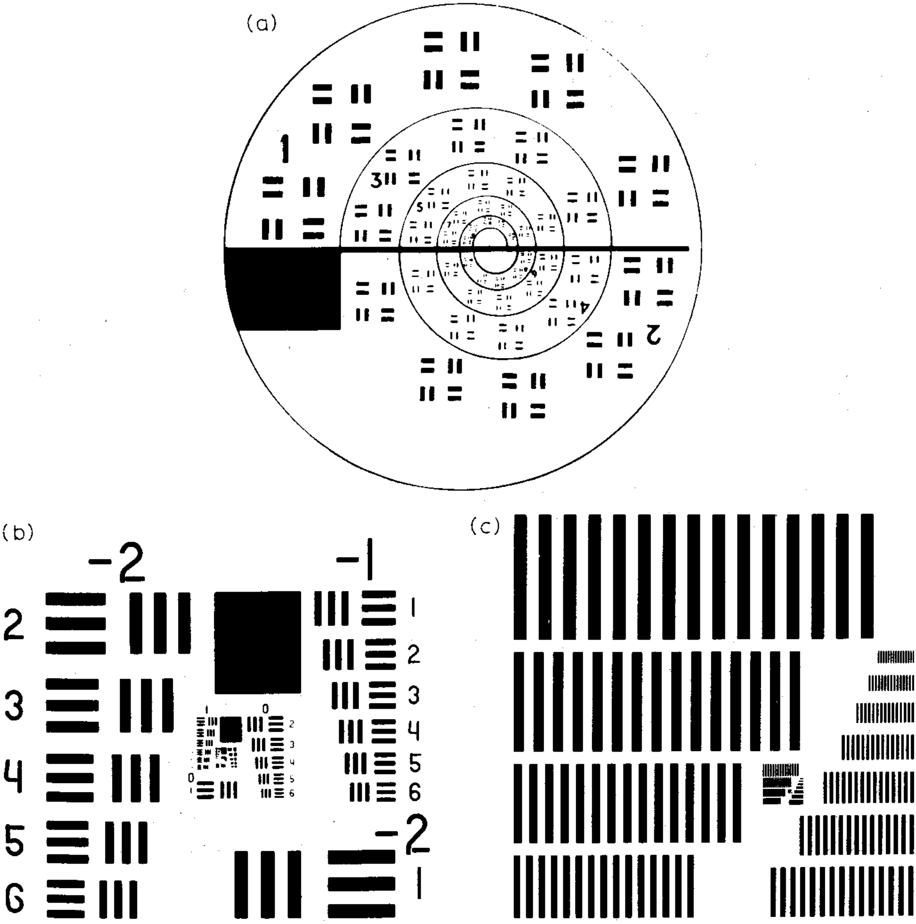

Fig. 10.1. Some of the many resolution test targets in current use. (a) British Cobb. (b) American 3-bar. (c) Sayce. Ealing High Resolution Test Target.

in astronomy, where the objects of interest were usually stars, but was of questionable use for any other application. In an attempt to overcome this for for practical measurement of the resolution of photographic equipment and visual aids, various resolution test charts were proposed. A number of these still retain considerable favour, e.g. the Cobb Chart,[8] and the American 3 Bar Chart.[9] Figure 10.1 shows some of these forms of chart. When one attempts to measure resolution using any of these charts, the first discovery is that no two charts give the same resolution figure. It appears from observation that the shape of the bars and the number of the bars comprising an *element* both affect the results. To someone conversant with all the threshold effects discussed in previous chapters this is not surprising, but what is the *best* shape? The answer is that there is no *best* shape – it depend on what the equipment is to be used for. Equally well it is found by observation that the *contrast* of the test pattern affects results markedly. Again from threshold data this is no surprise – and again there is no *best* contrast. Once again the scene luminance can affect results markedly, as can also the eyesight of the observer. It must therefore be concluded that resolution is a very inadequate method of specifying optical quality. Indeed, not only may it be grossly misleading in *absolute* terms, it *can* be misleading in relative terms.

For extended discussion on problems associated with resolution measurement the reader is referred to the papers of Vasco Ronchi[1] and Overington and Gullick.[10] In the author's opinion the only point in favour of resolution as applied to visual systems is that it does include the observer – a necessary requirement for any measurement technique to be used reliably for assessment of visual instrumentation.

10.2 SPATIAL FREQUENCY RESPONSE (THE OPTICAL TRANSFER FUNCTION)

10.2.1 Concepts

The basic concept of frequency response is arrived at by considering the transmission of sine waves through any system. If a system is linear,* then any sine wave input will produce a sine wave output. However, in general the output sine wave will be reduced in amplitude and have a phase-shift relative to the input. The functional relationship between relative amplitude, phase-shift and frequency is then the frequency response.

When applied to the quality of optical systems, the domain of interest is usually two-dimensional space perpendicular to the optical axis of the system.

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*A *linear* system is defined here as one where the average output is proportional to the average input and where there is no distortion of signal information due to such factors as saturation effects.

Since the concept of two-dimensional frequency and phase-shift is very complex, it has become conventional to describe optical performance in terms of two orthogonal one-dimensional frequency responses. The test material is a one-dimensional bar pattern of effectively infinite extent, the brightness being modulated across the bars according to the law

$$B_L = B_m + (\Delta B)_{\max} \cos 2\pi f_s x \tag{10.1}$$

In the above B_L is the local luminance, B_m is the mean luminance, $(\Delta B)_{\max}$ is the maximum deviation from the mean luminance, f_s is the spatial frequency of the pattern and x is the distance from an arbitary zero.

Then, in general, the output will be

$$B'_L = B_m + \gamma(\Delta B)_{\max} \cos (2\pi f_s x + \phi) \tag{10.2}$$

where γ is the relative amplitude and ϕ is the phase angle.

The trend of γ as a function of f_s is then known as the Modulation Transfer Function (MTF), whilst the trend of ϕ as a function of f_s is the Phase Transfer Function (PTF). The combination of MTF and PTF is the Optical Transfer Function (OTF). The concept is illustrated in Fig. 10.2.

In order for the concept to be applicable it is necessary for the optical system to be *linear* in the space domain and also for the image field to be homogeneous

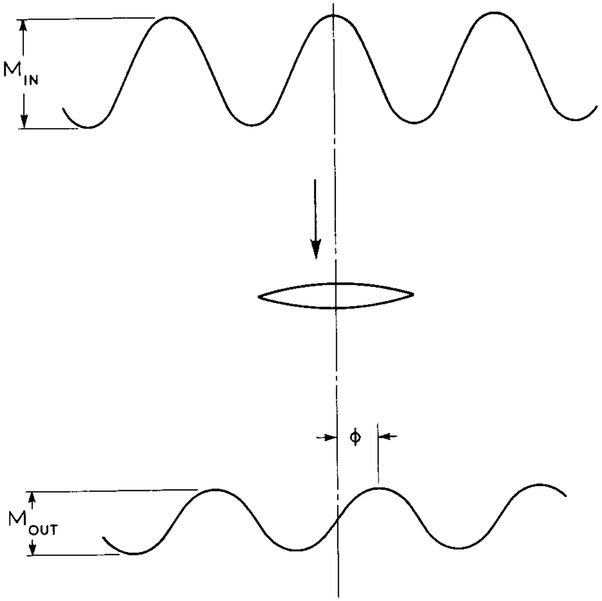

Fig. 10.2. Illustrating the transmission of spatial sinusoidal modulation through an optical system. $M_{OUT}/M_{IN} = \gamma = MTF$, *$\phi$ = phase displacement.*

over a large area compared to one cycle of the bar pattern. Most normal optical transmission systems are linear and many detector systems are adequately linear over restricted ranges of luminance for this concept to be applied. Homogeneity of the image field can usually be provided in a laboratory situation but care needs to be exercised.

It is usual to determine the OTF for bar patterns with the lines perpendicular to the radius from the optical axis (tangential OTF) and parallel to the radius from the optical axis (saggital or radial OTF) for other than axial imagery. In general the plane chosen for measurement of the radial and tangential OTF's must depend on the use the system is going to be put to, since most systems will exhibit some degree of astigmatism and curvature of field. For instance, in testing photographic lenses the OTF must be measured in some chosen optimum image plane (which will not usually be that yielding best on-axis performance). Conversely, for visual aids, the optimum imagery at any local field point may be considered, subject to the limitations of accommodation of the eye. However, in such cases the optimal radial and tangential imagery will usually be in different planes due to astigmatism, and due attention must be paid to the fact that lines and periodic patterns at orientations other than radial or tangential will not yield performance as high as either optimal radial or optimal tangential. Indeed, in such cases it is desirable to study the optimal OTF as a function of pattern orientation.[11,12] For axial imagery and a symmetrical system in optimum focus there is obviously only one OTF. However, in the case of practical systems exhibiting astigmatism or other defects such as mechanical centering errors, the OTF may *not* be symmetrical on axis. In such cases it is conventional to consider the *vertical* bars as tested to yield a tangential OTF.

The OTF is closely related to the line spread function of an optical system, the two being a Fourier transform pair, i.e.

$$F(\mathrm{j}\omega) = \int_{-\infty}^{+\infty} G(x) \exp(-\mathrm{j}\omega x)\, \mathrm{d}x \qquad (10.3)$$

where $\omega = Z\pi f_s$, $F(j\omega)$ is the OTF and $G(x)$ is the line spread function.

The integral of the line spread function is the edge profile of the image of a perfect edge, and the line spread function is itself the integral of the point spread function. The point spread function in turn, when convolved with any object profile, generates the image luminance distribution. Therefore, the OTF is seen to be directly related to all image functions of an optical system. The reader wishing to pursue the theory of OTF and its relationship to image formation is referred to Hopkins[13] and Brock.[14]

10.2.2 Measurement methods

Over the last two decades many methods have been devised for measurement of OTF. These include *direct* methods, where sinusoidally modulated patterns of

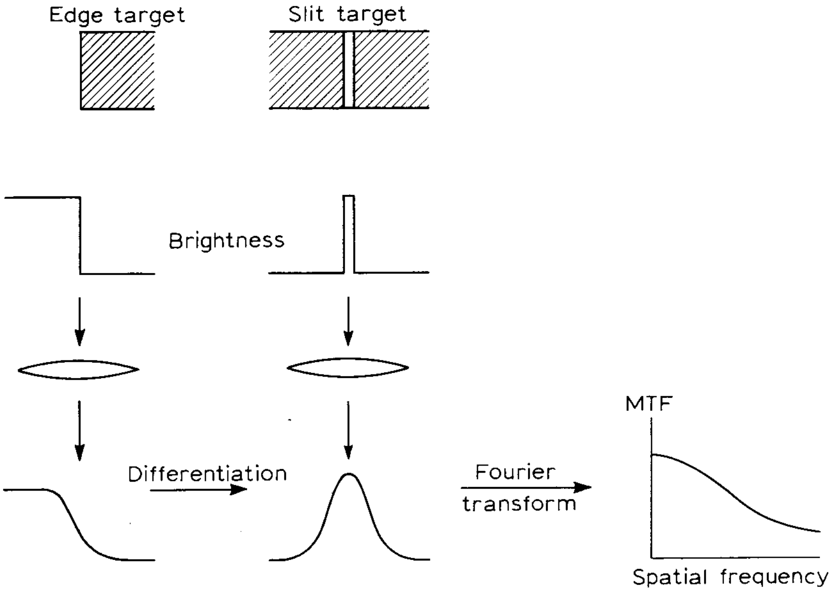

Fig. 10.3. Illustrating the determination of MTF from the images of slits and edges.

various frequencies are passed through a system under test, and various forms of *indirect* methods. These latter include methods where the image of a line or edge is scanned and the resultant output is mathematically processed to yield the OTF (simple Fourier transformation in the case of line images, differentiation and Fourier transformation in the case of edge images, Fig. 10.3) and also methods where the wavefront aberrations of a system are measured, the spread functions and OTF being computed from the wavefront aberrations and pupil size (Fig. 10.4). Below is a survey of some of the more popular methods. More general surveys are given by Rosenhauer and Rosenbruch.[15,16]

EROS.[17,18] This equipment developed by the SIRA Institute at Chislehurst, UK in conjunction with the Royal Aircraft Establishment, Farnborough, and marketed by the Ealing-Beck Corporation, produces a continuously varying frequency of sinusoidal pattern by rotating one slit pattern with respect to a second. The resultant moving Moiré fringe pattern is projected through the system under test and imaged on an analyser slit connected to a photomultiplier tube. An immediate output is produced which can be displayed as MTF and PTF on an oscilloscope. Various versions of the equipment exist, ranging from a portable, modular system to a very expensive, rigidly mounted version for the most precise work.

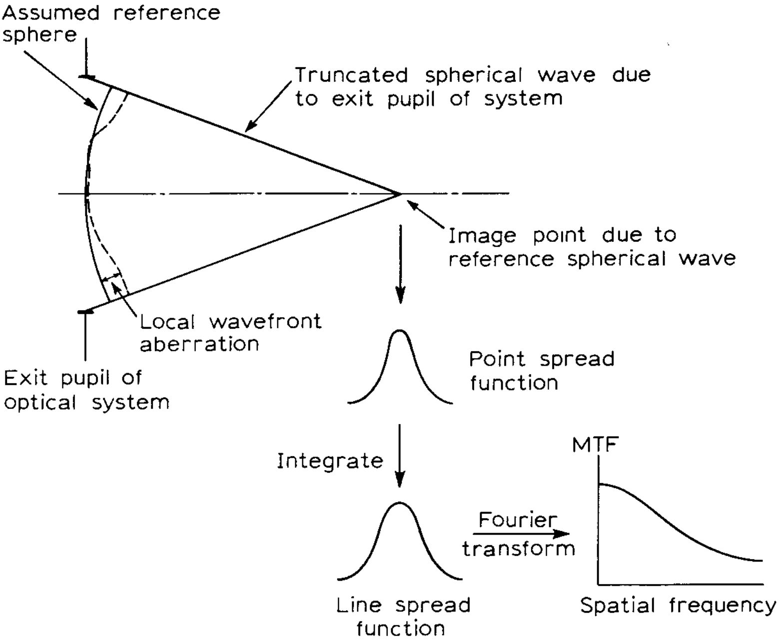

Fig. 10.4. Illustrating the derivation of MTF from analysis of wavefront aberrations. The point spread function is the resultant interface pattern from the truncated, aberrated wavefront.

ODETA.[19] This portable equipment is developed and marketed by the Oude Delft Company in Delft, Holland. It is based on a narrow object slit (2 μm) presented to the system under test and a Moiré scanner as an analyser (i.e. essentially the reverse of the EROS equipment). The output from the scanner is spectrum analysed and may be presented either as an oscilloscope trace of the MTF or as a graphical output on an $X - Y$ recorder. The equipment is claimed to be suitable for measurement of the MTF of lenses, image intensifier tubes, television systems, flourescent screens, etc.

ACOFAM.[20,21] This is a sturdily built, nonportable equipment originally developed by the AQMEL Company of Southern France. It is arranged to measure and plot out the profiles of the images of sine wave patterns of seven specific spatial frequencies. The input sine patterns are projected into the test lens via a collimator mounted on a robust pivoting arm, the output modulation being recorded via a microscope objective and slit assembly mounted on a traverse slide. A recent modification of the system[21] enables the equipment to be used for testing in the infra-red out to 20 μm.

Edge Trace Methods. Several edge trace methods are in use throughout the world. In the USA the Perkin-Elmer Corporation were one of the first to employ this technique (for photographic image assessment[22]). For such measurements the edge trace technique is ideally suited, of course, since the photographic emulsion is its own detector. Others in the USA employing similar techniques were R. A. Jones of Itek[23] and Hopkins and Dutton of Rochester University.[24] These latter used scanning photoelectric detectors in place of the photographic emulsion. More recently Tropel Inc. have developed a commercial equipment based on edge scanning.[16] Meanwhile, in the UK, Overington and Gullick were experimenting with photographic edge trace techniques as a *general* method of measuring OTF, using the photographic system in such a way that it contributed little to the overall performance.[25,26]

Slit Methods. A number of systems have been devised where a slit source is used in place of an edge, the image of the slit being analysed by a narrower slit. Such systems, of which the Rodenstock-Askania[16] and the Cannon Lens Analyser[27] are two, are limited to some extent by the available energy, but have the virtue of producing the line spread function directly (after due compensation for finite object slit width).

Interferometric Methods. An alternative approach to OTF measurement preferred by a number of workers is to study the wavefront aberrations of an optical system by interferometric methods and then to compute the OTF. For this method it is necessary first to compute the point spread function from the measured aberrations and the diffraction due to wavefront truncation.[28,29] Having derived the point spread function it is a relatively simple matter in theory to arrive at the line spread function (by integration) and subsequently the OTF (by Fourier Transformation) (Section 10.2.1). However, in practice significant errors can occur if great care is not taken in the computational stages.

The interferometric methods have one striking advantage over the more direct methods of OTF measurement, provided that the computation is reliable; they contain *all* the information about an imaging wavefront. Hence one measurement enables computation of 'quality' at any point in image space. Furthermore, effects of coupling of two systems such as a visual aid and the eye (Chapter 9) amount to no more than summation of wavefront aberrations. A typical facility for wavefront aberration measurement is the interferometer built by the National Bureau of Standards in the USA,[28] whilst other bodies use various other standard forms of interferometer for appropriate measurements (e.g. Haines and King,[30] Baker[31] and Herriot and Bruning.[32]

10.2.3 Limitations of OTF

As will be obvious from the preceding section, OTF as usually used is an *instrumental* technique. Thus, although one can derive the frequency response of the aerial image of an optical system by one of the many methods listed – or the frequency response of the final photographic image if desired – in all cases where the human being is involved the final image has subsequently to be viewed by the eye. Thus the *effect* of such a frequency response as may be measured depends, in the end, on how it is viewed – and what the eye does with the frequency information. Now we have already seen in Section 4.14 that the eye has a form of total frequency response known as the 'Contrast Sensitivity Function'. We have also observed that this function is dependent on the viewing conditions – in particular the state of eye focus and scene luminance. Now in general, for viewing incoherent images (i.e. on screens, etc.), the OTF of the system incorporated in that final image and the contrast sensitivity of the eye may be multiplied together. However, having done so one must decide on how the eye works in order to predict the effect of any instrumental system OTF. Alternatively, still for viewing incoherent images, one may multiply the instrumentally derived MTF by the measured MTF of the refraction optics of the eye (see Section 2.3) in order to arrive at the MTF of the retinal image.

A further difficulty arises in viewing through transmission optical systems – the implications of direct coupling via an aerial image as discussed in Chapter 9. In such circumstances one should ideally study retinal imagery in terms of wavefront aberrations as discussed earlier in the Section on Interferomic Methods. However, the limited data available on the aberrations of the eye appear to show them to be rather variable, both from person to person and according to viewing condition[33,34] (see also Section 2.3). Thus in practice such an approach is not entirely satisfactory. The alternative is the measurement of total system contrast sensitivity, with subsequent allowance for the transfer functions of the neural networks in order to arrive at the retinal MTF.[10,35]

Recent image evaluation studies at BAC(GW) are believed to have shown a possible way of deriving retinal MTF's from contrast sensitivity. As part of our modelling of the visual system it has been necessary to assume that the bipolar cells in the retina provide a first difference signal from the retinal receptors as a result of local inhibition (Chapter 7). Now, for the general case of spatial sinusoidal modulation, the maximum sampled first difference can be shown to be proportional to sin $\pi f_s \Delta x$ for

$$\pi f_s \Delta x \leqslant \frac{\pi}{2}$$

and proportional to $(1 - \cos \pi f_s \Delta x)$ for

$$\pi f_s \Delta x > \frac{\pi}{2}$$

where f_s is the spatial frequency at the retinal image and Δx is the local receptor spacing for like receptors. For foveal imagery Δx is approximately 0.2 mrad. Therefore for

$$\pi f_s \Delta x = \frac{\pi}{2}$$

$f_s \approx 2.5$ c/mrad. But the practical contrast sensitivity of the eye is very poor at spatial frequencies above 2.5 c/mrad (see Section 4.14). Therefore, for practical purposes one may assume the sampled first difference to be proportional to $\sin \pi f_s \Delta x$ for all spatial frequencies. It has been shown[36] that if one starts with a measured contrast sensitivity for the naked eye under known viewing conditions and operates on it by the sampling function one generates a predicted retinal MTF which is in very close agreement with that predicted by operating on the MTF of the refraction optics to allow for tremor, drift and retinal diffusion (Chapter 7). It would thus appear that a reasonable estimate of the retinal MTF for *any* visual aid/observer combination can be obtained by operating on a total system contrast sensitivity by the same neural sampling function, since this sampling function should be dependent on the observer alone.

10.3 OTHER QUALITY MEASURES

Because of the lack of generality of OTF data when applied to visual performance a number of attempts have been made to find figures of merit associated with the OTF which are adequate descriptors of the relative quality of systems. In the following sections various figures of merit are discussed. Others are discussed by Birch.[37] At this stage it is assumed that all presented images are effectively noise free. Some implications of noise are discussed in Chapter 13.

10.3.1 Modulation Transfer Function Area (MTFA)

The MTFA concept was proposed in the middle '60's', primarily for photographic systems, and has been largely studied by Snyder in particular.[38] Basically MTFA is defined as the area between the MTF curve of a lens system and the detection threshold curve for optimally-viewed photographic representation of the American 3-bar resolution test target (see Fig. 10.5). But the 3-bar resolution threshold is an approximate inverse measure of the retinal MTF for an observer and film combination. Thus the MTFA is approximately representative of the area under the total system MTF referred to the retina, since the lens and film MTF's may be multiplied together.

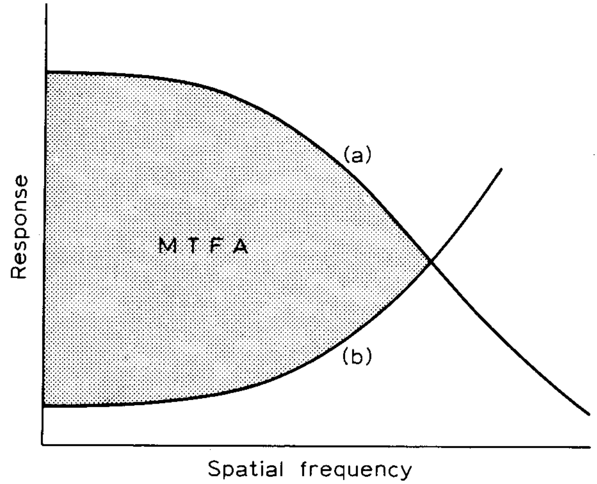

Fig. 10.5. Illustrating the concept of MTFA. (a) is the MTF of the transmission optics, (b) is the threshold detectivity curve for (typically) an American 3-bar target.

Several experimenters have attempted to relate subjective performance to MTFA and closely related factors with very considerable success. In addition to Snyder the most notable are Beidermann[39] and Higgins.[40] Snyder and Beidermann showed a strong correlation between MTFA for photographs of miscellaneous subjects and the subjective ranking of goodness. Higgins showed an even stronger correlation for a similar exercise when he compared subjective performance to the square of the area under the resultant curve from multiplying together the instrumental MTF and that due to the refraction optics of the eye.

10.3.2 Acutance measures

Whilst Snyder was investigating the range of validity of MTFA, large scale studies at Eastman Kodak were seeking to establish forms of quality factor which could predict subjective 'sharpness' of photographs well. Such factors had, of necessity, to take account of a chain of optical and photographic components – typically a camera lens, a camera film, a projector lens, a viewing screen and the observer's eye. These studies led to a proposal of system modulation transfer (SMT) acutance (Crane[41]), this being defined for a camera/projector system as

$$\text{SMT acutance} = 120 - 25\log\left[\left(\frac{200 \times \text{magnification}}{\text{MTC area}_{(\text{camera})}}\right)^2 + \left(\frac{200 \times \text{magnification}}{\text{MTC area}_{(\text{film})}}\right)^2 + \left(\frac{200 \times \text{magnification}}{\text{MTC area}_{(\text{projector})}}\right)^2 + \left(\frac{200 \times \text{magnification}}{\text{MTC area}_{(\text{screen})}}\right)^2 + \left(\frac{200}{\text{MTC area}_{(\text{observer})}}\right)^2\right] \quad (10.4)$$

where magnification is taken to be the ratio of the image width *on the observer's retina* to the image width in the specified component (camera, film, etc.) and MTC area is the area, in units of mm^{-1}, under an experimentally determined MTF curve for the specified component.

The factor was then extended for general use to

$$\text{SMT acutance} = 120 - 25\log\left[\sum_{i=\text{camera}}^{\text{observer}}\left(\frac{200 \times \text{magnification}}{\text{MTC area}_i}\right)^2\right] \quad (10.5)$$

where the summation included a term for each component of the total system between camera and observer.

This factor was found to yield good correlation with sharpness judgements employing a scale of sharpness determined by pair comparison techniques,[42] so long as there were no significantly nonlinear components in the system.

Subsequently SMT acutance was found considerably lacking when using modern film materials exhibiting strong adjacency effects (see Section 9.2.2 for an explanation of adjacency effects). In consequence a modified acutance factor – contrast modulation transfer (CMT) acutance – was proposed (Gendron[43]). This factor essentially replaced the sum of component MTF functions by a product, yielding

$$\text{CMT acutance} = 125 - 20\log\left(\frac{200}{\text{MTC area}_{(\text{syst})}}\right)^2 \quad (10.6)$$

where

$$\text{MTC area}_{(\text{syst})} = \int_0^\infty \text{MTF}_c(\mu') \times \text{MTF}_f(\mu') \times \ldots \times \text{MTF}_0(\mu')\,d\mu',$$

MTF_c, MTF_f etc. being the MTF's at spatial frequency μ' as referred to the observer's retina for the camera, film, etc.

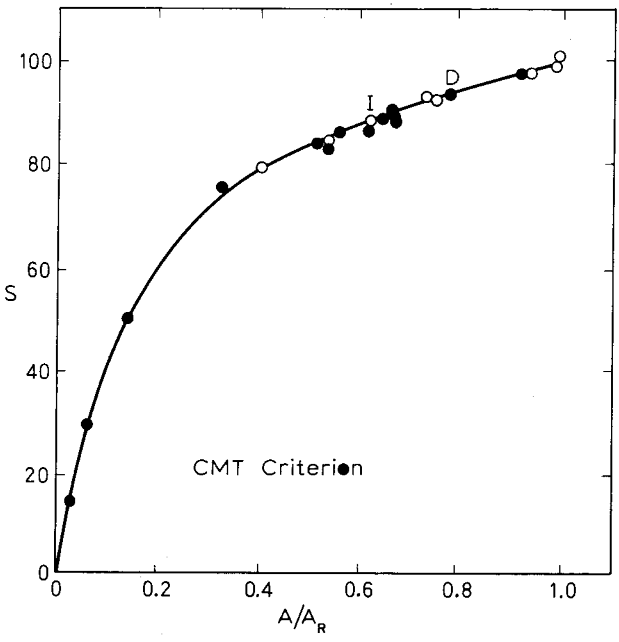

Fig. 10.6. Sharpness ratings as functions of CMT acutance for a variety of forms of image degradation. These include defocus, aberrations, photographic adjacency effects, halation and combinations of two or more forms of degradation. (Reproduced from Gendron[4 3] *by courtesy of the Society of Motion Picture and Television Engineers).*

It was found that this factor gave very high correlation with subjective sharpness judgements for a very wide range of forms of optical degradation, including asymmetric aberrations, gross adjacency effects and gross adjacency effects in the presence of halation. The goodness of fit for all these forms of degradation is illustrated in Fig. 10.6.

It has been shown by the present author that Equation 10.6 may be readily transformed to

$$\text{CMT acutance} = 40 \log (6.67 \text{ MTC area}_{(\text{syst})}) \qquad (10.7)$$

which immediately shows it to be closely related to MTFA.

10.3.3 MTFA Variants

Other workers have thought it desirable, for various reasons, to consider the most effective figure of merit to be the area under the instrumental MTF curve between certain frequencies. The frequency bands considered have ranged from

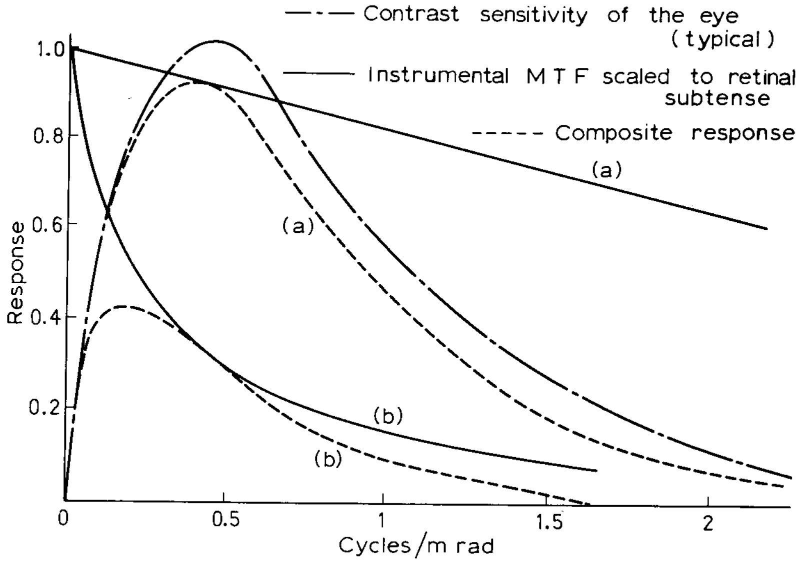

Fig. 10.7. The effect of interactions between instrumental MTF and the contrast sensitivity function of the eye. (a) High quality system, (b) low quality system.

the low frequencies, through the intermediate frequencies. Such ideas have usually been empirical, based on certain limited observations. Study of the implications of combining an instrumental MTF and a contrast sensitivity function for the eye will quickly show how such various selections can arise (Fig. 10.7). If the viewing conditions are such that the instrumental MTF *referred* to the angle subtended at the eye has good response out to 6 c/mrad or more, then the contrast sensitivity function will force the main weighting to be applied to the 'intermediate frequency' region. If, on the other hand, the referred response falls off at considerably less than 1 c/mrad, this will override the contrast sensitivity function and will force the main weighting to be applied to much lower frequencies.

The concept of a weighted or bandpass form of MTFA has recently been put on a firmer foundation by Granger,[44,45] who has considered to some extent the physiology of the eye, and has then determined a subjective quality factor (SQF) which, as with the acutance measures, considers all MTF data referred to the retinal image. He has then arbitrarily chosen a bandpass centred around the peak response of the visual system (as shown in Fig. 10.8). This function has again been shown to correlate very highly with subjective sharpness judgements over a considerable range of quality factors (including, in this case, colour contrast).[45] However, it is claimed by the team working with CMT acutance (private communication) that SQF does not work well for a combination of

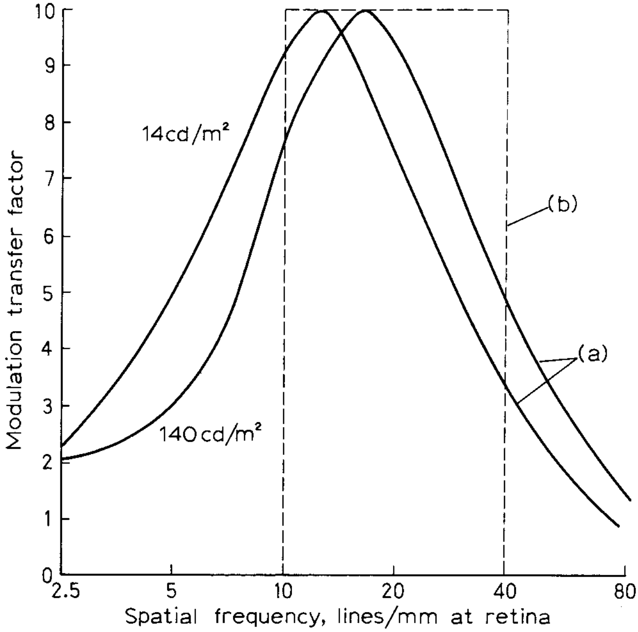

Fig. 10.8. Illustrating the concept of SQF. Curve (a): Typical contrast sensitivity functions for the eye as measured by O. Schade. Curve (b): SQF band as defined by Granger. (Reproduced with permission of the Society of Photographic Scientists and Engineers Inc., as published in Granger and Cupery[44]*. Copyright 1972).*

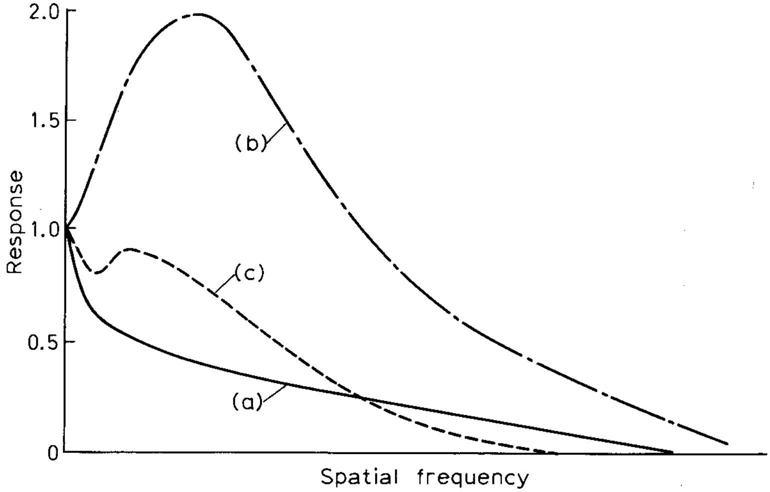

Fig. 10.9. The effect of a combination of halation and strong adjacency effects on low frequency response. Curve (a): halation 'MTF'. Curve (b): strong adjacency MTF. Curve (c): composite response.

adjacency effects and halation, this combination yielding a retinal system MTF with characteristic drop at very low frequencies (Fig. 10.9). There thus appears to be some conflict in terms of correlation with sharpness judgements as to whether it is only the intermediate frequencies in the retinal image, or both the low and intermediate frequencies, which contribute most.

10.3.4 Modulation Detectivity

An alternative approach to the variants on MTFA is that first developed for establishing performance limits for photographic systems by determining the intersection of the lens MTF curve and the threshold detection curve of the photographic emulsion for a given contrast of target,[46] (Fig. 10.10). This has been extended by Brown[47] for use in assessing visual systems. The present author considers such an approach of some use for incoherently coupled situations when viewing periodic object structure, but questions Brown's extension of the concept to visual aids involving direct coupling.

Since it seems inconceivable that any single frequency criterion can be applicable when viewing aperiodic objects (the normal form of visual task), it is not intended to pursue this form of quality factor further in this book.

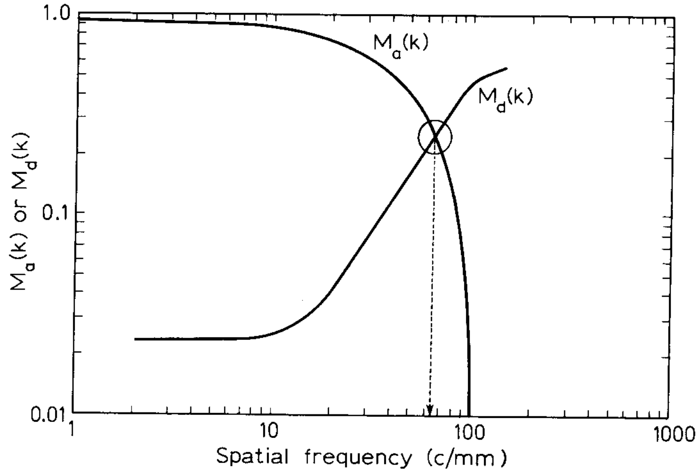

Fig. 10.10. Application of modulation detectability in determining the high contrast 3-bar resolution of a system. $M_a(k)$ = available image modulation. $M_d(k)$ = minimum modulation required for resolution. (Reproduced with permission of the Society of Photographic Scientists and Engineers Inc., as published in Scott[46]. Copyright 1966).

10.3.5 Visual Efficiency

Let us pause at this point to consider the implications of the relationship between OTF and line spread function as expressed in Equation 10.3, the high correlation between the MTFA, the square of the MTFA as applied to the retinal image, CMT acutance and subjective performance as discussed in Sections 10.3.1 and 10.3.2, and the visual modelling discussed in Chapter 7.

If, instead of defining the OTF in terms of the line spread function as in Equation 10.3, we define the spread function in terms of the OTF, then we get

$$G(x) = \frac{1}{\pi} \int_0^\infty F(j\omega) \cdot \exp(-j\omega x) \cdot \mathrm{d}\omega \tag{10.8}$$

Then, from Equation 10.8, the value of the spread function at $x = 0$ will be

$$G(x)_{(x=0)} = \frac{1}{\pi} \int_0^\infty F(j\omega) \cdot \mathrm{d}\omega \tag{10.9}$$

But this is the area under the MTF curve (i.e. approximately the MTFA) for symmetrical functions and is closely related to MTFA and CMT acutance for most situations. Furthermore, since most line spread functions have their central peak at $x = 0$, $G(x)_{(x=0)}$ as defined by Equation 10.9 is usually a very good estimate of the peak of the spread function. But for extended objects this peak value defines the maximum edge gradient, which is the basis of the visual model discussed in Chapter 7 and shown to be an accurate predictor of very many visual *threshold* situations. Thus for the first time we have a direct relationship between visual *threshold* performance and the OTF measured at the retina. With a few refinements it is then possible to propose a figure of merit based on the physical state of the eye which we have chosen to call *visual efficiency* (η_v). The derivation of this function and its application to viewing extended objects have been discussed at length by the author.[48] Basically it is defined as the ratio of the areas under the frequency-weighted retinal MTF curves for a composite visual system and for the naked eye under the same viewing conditions, the weighting being a frequency function accounting for the finite dimensions of the retinal mosaic and involuntary eye movements.

In theory the visual efficiency concept can be applied to imagery at any point on the retina, but in order to apply it in such a way it would be necessary to know in detail both the local quality function for the refraction optics (to use as a reference) and the local effective receptor grouping. Since for many practical purposes one is only interested in quality effects for near-foveal imagery – and in any case such imagery is by its nature the most critical – at present η_v is only considered for foveal imagery. For such imagery the quality factors for the refraction optics are fairly well established (see Section 2.3), whilst the frequency weighting functions for average tremor, drift and receptor spacing are considered to be roughly as shown in Fig. 10.11.

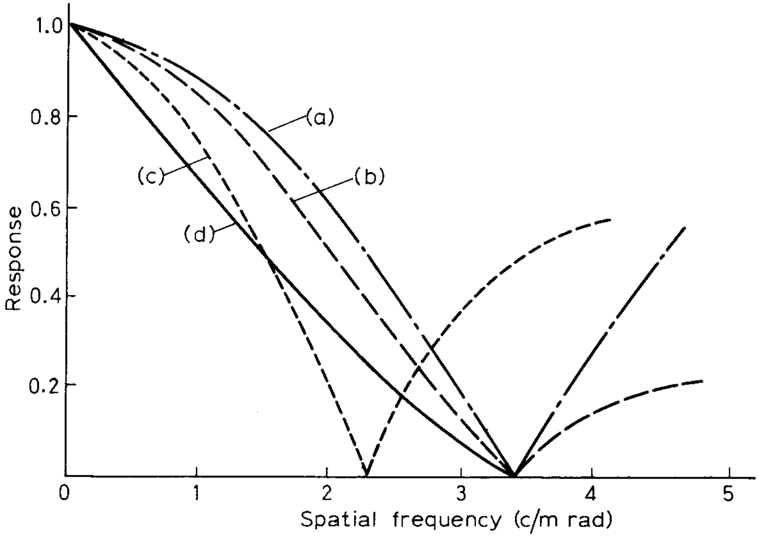

Fig. 10.11. The various frequency weighting functions to be applied in use of η_V. Curve (a): receptor sampling interval (central fovea). Curve (b): intersaccadic drift (0.3 mrads). Curve (c): tremor (±0.15 mrads). Curve (d): 2.5 mm eye pupil diffraction limited performance for comparison. (From Overington[48]).

Since the denominator of the ratio (the area under the weighted MTF for the naked eye) is a variable which is dependent on state of eye accommodation, pupil diameter, etc.,[48,49] it can be seen that the visual efficiency for a given instrumental quality of a visual system is not a constant. This, of course, is a necessary requirement for any visual quality measure if it is to be in any sense universal in application.

Unfortunately the ideal concept that it is only the peak regions of the retinal illuminance gradient which contribute to visual performance (which appears to be implied to be the case for 'sharpness' and 'goodness' judgements from MTFA and CMT acutance) does not apply universally, as illustrated by the results of blurred threshold experiments in which modelling was attempted in Section 7.7. Thus for general application of a quality factor such as visual efficiency to threshold situations it is necessary, in addition, to establish whether the form of blur broadens the central peak of the retinal line spread function sufficiently to cause additional probabilistic contributions to be made to the 'stimulus' from regions adjacent to the ribbon of maximum retinal illuminance gradient (see Section 7.7). In circumstances where such broadening occurs it is presently impractical to consider the idea of one simple single figure of merit, since complex interaction of various frequency responses contained within the MTF appears to be implied.

10.4 VEILING GLARE

All the measures of image quality discussed in Sections 10.2 and 10.3 assume that all the energy from small object detail transmitted by an optical system is utilised in generating the image of that detail. Unfortunately this is frequently not the truth. It is quite usual for some part of the tranmitted energy to be scattered and to fall on parts of the image plane widely removed from the image detail being studied. This has already been discussed in Chapter 9. One established technique is available for measuring this veiling glare – the measurement of 'Veiling Glare Index' (VGI). For several years it has become the practice to measure this VGI by viewing a small black area in the centre of a uniformly illuminated field of a few degrees subtense at the optical system under test (see Fig. 10.12). The exact size of the black area and the illuminated area have depended under what discipline the measurement was undertaken.[50,51] For example, for binoculars it has become the practice to use a 17.5 mrad diameter circular black area in the centre of a 87 mrad diameter illuminated field. Now the amount of veiling glare in the image plane must depend on the extent and form of the illuminated field. Also, since many systems are used in conditions where the illuminated field is very extensive, it seems that the standard VGI's above are not particularly useful in defining the extent of veiling glare in practical use. In an attempt to overcome this difficulty a new British Standard for veiling glare measurement has recently been compiled.[52] This Standard provides for more varied test conditions, and provides guidance for users in selection of the best test conditions for their particular requirements. In this

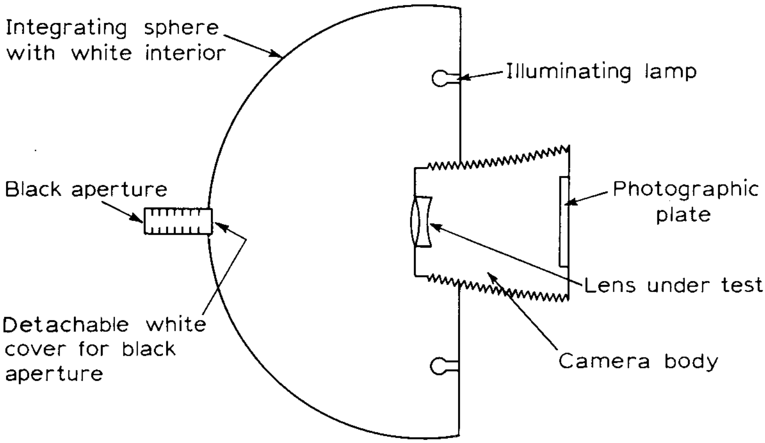

Fig. 10.12. Goldberg's apparatus for the measurement of veiling glare, on which most commonly used systems are based.

Standard is also introduced the concept of a glare spread function, this being the distribution of light in the image plane from any one object point. The SIRA Institute have developed an equipment for measuring this latter function.[5 3]

Whilst veiling glare can be treated as external to the eye for incoherently coupled systems, with directly coupled systems care must be taken to consider the interaction of veiling glare due to the optical aid and that due to the eye itself, since these need not necessarily sum in a scalar fashion. Little information on his aspect has been published to the present author's knowledge.

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