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IMAGE QUALITY METRICS AND APPLICATION OF THE SQUARE ROOT INTEGRAL (SQRI) METRIC: AN OVERVIEW

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13. ABSTRACT (Maximum 200 words)

The purpose of this report was to present an overview of image quality metrics and evaluate the performance of the Modulation Transfer Function Area (MTFA) and the Square Root Integral (SQRI) metrics on displays used at the Air Force Human Resources Laboratory (AFHRL). While the MTFA, as indicated by its name, correlates highly with the display modulation transfer function area, the SQRI, developed by Barten (1987), integrates display luminance, contrast as measured through the modulation transfer function, and resolution into a single measure in a different fashion. The scalar results obtained from the metrics act as an index of image quality for the display device. Results of the analyses showed that (a) image quality metrics lack the ability to incorporate the relative importance of display luminance; (b) the J measure from the SQRI metric emphasizes low spatial frequency information (< 5 cycles/degree) relative to high spatial frequencies; (c) only one of the two measures developed by Barten, the J index, yielded unambiguous results; (d) small variability in the low spatial frequencies of the MTF could cause large changes in the resulting SQRI image quality measure; and (e) the concept of the display modulation depth curve (or display MTF) employed in image quality metrics is ambiguous and requires some form of further standardization. To date, little is known about the manner in which humans combine spatial frequency-based information from displays, and most image quality metrics reflect this lack of knowledge. More basic psychophysical knowledge of these properties is required before image quality metrics will become useful. (KR)

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SUMMARY

This report contains an overview of image quality metrics and an in-depth analysis of two metrics, the Modulation Transfer Function Area (MTFA) and the Square Root Integral (SQRI). These metrics incorporate the display qualities of luminance, contrast, and resolution in determining an overall scalar metric of image quality for individual display devices.

The analytic work consisted of (a) using the MTFA and SQRI metrics to numerically evaluate the static, achromatic image quality of visual displays used at the Air Force Human Resources Laboratory (AFHRL) at Williams Air Force Base, Arizona, and (b) using computer simulation to investigate the effects of manipulating specific parameters dealing with luminance, contrast, and resolution, and observing the results as predicted by the SQRI metric.

Results of the analyses used in the present work show that (a) the SQRI metric heavily emphasizes low spatial frequency information and neglects those factors (e.g., resolution and luminance) which affect high spatial frequencies, (b) use of the J- measure from the SQRI metric for comparing systems with different bandwidths and luminance capabilities can yield erroneous results, (c) the actual sampling process used to obtain an MTF or modulation depth curve for a system has a large effect on the calculated SQRI image quality metrics for low frequencies but not for high frequencies (e.g., >15 Hz), (d) the concept of the MTF or modulation depth curve is ill-defined for use in metrics, and (e) the metrics are unable to capture the importance of overall display luminance to image quality.

Metrics such as the MTFA and the SQRI integrate information in multiple ways along the dimensions of spatial frequency and modulation depth. These metrics must first be associated with an operational definition of image quality, whether it be observer rankings of image quality from displays or accuracy and reaction time results from psychophysical experiments. Currently, there is little psychophysical evidence lending support to any of the methods of integration across these dimensions. More basic psychophysical data are required for further modification of these metrics.

PREFACE

The present effort was conducted in support of Air Force Human Resources Laboratory/Operations Training Division (AFHRL/OT) research concerning image quality. The goal of this effort was to examine display system parameters employed within the context of image quality metrics, for the purpose of predicting static, achromatic display image quality. The project was conducted under Work Unit 1123-03-85, Flying Training Research Support. One of the objectives of this work unit is the development of prediction schemes to determine image quality of display systems. Research support was provided by the University of Dayton Research Institute under Contract No. F33615-90-C-0005. The Contract Monitor was Capt Claire A. Fitzpatrick.

The goal of this specific research effort was (a) to identify important display system parameters necessary for predicting image quality and (b) to analyze current image quality metrics to assess their usefulness in this endeavor.

The author wishes to express thanks to Ms. Marge Keslin for final edit of the manuscript.

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I. INTRODUCTION

Personnel charged with the procurement of display systems for particular tasks typically have a wide range of display choices. Though cost, reliability, compatibility, and portability are important factors in the procurement process, image quality may be crucial to the successful use of the display system. The concept of image quality is quite difficult to define and has traditionally been inferred through performance measures (i.e., accuracy and reaction time on psychophysical tasks) or observer preferences (i.e., rankings or ratings of display systems by observers). These methods are time-consuming and involve a variety of assumptions, as well as performance or preference variability across observers. Metrics based upon physical display characteristics and standard observer characteristics are an alternative to these other methods for determining or ordering the image quality of display systems. The advantage of these metrics is that they are less time-consuming to employ and offer a more standardized form of display system comparison. Hypothetically, one can envision a display metric being included in the specification of a display system in the same manner that cost or reliability factors can be reported.

From the basic psychophysical literature, three important characteristics of visual displays pertinent to image quality are readily discernible: (a) the Modulation Transfer Function (MTF) or some estimate of the ability of display systems to maintain contrast as a function of spatial frequency, (b) the display resolution or number of independent pieces of information the display may present simultaneously, and (c) the display luminance. We begin with the development of an image quality metric based upon display brightness, contrast, and resolution in much the same way that simple models in statistics (e.g., linear regression) may be used for reducing the variability in predicting more complex relationships. Here those more complex relationships in image quality involve color and temporal factors. Thus, although color and temporal factors are also critical to image quality, these two factors are currently beyond the scope of quantitative inquiries into image quality.

The relative importance of brightness, contrast, and resolution may actually vary with the type of system and the task being considered. For example, in flight simulation with wide-field-of-view (WFOV) dome displays, display luminance is on the order of a moonlit night. Asking subjects to compare this type of display with a small, bright cathode ray tube (CRT) may be similar to asking the subject to compare apples with oranges. However, if we ask subjects to perform target identification tasks, the brightness advantage of the small CRT will probably be the most significant factor in determining overall performance.

Multidimensional scaling of preference data is a method which could be used to uncover the relative importance of physical display quantities (e.g., brightness, contrast, and resolution) if the domain of stimuli (display devices and brightness, contrast, and resolution ranges of individual devices) were broad enough to properly sample the space. However, with the limited variety of display devices and ranges available for conducting such a preference rating experiment, the feasibility of this experiment decreases.

The focus of the present report is to consider the importance of individual components in the image quality process. A quantitative method which employs the three display parameters noted above is analyzed in terms of its usefulness in determining the image quality provided by display systems. The Square Root Integral (SQRI) metric developed by Barten (1987) has evolved as a measure of image quality mostly as a trial-and-error method. This measure sums the capability of a display device to present information over spatial frequency bands while weighting the information according to how sensitive the human viewer is in the given frequency range. As an alternative to the SQRI method, the Modulation Transfer Function Area (MTFA), being representative of other metrics, is also introduced as a measure of image quality.

Before introducing these metrics, we will present a short introduction to brightness, contrast, and resolution for display devices.

II. EMPIRICAL MEASURES OF BRIGHTNESS, CONTRAST, AND RESOLUTION

The terms "brightness," "contrast," and "resolution" are ambiguous when applied to displays as all-encompassing display parameters. Brightness refers to the psychological correlate of luminance. Luminance is typically measured in foot-lamberts or candles/m^2 where 3.43 cd/m^2 = 1 foot-lambert and one cd/m^2 is sometimes called a "nit." Luminance is computed by weighting spectral radiation by its efficiency in lumens per watt on the receptor system of interest (i.e., rods or cones) and then integrating the result over the wavelength spectrum (see Figure 1). If we illuminate a screen with 1 lumen/ft^2 and get 100% reflection, the display luminance is equivalent to 1 foot-lambert. Likewise, 70% reflection would result in .7 foot-lambert. Using Figure 1, then, it is straightforward to note that for equal energy amounts of blue, green, and red light, the green light will always be perceived as the brightest when presented foveally (i.e., to the cone system).

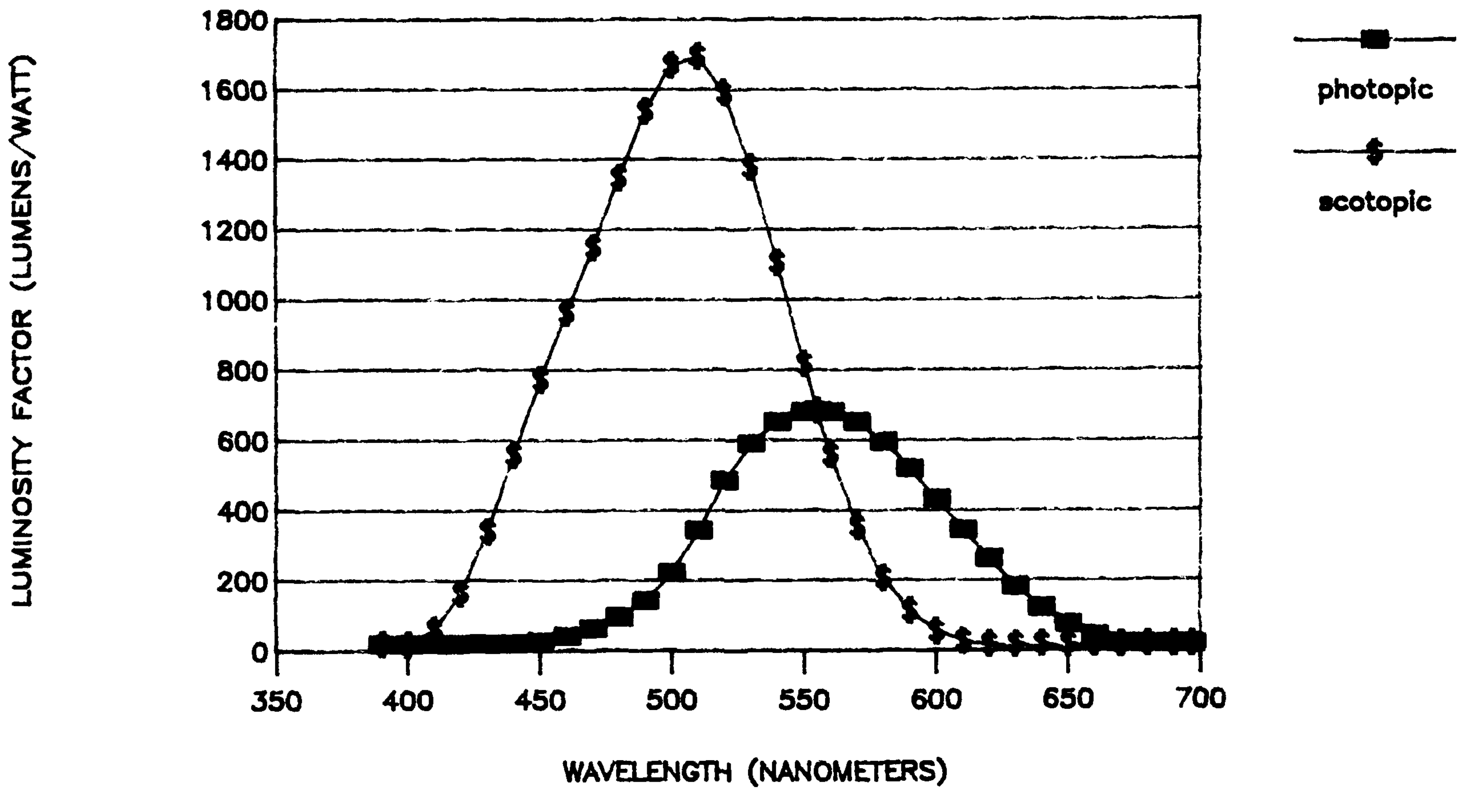

Figure 1. Scotopic (Left) and Photopic (Right) Sensitivity Curves.

Luminance, then, is not a measure of actual physical display energy but a measure of physical energy weighted by its efficiency in terms of the human photoreceptor system. In dealing with actual physical measurements of light, radiometric quantities are used; the term "photometric" applies when radiometric quantities are scaled according to the efficiency of the receptor system. Brightness perception changes with receptor type (rod versus cone). It also varies as a function of retinal eccentricity due to changes in receptor connectivity and summation across the retina.

Brightness correlates well with changes in luminance over small intervals. It is, however, a logarithmic function of luminance over larger ranges of luminance and may change as a function of color and spatial properties within a display. In the present report, we use luminance measurements (i.e., photometric quantities) and assume a direct mapping between luminance and brightness, the psychological correlate.

Contrast may be computed in various ways which do not map directly to one another. Equations 1, 2, and 3 denote the typical ways of computing contrast where L_T represents the target luminance and L_B represents the background luminance.

$$(1) \quad C = \frac{L_T - L_B}{L_B} \qquad (2) \quad C_M = \frac{L_T - L_B}{L_T + L_B} \qquad (3) \quad C = \frac{L_T}{L_B}$$

Equation (1) is a traditional method used by Blackwell (1946) and other researchers, where contrast is defined as the difference between target and background luminances divided by background luminance when the target is brighter than the background. Equation (2), referred to as the Michelson Contrast or the modulation depth, is an alternative used currently by vision researchers regarding the detection of periodic targets (e.g., sine wave gratings). This contrast measure is defined as the difference between the brightest and darkest portions of the target area divided by the sum of the two luminances. For low contrast levels (e.g., .1 or less), the Michelson estimate in Equation (2) can be considered approximately equivalent to Equation (1). Equation (3), the contrast ratio, is defined as the ratio of the target luminance to the background luminance. Mathematically, this contrast measure is equivalent to that derived by Equation (1) plus 1.0. Equations (1) and (3) are prominent in the engineering literature whereas Equation (2) is more often used in psychophysical and physiological research. Display manufacturers measure the bright and dark fields and typically report the contrast ratio as in Equation (3). As will be shown later, these values reported in isolation can be quite misleading for purposes of display systems.

In a particular display, luminance output may not be homogeneous across the display, and the amount of luminance may have an effect on distortion, affecting contrast and noise in the display. For example, Crane, Gerlicher, and Bell (1986) found significant increases in resolution threshold in a Landolt C task for a light valve projector as they increased display luminance from 60 to 100 foot-lamberts (206 to 343 cd/m^2). Display contrast capabilities vary as a function of the luminance level and the detail or spatial frequency of the pattern displayed. In addition, displays such as light valve projectors with higher luminance capabilities may have brighter dark fields, resulting in a reduced contrast capability in some instances. With contrast defined as in Equation (1) or (2), an increase of target and background luminance by a constant (i.e., an increase in the mean luminance level) results in decreased contrast. Visual acuity increases with increasing overall luminance but it also decreases with decreasing contrast. Anytime we increase dark field luminance or mean luminance level in a display system, we may obtain counteracting effects in overall luminance and contrast. The overall effect on visual acuity will then depend upon the specific levels of luminance and contrast, and psychophysical data would be required to predict the level of acuity.

Resolution, for display manufacturer purposes, is typically defined as the number of raster lines in the display or some combination of the raster lines multiplied by the addressability of a single raster line. Theoretically, static display resolution is a measure of the number of independent pieces of resolvable spatial information which may be displayed in a nearly simultaneous fashion per unit of visual angle. For raster display systems, this measure can be a function of the number of raster lines, the vertical spread function between raster lines, the addressability or spatial spread of a pixel or writing element in the horizontal direction along a single raster line, the rise time for a pixel, the width of the raster line, and phosphor masks or other physical elements which filter the visible energy in some fashion. The relationship between vertical and horizontal resolution can be ascertained by photometrically measuring and comparing the spatial spread of a raster line in the vertical direction with the spatial spread of a single pixel in the horizontal direction. Because the number of raster lines per unit of vertical dimension and the number of pixels per unit of horizontal dimension are correlated with the more intricate measures, most manufacturers report only the number of raster lines by the number of pixels per raster line, along with the vertical and horizontal dimensions of the display device.

Altogether, luminance, contrast, and resolution are intricately linked to one another. Resolution, or the ability to distinguish between two adjacent pieces of information along the two-dimensional grid, will be a function of the minimum contrast required to distinguish between the two pieces of information. The required contrast in a psychophysical sense will depend upon the overall luminance in the local area of the display. Totally unrelated to this use of luminance, however, is the fact that the luminance output from the display will have an effect on resolution. The spatial spread function for the luminance profile of individual pixels may change as a function of luminance for the display device. The magnitude of the Fourier transform of the spatial spread function yields the MTF for the display device, and changes in the shape of the spatial spread function will yield different display MTFs. For example, sample MTFs generated for General Electric light valves at AFHRL by George Kelly (personal communication, May 1990) using this Fourier transform method (i.e., the indirect method) showed improvement in the MTF as peak display luminance was increased to the manufacturer's recommended maximum. Alternatively, if we assume the spatial spread function for luminance of a pixel is Gaussian-shaped and we increase the variance of the distribution, the resulting display MTF is lowered or decays more quickly. This type of situation can occur when either hardware components are not properly adjusted or additional components are introduced which degrade the image. Because of these numerous interactions, none of the three parameters of brightness, contrast, and resolution can be stated unambiguously for use in image quality work without consideration of the other two parameters.

III. IMAGE QUALITY METRICS AND COMPONENTS

In order to systematically study image quality and ascertain important factors for static, achromatic imagery, a systems framework is employed. Motion and color are disregarded here in order to simplify the issue. Figure 2 diagrams a systems approach to the study of image quality. The representation of the image, the hardware that captures and displays the image, and the human constitute the three major components in the system. With a static image presented in two dimensions, a two-dimensional spatial frequency representation of display luminance can be used to mathematically capture the information being passed through the system.

Figure 2. Systems Approach to Image Quality.

To date, attention has centered on the static modulation transfer function (MTF) of the display or image-forming system in studying image quality. For display system purposes, a static MTF is a measure of a display's ability to maintain input contrast levels as a function of the spatial frequency of the input wave form. For example, an input to a display system may consist of a one-dimensional luminance-varying sine wave. The maximum and minimum values of luminance (L_{max} and L_{min}) are photometrically measured at the display output, and the modulation depth or Michelson Contrast (Equation (2)) is computed from these two values and plotted as a function of spatial frequency. Figure 3 shows approximated MTF curves (not normalized) from data collected by Howard (1989) for General Electric Single and Multiple Light Valves (SLVs and MLVs) in the vertical and horizontal directions. There are multiple methods of estimating the system MTF, and the method of estimation itself can be quite a large source of variability. Beaton (1988) discusses MTF measurement in greater detail.

The MTF was first associated with Strehl in 1902 (see Chapter 1 of Biberman, 1973), who suggested computing the area under the two-dimensional transfer function or MTF as a measure of image quality. Schade (1973, 1975), though, is generally credited with popularizing the use of the system MTF for describing image quality in television during the 1940s. He defined the upper frequency cutoff of a square wave with unit height and area equal to that of the MTF as a measure of image quality.

While using the MTF, Schade was well aware of nonlinear factors such as time-varying noise, gamma functions relating input voltages to gray-scale levels, spatial non-uniformities, and other effects which tended to degrade the original image (e.g., Vandenberghe, De Clercq, Schaumont, & Bracke, 1990). However, the use of display system MTFs--whether it was the height of the MTF at specific spatial frequencies or the integrated area under the MTF curve--proved beneficial in the understanding and comparison of image quality for display systems.

In terms of Figure 2, display MTF applies only to the display system component. This MTF allows us to report what spatial frequencies can be presented to the viewer. This rather narrow viewpoint neglects the spatial frequency content of the original image and the filtering applied to the signal at the receiver (i.e., the human visual system). Only that information which has passed through this final filter should be considered in the determination of image quality.

Many researchers tend to neglect the spatial frequency representation of the original image. For example, with computer-generated imagery, the construction of the original database model may be the limiting factor in the image quality analysis. Comparison of image quality across display systems can be useful only to the extent that the spatial frequency representation of the original image is considered. For example, if two display systems differ only in their high-frequency cutoff, and the test stimuli are predominantly composed of low spatial frequencies, the probability of obtaining significant performance differences across the two display systems is reduced. Of course, if the task for which the systems are to be used requires only low-resolution work,

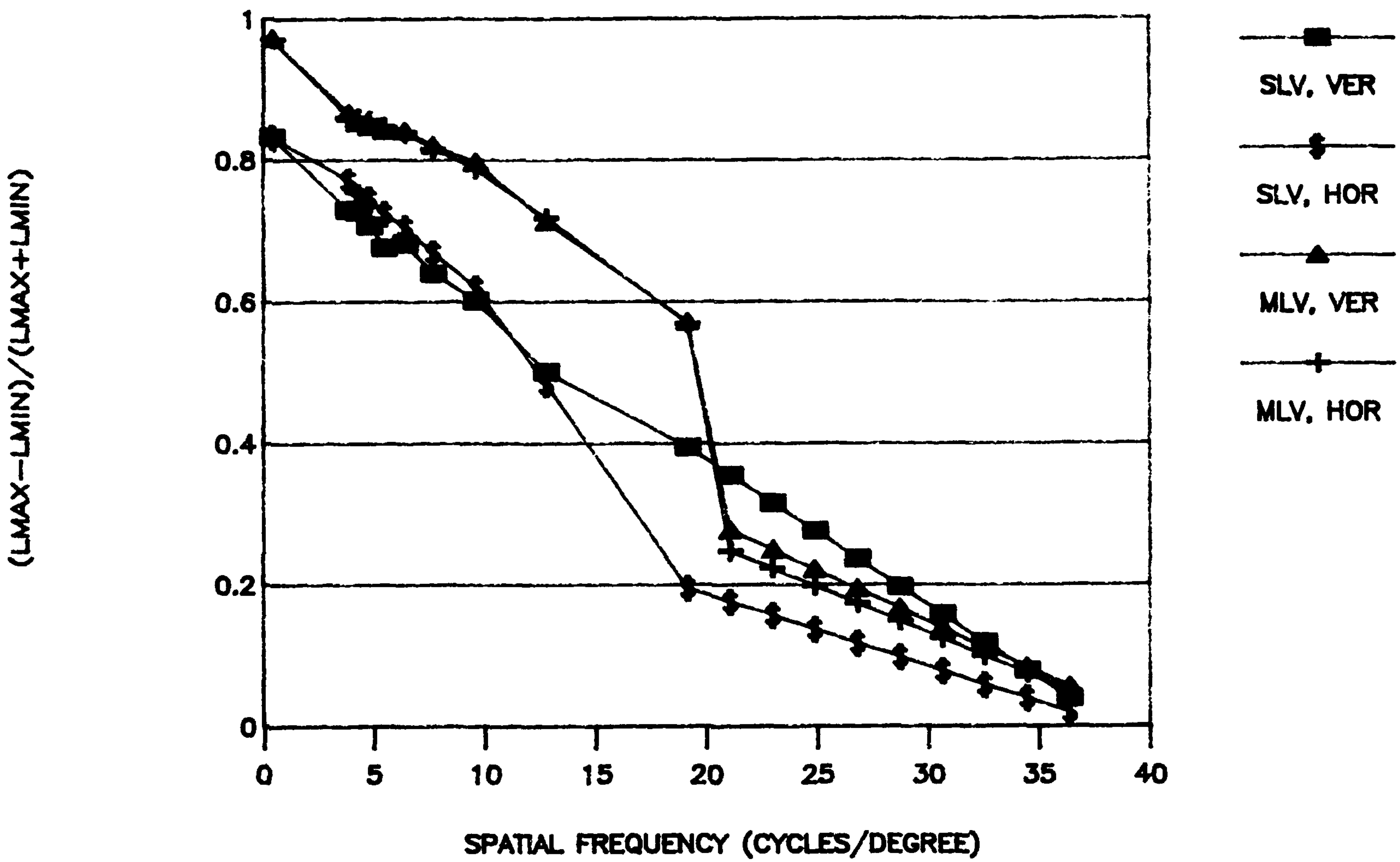

Figure 3. Unnormalized Howard (1989) Single and Multiple Light Valve (SLV & MLV) Modulation Depth Curves in Vertical and Horizontal Directions.

the two display systems should be considered equivalent. This type of situation would require an indexing of display system by task requirements to ascertain the appropriateness of a display for a given situation. Current image quality metrics are not indexed by task requirements. By default, then, it is assumed that the image in Figure 2 contains equally relevant information at all spatial frequencies. The emphasis in our systems approach is then shifted toward the system and the human observer.

With the MTF as an indicator of how well the display system passes spatial frequencies, it is the human component in Figure 2 that determines how the information is filtered from the displayed image. Information not used or not available to the observer should not influence the image quality metric. The human Contrast Sensitivity Function (CSF) is a traditional method used to measure the sensitivity of the visual system to one-dimensional, luminance- and contrast-varying sine waves at various spatial frequencies. The inverse of the CSF at any spatial frequency is the estimated minimum contrast (defined in terms of Equation (2)) necessary to discriminate a one-dimensional, luminance-varying sinusoidal waveform from a homogeneous field.

For the prediction of luminance-dependent CSFs, Van Meeteren (1972) reported an equation of the following general form:

$$CSF(u) = (A)(u)e^{(-Bu)}(1+(c)\exp^{(Bu)})^{1/2} \qquad (4)$$

where $A = \dfrac{440}{(1 + .7/L)^{.2}}$, $B = .3(1 + 100/L)^{.15}$, $C = .06$,

L denotes average display luminance in candles/m^2, and u denotes spatial frequency in cycles/degree. Figure 4 shows two luminance-dependent CSF curves generated from Van Meeteren's approximation. The inverse of each of these curves is referred to as the modulation threshold curve and denotes the minimum detectable contrast required to detect the presence of a luminance-modulated sinusoidal waveform. The contrast measure used here is the Michelson Contrast, as defined in Equation (2).

When plotted together, the horizontal display system MTF (i.e., luminance modulation across a raster line) and the inverse of the CSF appear as in Figure 5. In Figure 5, modulation threshold curves are presented for display luminances of 10 cd/m^2 and 100 cd/m^2. These luminance values correspond to brightnesses found with large dome display systems and small CRTs, respectively.

From Figure 5, two pieces of information are readily apparent. First, there exists a crossover frequency, f_c, above which the modulation from the display device is below threshold for viewing. Thus, any spatial frequencies from the image that are higher than f_c are assumed to be lost to the observer. For an average display luminance of 10 cd/m^2, f_c is approximately 25 cycles/degree, as

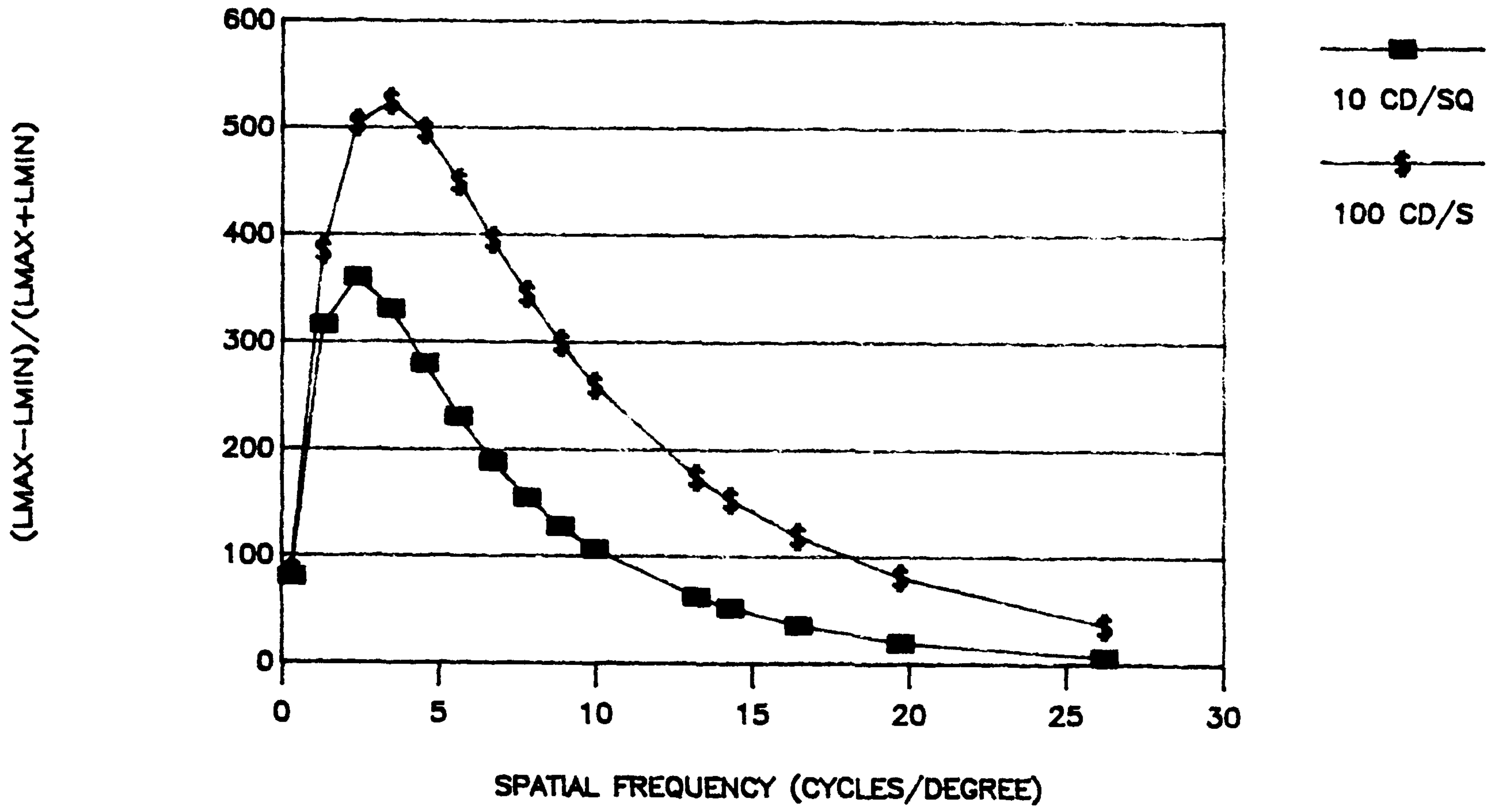

Figure 4. Van Meeteren Contrast Sensitivity Curves for 10 and 100 cd/m^2 Average Luminance.

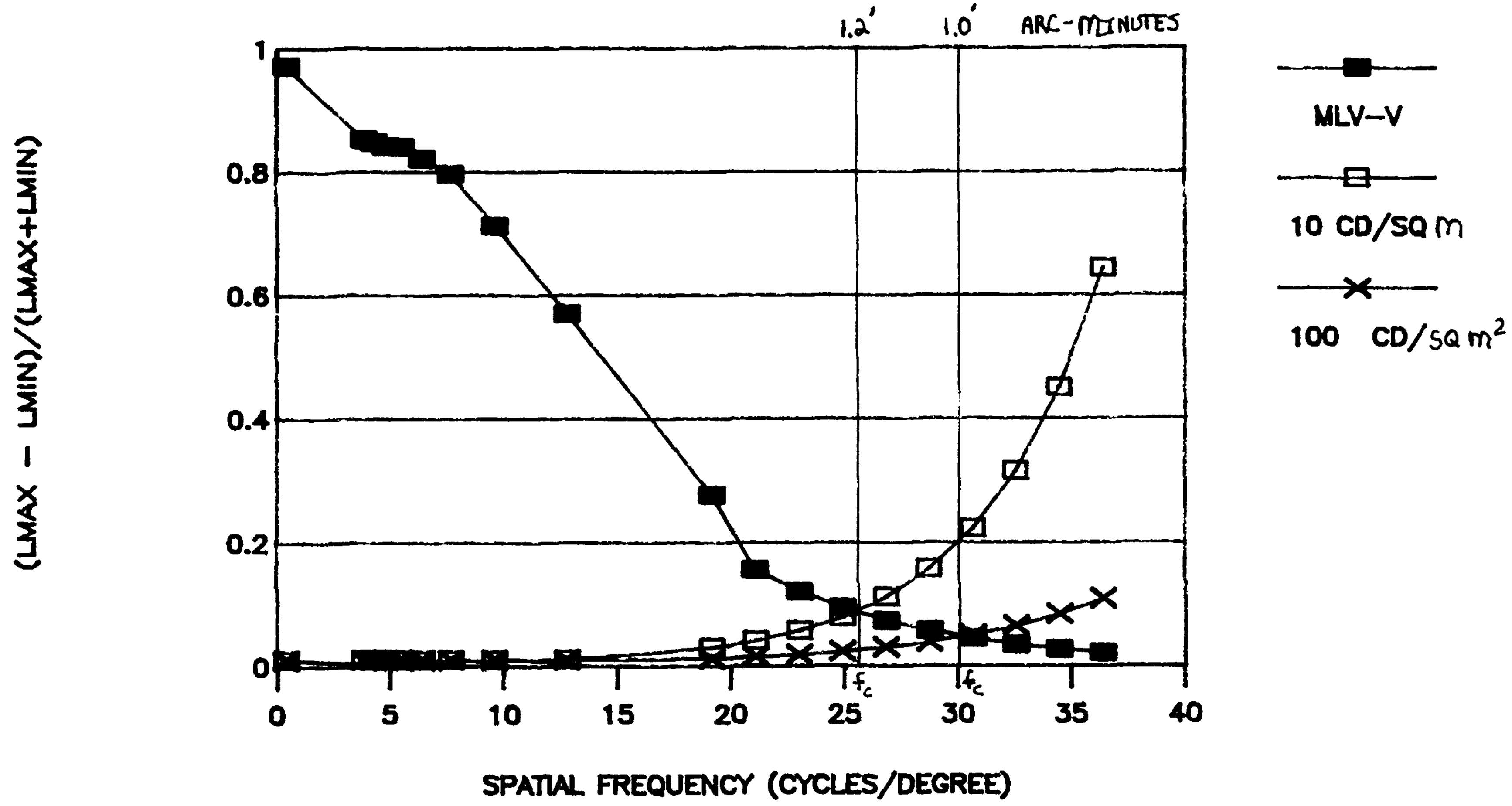

Figure 5. Display Modulation Depth Curve and Observer Modulation Thresholds for 10 and 100 cd/m^2.

shown by Figure 5. This corresponds to a target size of about 1.2 arc-minutes and indicates that a periodic target must subtend about 1.2 arc-minutes of vertical arc in order to be detectable on the MLV. For a luminance of 100 cd/m^2, f_c is approximately 30 cycles/degree of visual angle. This corresponds to a target subtending approximately 1 arc-minute of visual angle.

For all frequencies less than f_c, there is an area within the graph which is below the system MTF curve but above the observer threshold curve. It is variations of this area which are of interest in image quality research. The Modulation Transfer Function Area (MTFA) is an image quality metric which computes this area. Mathematically, it is defined as:

$$\text{(5)} \qquad \text{MTFA} = \int_0^{f_c} (\text{MTF}(u) - \text{CSF}(u)^{-1})\, du.$$

The MTFA is discussed more thoroughly by Snyder (1974, 1985). As Figure 5 shows, if we subtract the observer threshold modulation from the display modulation at each spatial frequency, the result will be approximately the display modulation until spatial frequency approaches f_c. For example, at a luminance of 10 cd/m^2, the display modulation depth is approximately .1 at f_c. In this instance, the difference between the integrated MTF and the MTFA is about .5. As luminance levels decrease, f_c decreases. Thus, for very low luminance levels, such as those found in large dome simulators (e.g., 1 cd/m^2), the modulation threshold curve cuts off a significant amount of the tail of the display modulation depth curve, yielding a more significant reduction of image quality as seen through the MTFA. Intuitively, this result makes sense, in that we know brightness is closely tied to the perception of image quality.

A theoretical matter of interest is how the human visual system and brain treat the spatially based information they receive. For example, as spatial frequency (u in Equation (5) above) increases, does the importance of spatially based information increase, decrease, or remain the same? In the MTFA, all frequencies between 0 and f_c are treated equally by the integration. Other metrics, such as Barten's Square Root Integral (SQRI) metric (Barten, 1987), decrease the contribution of spatial frequency to the metric as spatial frequency increases. If the decision is made to decrease the importance of higher spatial frequency information, the rate of decrease across spatial frequency becomes important.

Alternatively, the use of recognition and identification performance in experiments places emphasis on high spatial frequency content in the final image. If these experiments are to be indicators of image quality, it might be true that high frequencies below f_c should be weighted more heavily than low frequencies. Typically, if the MTF of one display dominates or has greater modulation depth than the MTF of another display in the high-frequency range, it will dominate at low frequencies. If our image quality metric depends only on low spatial frequencies, the metric may prove to be a good indicator of image quality only because the modulation depth at low spatial frequencies correlates well with modulation depth at high spatial frequencies. Traditional displays, such as CRTs, are associated with well-behaved MTF curves where the modulation depth at high frequencies may be predicted from the modulation depth at lower frequencies. Metrics predicting image quality based upon low spatial frequencies alone will generally perform well in these instances. However, when two display MTFs cross over at a mid- to high-level frequency and the metric's prediction is based on only low spatial frequency information, the metric may be in error because it is disregarding the high spatial frequency information.

One model of image quality does weight the contribution along the spatial frequency axis based on assumptions about the human visual system. Psychophysical studies involving detection of sinusoidal gratings have led researchers to postulate the existence of seven bandpass filters in the visual hierarchy. Carlson and Cohen (1980) performed experiments aimed at identifying just noticeable differences (jnd's) in contrast changes for sinusoidal waveforms at each of the postulated frequencies. At each spatial frequency, contrast is increased until the increase is just noticeable on 75% of the trials. This new contrast is noted as being 1 jnd from the baseline. The new contrast is then designated as the baseline, and contrast is increased again until another jnd occurs. At each of the spatial frequency bands, a number of jnd contrast values have been designated, beginning at the contrast threshold. The number of jnd's occurring under the display MTF for all of the bands represents the image quality metric for the display device. Carlson (1988) presents a diagram of the seven postulated filters centered at .5, 1.5, 3.0, 6.0, 12.0, 24.0, and 48.0 cycles/degree. The Carlson and Cohen jnd method also weights lower spatial frequencies more heavily because there are more jnd's at the lower spatial frequency bands.

The weighting of the y-axis (modulation depth) is of as much concern as the weighting along the spatial frequency axis. In the MTFA, the height of the detection threshold curve is subtracted from the height of the display system MTF, implying a constant weighting across contrast in the y-direction. Other metrics, such as van Meeteren's (1973) Integrated Contrast Sensitivity and Barten's SQRI metric (1987) employ equations involving the ratio of the height of the display MTF to the detection threshold curve.

Intuitively, for performance experiments, it would be expected that the height of the display MTF above the threshold curve would decrease in importance as the difference increases. This observation typically holds true regardless of whether the variable of interest is modulation depth, luminance, contrast, or resolution. Psychological responses to many physical stimuli are logarithmic in shape. Therefore, the contribution to the metric should be a negatively accelerated function of the difference in the heights of the two curves. If we use the ratio of the heights of the two curves, as opposed to the difference, a different characterization of the function is required. Here, the modulation threshold curve may be considered as a weighting of the display MTF at each spatial frequency. Therefore, at spatial frequencies where the detection threshold is quite low or good, the importance of the display MTF to the image quality metric is decreased. Likewise, at spatial frequencies where the observer modulation threshold is high, the display MTF will weigh more heavily in its contribution to the image quality metric. Conceptually, it is not clear why one would want to weight the display MTF in this manner (i.e., increasing the importance of the display MTF at spatial frequencies where the observer threshold is high).

In order to de-emphasize large differences between the MTF and the modulation threshold across spatial frequency, the difference or the ratio of the display MTF to the observer modulation threshold may be taken to a power less than 1. Barten (1987), for example, used the square root of the ratio (SQRI Method), which provides a negatively accelerated function of the ratio of the display MTF to the inverse CSF.

The concepts of display luminance, contrast, and resolution capabilities presented here denote basic questions about how these physical quantities from displays are used by the human visual system to perform visual tasks. The answers to these questions will be revealed only through psychophysical experimentation. Although there is still much doubt about how the human visual system combines the physical information, individual metrics can be analyzed to identify how these physical display parameters are combined within them. The next section provides a more thorough investigation of the SQRI method for this purpose.

IV. EVALUATION OF THE SQRI METHOD AS AN IMAGE QUALITY MEASURE FOR DISPLAY SYSTEMS

The SQRI method (Barten, 1987) has been suggested as a measure of image quality for display systems. This method incorporates both the Modulation Transfer Function (MTF) of the system of interest and the Contrast Sensitivity Function (CSF) of the observer for a specified level of display luminance within a single function to arrive at a measure of image quality. In this section, results are presented which (a) validate the output metric produced by the SQRI method by logically varying the input, and (b) evaluate the SQRI and the MTFA metrics using sample MTF data obtained from Ericksen (1984) and Howard (1989). Estimated MTF data in Ericksen's report were obtained from three display systems: a monochrome light valve, a color light valve, and a CRT. Estimated modulation depth or MTF data in Howard's report were obtained from two projection systems, the General Electric Single and Multiple Light Valves, currently being used on the Advanced Visual Technology System (AVTS) at the Air Force Human Resources Laboratory (AFHRL), Williams AFB, Arizona. Use of the empirically sampled data as well as the simulated data, provides greater insight into the usefulness of the SQRI method.

Barten (1987) suggests two forms for the SQRI measure, J and J-. These measures are computed as follows:

$$(6) \qquad J = \frac{1}{\ln 2} \int_{0}^{u_{max}} (\mathrm{MTF}(u) \times \mathrm{CSF}(u))^{1/2} \frac{du}{u}$$

and

$$(7) \qquad J- = \frac{1}{\ln 2} \int_{0}^{u_{max}} (\mathrm{MTF}(u)^{1/2} - 1) \times \mathrm{CSF}(u)^{1/2} \frac{du}{u}.$$

In Equations (6) and (7), u represents spatial frequency (typically in cycles per degree of visual angle), u_{max} represents the maximum spatial frequency obtainable with the display system, MTF(u) represents the modulation transfer function at spatial frequency u, and CSF(u) represents the contrast sensitivity function at spatial frequency u.

Both equations (6) and (7) contain the factor du/u. This is equivalent to integrating the product inside the integral by the natural log of the spatial frequency, u, or dln(u). The effect of using the natural log of spatial frequency as the variable of integration results in a decrease in weighting of the inner product as spatial frequency increases. This type of integration places extreme emphasis on the value of the integrand between spatial frequencies of 0 and 1 cycle/degree. The effect of this extreme emphasis will be shown later in this report. The premultiplier in Equations (6) and (7), 1/ln2, was chosen for mathematical tractability. If the MTF is identical to the inverse CSF over a spatial frequency channel (defined as one log unit of frequency) and zero across all other channels, then 1/ln2 as a premultiplier yields J = 1. Barten (1987) assumes that a one-unit change in either J or J- is equivalent to a just noticeable difference (jnd) where a jnd is defined as a 75% correct response rate in a two-alternative, forced-choice experiment. The fact that the display device passes no more information at a given frequency than the threshold for a subject means that the subject would be guessing on each trial. If we assume that the threshold is an average that is surpassed on 50% of the trials, then the response would consist of pure guessing on 50% of the trials and be correct 100% of the time on the other 50% of the trials, yielding 75% accuracy overall.

Realistically, it is difficult to interpret the resulting value of J or J-, noted as the number of jnd's. Carlson and Cohen (1980) considered a 1-jnd change to be practically insignificant, a 3-jnd change to be significant, and a 10-jnd change to be substantial. In addition, they noted that J- = -4 for a display device could be taken as a requirement for good resolution.

In Barten's (1987) paper, the data fitting of his measures to experimentally obtained data was quite limited. All of the experimentally obtained data considered only the amount of change necessary to obtain 1 jnd from subjects. That is, at a given level of the physical parameter (e.g., bandwidth, focus voltage), the amount of change necessary to elicit a response of "different" from the subject was measured. The fact that the SQRI method fit the data profile for 1 jnd does not imply much concerning the appropriateness of the model at higher jnd levels. Without further testing, it would be appropriate to employ the metric only as an ordinal measure of image quality. This allows us to order the quality of displays, but not, for example, to specify that the image quality difference between systems A and B is equal to the difference between systems C and D (where systems A, B, C, and D are any four display systems of interest).

In Equation (6), the MTF of a display system is weighted by the observer CSF. Therefore, at spatial frequencies where contrast sensitivity is very high, the equation places greater importance on the amount of modulation the display device is capable of at that spatial frequency. The full integrand in Equation (6) is:

$$(MTF(u) \times CSF(u))^{1/2}.$$

If we take the natural log of this value, the result is:

$$1/2(\ln(MTF(u)) + \ln(CSF(u))) = 1/2(\ln(MTF(u)) - \ln(CSF(u)^{-1})).$$

Because the logarithm of a number is monotonically related to the number itself, the result above correlates well with the integrand in the MTFA (which is simply the $MTF - CSF^{-1}$). In the MTFA, the spatial frequency axis is weighted in a linear fashion though, as opposed to the natural log weighting of the spatial frequency axis in the SQRI. Thus, although the integrands of the two metrics are highly correlated, the different units of integration (logarithmic for the SQRI and linear for the MTFA) can produce significantly different orderings of image quality across display systems.

Equation (7) is a small modification of Equation (6) in that a value of 1 is subtracted from the MTF in the numerator of the integrand. The relationship between J and J- can then be shown to be:

$$(8)\quad J- = J - (1/\ln(2)) \int_0^{u_{max}} CSF(u)^{1/2} \frac{du}{u} = J - J_{max}.$$

As indicated, the factor subtracted from J in Equation (8) is the J value for an ideal display device, where an ideal display device is defined as having an MTF of 1 for all spatial frequencies below u_{max}. By subtracting the maximum or ideal J value from the observed J for a specific display device, a new measure is created, J-, which has a maximum value of zero. In addition, the integrand of Equation (7) evaluated at a spatial frequency of zero is zero, whereas the integrand of Equation (6) evaluated at a spatial frequency of zero is 1.0. The purpose of making the revisions from Equation (6) to Equation (7) was to create a function J- with a maximum value of zero (denoting an ideal display device). Equation (7) is also easier to numerically integrate at frequencies near zero due to the fact that the integrand is close to zero at low spatial frequencies. As will be shown, though, the subtraction correction in Equation (7) will lead to intuitively contradictory results when comparing display devices with, for example, different u_{max} values.

Fortran programs were written to compute values of J and J- from Equations (6) and (7). These two quantities represent the unidimensional image quality metric produced by the SQRI method. The mathematical formulation for the human CSF required in Equations (6) and (7) is given in Equation (4). The system MTF, also needed as input to the algorithm, could be provided through either:

(a) an input table which lists spatial frequencies and corresponding luminance contrast values obtained for these spatial frequencies (i.e., sampling points for the MTF)

or

(b) use of Equation 19 in Barten (1987), which approximates the modulation transfer function with the equation $MTF(u) = \exp(-(3.14 \times d \times u)^2/12)$, where u is spatial frequency in, for example, cycles/degree of visual angle and d denotes the 5% width of the diameter of electron gun spot or the diameter containing 95% of the energy.

Sample MTF data points resulting from (a), the tabular method, represent data which would be collected empirically using photometric equipment. Here square or sinusoid waveforms of specific spatial frequencies would be used as input to the display device. The photometric equipment would be used to measure output modulation depth, defined in Equation (2), for a wide range of spatial frequencies.

A series of these measurements (normalized by the modulation depth at zero frequency) would constitute a table of sample MTF values for the range of frequencies. As will be shown later, though, normalization of the modulation depth is problematic and leads to ambiguous results in many instances of display system comparison.

Programs using data which approximate the system MTF mathematically (i.e., type (b)) were designed such that user input consisted of:

(a) the 5% spot size;
(b) the height of the screen divided by the number of raster lines or an approximate vertical pixel size or diameter;
(c) the viewing distance; and
(d) the number of raster lines per display height.

Given the parameters above, screen height is simply the number of raster lines multiplied by (b) above. Also note that (a) will normally be larger than (c) in order to sufficiently blur the raster lines--unless we want to see a distinct raster effect.

The first step in the validation process was to verify the numerical correctness of the computer algorithms written to handle the empirically sampled MTF data from (a) and the mathematically estimated MTF functions from (b). First, sample runs of (b) were made to compare the output for J- (i.e., Equation (7)) taken from Figures 13 and 14 of Barten (1987) with computations from the computer algorithm. Output from these two runs is shown in Examples 1 and 2 below. For Examples 1 and 2, the input parameters and computed J- and J values were as follows:

Parameter	Example 1	Example 2
5% spot size	1 mm	.5 mm
pixel size	.3 mm	.5 mm
# of raster lines	400	400
viewing distance	500 mm	500 mm
J-	-10.83	-1.47
J	122.39	121.05

The J- values estimated from the program were indistinguishable from the graph values plotted in Figures 13 and 14 of Barten (1987) for the input parameters supplied. From these fits, we determined that the numerical integration techniques employed in the software provided reasonable estimations of J-. Estimating J through numerical integration techniques was a more difficult task. The Contrast Sensitivity Function shown in Equation (5) has a large derivative at low spatial frequencies, making it difficult to integrate numerically. In addition, division by spatial frequency, u, also makes Equations (6) and (7) difficult to integrate numerically at low frequencies. In the numerator of the J- measure, a value of 1.0 is subtracted from the square root of the MTF. The result is approximately zero for low frequencies, which makes the J- measure much easier to integrate numerically for low frequencies. In contrast, the numerator of the J measure contains the square root of the MTF. This is approximately 1.0 at low frequencies so that the remainder of the integrand, the CSF divided by u (the spatial frequency), must be dealt with in the numerical integration. Although step size in the numerical integration of J- could be quite large (du=.5 or 1.0) without any adverse effects on the stability of the integration, it was necessary to make the step size quite small at low spatial frequencies (du=.01) to stabilize the estimate of J.

To validate the algorithm written for data of type (a), empirically sampled MTF data points (i.e., the sample MTF data obtained from Ericksen, 1984) were employed. These data were input to the algorithm written for (a), and a J- value was obtained. Then sample input parameters were tried until an MTF simulated from the equation in (b) could be estimated which approximated (by simple viewing) the MTF data obtained from the report. Their J-values were within one unit (i.e., a jnd) of each other. From this it was concluded that the algorithm designed for input from (a), the tabular MTF form, was acceptable.

The next step in evaluating the SQRI method was to incorporate MTF data from actual display devices previously used with AFHRL's Advanced Simulator for Pilot Training (ASPT). MTF data were obtained from Ericksen (1984) for the following display devices:

(1) Thomas Electronics 36" CRT
(2) GE Color LV Projector, Model PJ5155C1
(3) GE Monochrome LV Projector, Model PJ7155C1

The three displays were run at 1024 lines by 1000 pixels/line, and projector display size was set to equal the 36" CRT. However, the CRT was capable of raster rates of 2000 lines, whereas the projectors had virtually no resolution at display rates of 1024 lines in the vertical dimension. Projections of the CRT were made through (a) the CRT alone and (b) the pancake window. Projections of devices (2) and (3) were through (a) the pancake window, (b) a front-projection screen, and (c) a rear-projection screen. For the purposes of this report, the following MTFs were employed to compute SQRI measures:

(1) monochrome light valve, front-screen projection, vertical MTF (Tables 1a and 1b);
(2) color light valve, front-screen projection, vertical MTF (Tables 2a and 2b);

(3) Thomas CRT at the CRT face, vertical MTF-sample 1 (Tables 3a and 3b);
(4) Thomas CRT at the CRT face, vertical MTF-sample 2 (Tables 4a and 4b);
(5) monochrome light valve, pancake window, vertical MTF (Tables 6a and 6b); and
(6) color light valve, pancake window, vertical MTF (Tables 5a and 5b).

Luminance output capabilities of these six devices vary greatly. In the computation of J and J-, luminance has an effect only through the CSF, as noted in Equation (5). However, increases in luminance have opposite effects on the two SQRI equations. That is, an increase in luminance increases the CSF at all spatial frequencies. An increase in the CSF, however, will increase J from Equation (6) but it will decrease J- in Equation (7). This inconsistency is certainly one aspect of the SQRI method which must be taken into consideration. Realistically, image quality should be an inverted u-shaped function of display luminance such that increases in display luminance would provide better image quality up to a point, and then the image quality would grow increasingly worse. This effect would be an interaction between the improvement in human visual system performance with increasing display luminance and the decrement in display system capability as the system becomes overdriven. In Equation (6), the luminance-dependent CSF will mimic the improvement in human performance with increasing display luminance. The display system MTF would improve and then eventually deteriorate as a function of increasing luminance. For most display systems, however, a single MTF measured at a single value of L_{max} (the maximum luminance) will be reported. The value of L_{max} will not be given, and we have little knowledge of how the MTF will change with changes in L_{max}. This is a major shortcoming in determining and comparing image quality between systems as a function of display luminance, contrast, and resolution.

Tables 1 through 6 (a and b) show the results of using the SQRI Method on the six displays listed previously. Tables 1-6a show SQRI analysis of unnormalized MTF data for the respective devices. Tables 1-6b show SQRI analysis of normalized MTF data for the respective devices. The left-most column in each table denotes a spatial frequency; the next two columns denote the system MTF and the human CSF for that spatial frequency. The last two columns denote partial integrations of J- and J to the spatial frequency listed in the next row. For example, in Column 1 of Table 1a the spatial frequency given in the first row is .0000 cycles/degree. The J- contribution (Column 4) of the spatial band between 0 and 2.6180 cycles/degree is -3.562. Similarly, the contribution to J- from 0 to 10.4719 cycles/degree appears in the fourth row (Column 4) as -7.162.

Table 1a. SQRI Computation for Monochrome GE Light Valve Displayed on a Front-Projection Screen (Vertical MTF)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.9200	.0000	-.3562E+01	.7692E+02
2.6180	.9000	543.2265	-.4930E+01	.9902E+02
5.2359	.8700	515.8671	-.6050E+01	.1104E+03
7.8539	.7800	389.8523	-.7162E+01	.1169E+03
10.4719	.6700	283.2145	-.8332E+01	.1208E+03
13.0898	.5000	208.3650	-.9569E+01	.1231E+03
15.7078	.3400	155.7946	-.1078E+02	.1244E+03
18.3258	.2200	117.1211	-.1190E+02	.1253E+03
20.9437	.1400	87.7464	-.1289E+02	.1258E+03
23.5617	.0800	65.2416	-.1375E+02	.1260E+03
26.1797	.0400	48.0885	-.1450E+02	.1262E+03
28.7976	.0100	35.1496	-.1514E+02	.1262E+03
31.4156	.0000	25.4987	-.1568E+02	.1262E+03
34.0336	.0000	18.3752	-.1610E+02	.1262E+03
36.6515	.0000	13.1654	-.1643E+02	.1262E+03
39.2695	.0000	9.3852	-.1670E+02	.1262E+03
41.8875	.0000	6.6608	-.1690E+02	.1262E+03
44.5054	.0000	4.7089	-.1707E+02	.1262E+03
47.1234	.0000	3.3175	-.1730E+02	.1262E+03
52.3593	.0000	1.6319	-.1734E+02	.1262E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 360.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -17.34382 126.22320

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 1b. SQRI Computation for Monochrome GE Light Valve Displayed on a Front-Projection Screen (Vertical MTF; MTF Normalized)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	1.0000	.0000	-.2868E+00	.8020E+02
2.6180	.9783	543.2265	-.7145E+00	.1032E+03
5.2359	.9457	515.8671	-.1350E+01	.1151E+03
7.8539	.8478	389.8523	-.2186E+01	.1219E+03
10.4719	.7283	283.2145	-.3191E+01	.1259E+03
13.0898	.5435	208.3650	-.4330E+01	.1283E+03
15.7078	.3696	155.7946	-.5487E+01	.1297E+03
18.3258	.2391	117.1211	-.6569E+01	.1306E+03
20.9437	.1522	87.7464	-.7537E+01	.1311E+03
23.5617	.0870	65.2416	-.8386E+01	.1314E+03
26.1797	.0435	48.0885	-.9125E+01	.1315E+03
28.7976	.0109	35.1496	-.9766E+01	.1316E+03
31.4156	.0000	25.4987	-.1030E+02	.1316E+03
34.0336	.0000	18.3752	-.1073E+02	.1316E+03
36.6515	.0000	13.1654	-.1106E+02	.1316E+03
39.2695	.0000	9.3852	-.1132E+02	.1316E+03
41.8875	.0000	6.6608	-.1153E+02	.1316E+03
44.5054	.0000	4.7089	-.1169E+02	.1316E+03
47.1234	.0000	3.3175	-.1193E+02	.1316E+03
52.3593	.0000	1.6319	-.1197E+02	.1316E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 360.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -11.97023 131.59670

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 2a. SQRI Computation for Color Light Valve Displayed on a Front-Projection Screen (Vertical MTF)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.9400	.0000	-.2711E+01	.7742E+02
2.6180	.9200	529.3782	-.3705E+01	.9947E+02
5.2359	.9100	491.6848	-.4323E+01	.1110E+03
7.8539	.8900	365.4897	-.4793E+01	.1179E+03
10.4719	.8600	262.7811	-.5206E+01	.1223E+03
13.0898	.8100	191.9336	-.5609E+01	.1253E+03
15.7078	.7400	142.3979	-.6013E+01	.1274E+03
18.3258	.6550	106.0217	-.6418E+01	.1288E+03
20.9437	.5600	78.5388	-.6821E+01	.1298E+03
23.5617	.4500	57.6795	-.7220E+01	.1305E+03
26.1797	.3300	41.9691	-.7607E+01	.1309E+03
28.7976	.2300	30.2739	-.7973E+01	.1312E+03
31.4156	.1300	21.6701	-.8307E+01	.1313E+03
34.0336	.0800	15.4077	-.8598E+01	.1314E+03
36.6515	.0400	10.8915	-.8848E+01	.1315E+03
39.2695	.0200	7.6601	-.9062E+01	.1315E+03
41.8875	.0000	5.3636	-.9247E+01	.1315E+03
44.5054	.0000	3.7409	-.9393E+01	.1315E+03
47.1234	.0000	2.6002	-.9508E+01	.1315E+03
49.7414	.0000	1.8017	-.9599E+01	.1315E+03
52.3593	.0000	1.2450	-.9636E+01	.1315E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 170.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -9.63553 131.51180

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 2b. SQRI Computation for Color Light Valve Displayed on a Front-Projection Screen (Vertical MTF; MTF Normalized)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	1.0000	.0000	-.2785E+00	.7985E+02
2.6180	.9787	529.3782	-.5796E+00	.1026E+03
5.2359	.9681	491.6848	-.8351E+00	.1145E+03
7.8539	.9468	365.4897	-.1089E+01	.1216E+03
10.4719	.9149	262.7811	-.1363E+01	.1262E+03
13.0898	.8617	191.9336	-.1671E+01	.1292E+03
15.7078	.7872	142.3979	-.2011E+01	.1314E+03
18.3258	.6968	106.0217	-.2371E+01	.1329E+03
20.9437	.5957	78.5388	-.2742E+01	.1339E+03
23.5617	.4787	57.6795	-.3121E+01	.1346E+03
26.1797	.3511	41.9691	-.3494E+01	.1350E+03
28.7976	.2447	30.2739	-.3851E+01	.1353E+03
31.4156	.1383	21.6701	-.4180E+01	.1355E+03
34.0336	.0851	15.4077	-.4468E+01	.1356E+03
36.6515	.0426	10.8915	-.4716E+01	.1356E+03
39.2695	.0213	7.6601	-.4929E+01	.1356E+03
41.8875	.0000	5.3636	-.5115E+01	.1356E+03
44.5054	.0000	3.7409	-.5261E+01	.1356E+03
47.1234	.0000	2.6002	-.5376E+01	.1356E+03
49.7414	.0000	1.8017	-.5467E+01	.1356E+03
52.3593	.0000	1.2450	-.5503E+01	.1356E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 170.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -5.50326 135.64400

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 3a. SQRI Computation for Thomas 36" CRT Displayed at the CRT Face (Vertical MTF; Sample Number 1)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.8800	.0000	-.6290E+01	.9530E+02
5.2359	.8800	536.8716	-.7568E+01	.1147E+03
10.4719	.8800	301.6370	-.8139E+01	.1230E+03
15.7078	.8700	167.9954	-.8468E+01	.1274E+03
20.9437	.8600	96.2192	-.8676E+01	.1299E+03
26.1797	.8500	53.8314	-.8810E+01	.1315E+03
31.4156	.8400	29.1766	-.8902E+01	.1324E+03
36.6515	.8200	15.4036	-.8966E+01	.1330E+03
41.8875	.8000	7.9694	-.9013E+01	.1334E+03
47.1234	.7700	4.0591	-.9046E+01	.1336E+03
52.3593	.7500	2.0419	-.9070E+01	.1337E+03
57.5953	.7200	1.0169	-.9087E+01	.1338E+03
62.8312	.6800	.5023	-.9100E+01	.1339E+03
68.0671	.6300	.2463	-.9110E+01	.1339E+03
73.3031	.5500	.1201	-.9119E+01	.1339E+03
78.5390	.4600	.0583	-.9125E+01	.1339E+03
83.7749	.3600	.0281	-.9131E+01	.1339E+03
89.0109	.2500	.0135	-.9135E+01	.1339E+03
94.2468	.1500	.0065	-.9139E+01	.1339E+03
99.4827	.0600	.0031	-.9142E+01	.1339E+03

NUMBER OF RASTER LINES = 2000
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 1633.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 104.71870
J- AND J = -9.14182 133.94610

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 3b. SQRI Computation for Thomas 36" CRT Displayed at the CRT Face (Vertical MTF; MTF Normalized; Sample Number 1)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	1.0000	.0000	.0000E+00	.1016E+03
5.2359	1.0000	536.8716	.0000E+00	.1222E+03
10.4719	1.0000	301.6370	-.2228E-01	.1311E+03
15.7078	.9886	167.9954	-.6147E-01	.1358E+03
20.9437	.9773	96.2192	-.1003E+00	.1385E+03
26.1797	.9659	53.8314	-.1334E+00	.1401E+03
31.4156	.9545	29.1766	-.1628E+00	.1411E+03
36.6515	.9318	15.4036	-.1887E+00	.1418E+03
41.8875	.9091	7.9694	-.2111E+00	.1422E+03
47.1234	.8750	4.0591	-.2294E+00	.1424E+03
52.3593	.8523	2.0419	-.2436E+00	.1425E+03
57.5953	.8182	1.0169	-.2551E+00	.1426E+03
62.8312	.7727	.5023	-.2645E+00	.1427E+03
68.0671	.7159	.2463	-.2725E+00	.1427E+03
73.3031	.6250	.1201	-.2795E+00	.1428E+03
78.5390	.5227	.0583	-.2854E+00	.1428E+03
83.7749	.4091	.0281	-.2904E+00	.1428E+03
89.0109	.2841	.0135	-.2946E+00	.1428E+03
94.2468	.1705	.0065	-.2981E+00	.1428E+03
99.4827	.0682	.0031	-.3009E+00	.1428E+03

NUMBER OF RASTER LINES = 2000
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 1633.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 104.71870
J- AND J = -.30090 142.78710

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 4a. SQRI Computation for Thomas 36" CRT Displayed at the CRT Face (Vertical MTF; Sample Number 2)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.8800	.0000	-.6290E+01	.9530E+02
5.2359	.8800	536.8716	-.7568E+01	.1147E+03
10.4719	.8800	301.6370	-.8118E+01	.1230E+03
15.7078	.8800	167.9954	-.8433E+01	.1274E+03
20.9437	.8600	96.2192	-.8654E+01	.1299E+03
26.1797	.8300	53.8314	-.8816E+01	.1315E+03
31.4156	.8000	29.1766	-.8939E+01	.1324E+03
36.6515	.7500	15.4036	-.9038E+01	.1329E+03
41.8875	.6800	7.9694	-.9116E+01	.1332E+03
47.1234	.6200	4.0591	-.9178E+01	.1334E+03
52.3593	.5400	2.0419	-.9227E+01	.1336E+03
57.5953	.4500	1.0169	-.9266E+01	.1336E+03
62.8312	.3500	.5023	-.9297E+01	.1337E+03
68.0671	.2400	.2463	-.9323E+01	.1337E+03
73.3031	.1200	.1201	-.9343E+01	.1337E+03
78.5390	.0400	.0583	-.9360E+01	.1337E+03
83.7749	.0000	.0281	-.9372E+01	.1337E+03
89.0109	.0000	.0135	-.9380E+01	.1337E+03
94.2468	.0000	.0065	-.9385E+01	.1337E+03
99.4827	.0000	.0031	-.9389E+01	.1337E+03

NUMBER OF RASTER LINES = 2000
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 1633.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 104.71870
J- AND J = -9.38885 133.69920

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 4b. SQRI Computation for Thomas 36" CRT Displayed at the CRT Face (Vertical MTF; MTF Normalized; Sample Number 2)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	1.0000	.0000	.0000E+00	.1016E+03
5.2359	1.0000	536.8716	.0000E+00	.1222E+03
10.4719	1.0000	301.6370	.0000E+00	.1311E+03
15.7078	1.0000	167.9954	-.2438E-01	.1358E+03
20.9437	.9773	96.2192	-.7769E-01	.1385E+03
26.1797	.9432	53.8314	-.1394E+00	.1401E+03
31.4156	.9091	29.1766	-.2018E+00	.1411E+03
36.6515	.8523	15.4036	-.2645E+00	.1417E+03
41.8875	.7727	7.9694	-.3214E+00	.1420E+03
47.1234	.7045	4.0591	-.3698E+00	.1423E+03
52.3593	.6136	2.0419	-.4110E+00	.1424E+03
57.5953	.5114	1.0169	-.4456E+00	.1425E+03
62.8312	.3977	.5023	-.4745E+00	.1425E+03
68.0671	.2727	.2463	-.4988E+00	.1425E+03
73.3031	.1364	.1201	-.5190E+00	.1425E+03
78.5390	.0455	.0583	-.5351E+00	.1425E+03
83.7749	.0000	.0281	-.5475E+00	.1425E+03
89.0109	.0000	.0135	-.5555E+00	.1425E+03
94.2468	.0000	.0065	-.5608E+00	.1425E+03
99.4827	.0000	.0031	-.5642E+00	.1425E+03

NUMBER OF RASTER LINES = 2000
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 1633.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 104.71870
J- AND J = -.56423 142.52380

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 5a. SQRI Computation for Monochrome GE Light Valve Displayed Through Pancake Window (Vertical MTF)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.8400	.0000	-.6825E+01	.7163E+02
2.6180	.8200	468.8498	-.8930E+01	.9072E+02
5.2359	.8000	393.8417	-.1011E+02	.1002E+03
7.8539	.7800	272.9443	-.1091E+02	.1057E+03
10.4719	.7400	188.1845	-.1151E+02	.1092E+03
13.0898	.7100	132.8922	-.1199E+02	.1115E+03
15.7078	.6700	94.6680	-.1237E+02	.1131E+03
18.3258	.6300	67.0549	-.1270E+02	.1142E+03
20.9437	.5600	46.9561	-.1300E+02	.1150E+03
23.5617	.4700	32.4843	-.1328E+02	.1155E+03
26.1797	.3600	22.2258	-.1354E+02	.1158E+03
28.7976	.2500	15.0628	-.1379E+02	.1160E+03
31.4156	.1400	10.1260	-.1402E+02	.1161E+03
34.0336	.0500	6.7605	-.1422E+02	.1162E+03
36.6515	.0200	4.4869	-.1439E+02	.1162E+03
39.2695	.0100	2.9628	-.1453E+02	.1162E+03
41.8875	.0000	1.9477	-.1464E+02	.1162E+03
44.5054	.0000	1.2754	-.1472E+02	.1162E+03
47.1234	.0000	.8323	-.1479E+02	.1162E+03
49.7414	.0000	.5414	-.1483E+02	.1162E+03
52.3593	.0000	.3513	-.1485E+02	.1162E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 33.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -14.85348 116.20910

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 5b. SQRI Computation for Monochrome GE Light Valve Displayed Through Pancake Window (Vertical MTF; MTF Normalized)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	1.0000	.0000	-.3008E+00	.7815E+02
2.6180	.9762	468.8498	-.6663E+00	.9898E+02
5.2359	.9524	393.8417	-.9832E+00	.1094E+03
7.8539	.9286	272.9443	-.1284E+01	.1153E+03
10.4719	.8810	188.1845	-.1569E+01	.1191E+03
13.0898	.8452	132.8922	-.1829E+01	.1217E+03
15.7078	.7976	94.6680	-.2068E+01	.1234E+03
18.3258	.7500	67.0549	-.2295E+01	.1246E+03
20.9437	.6667	46.9561	-.2525E+01	.1255E+03
23.5617	.5595	32.4843	-.2759E+01	.1260E+03
26.1797	.4286	22.2258	-.2992E+01	.1264E+03
28.7976	.2976	15.0628	-.3221E+01	.1266E+03
31.4156	.1667	10.1260	-.3442E+01	.1267E+03
34.0336	.0595	6.7605	-.3642E+01	.1268E+03
36.6515	.0238	4.4869	-.3807E+01	.1268E+03
39.2695	.0119	2.9628	-.3941E+01	.1268E+03
41.8875	.0000	1.9477	-.4052E+01	.1268E+03
44.5054	.0000	1.2754	-.4136E+01	.1268E+03
47.1234	.0000	.8323	-.4200E+01	.1268E+03
49.7414	.0000	.5414	-.4249E+01	.1268E+03
52.3593	.0000	.3513	-.4268E+01	.1268E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 33.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -4.26805 126.79460

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 6a. SQRT Computation for Color GE Light Valve Displayed Through Pancake Window (Vertical MTF)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.9800	.0000	-.1016E+01	.7563E+02
2.6180	.9600	412.6381	-.1538E+01	.9455E+02
5.2359	.9300	314.4123	-.1961E+01	.1035E+03
7.8539	.8900	205.1057	-.2306E+01	.1086E+03
10.4719	.8600	136.3541	-.2608E+01	.1117E+03
13.0898	.8000	92.6575	-.2901E+01	.1137E+03
15.7078	.7200	62.8229	-.3193E+01	.1150E+03
18.3258	.6100	42.0119	-.3487E+01	.1159E+03
20.9437	.4800	27.6593	-.3781E+01	.1164E+03
23.5617	.3200	17.9557	-.4078E+01	.1167E+03
26.1797	.1500	11.5190	-.4357E+01	.1168E+03
28.7976	.0700	7.3172	-.4590E+01	.1169E+03
31.4156	.0400	4.6100	-.4773E+01	.1169E+03
34.0336	.0200	2.8843	-.4915E+01	.1169E+03
36.6515	.0100	1.7939	-.5025E+01	.1170E+03
39.2695	.0000	1.1100	-.5113E+01	.1170E+03
41.8875	.0000	.6838	-.5177E+01	.1170E+03
44.5054	.0000	.4196	-.5224E+01	.1170E+03
47.1234	.0000	.2566	-.5259E+01	.1170E+03
49.7414	.0000	.1564	-.5285E+01	.1170E+03
52.3593	.0000	.0951	-.5295E+01	.1170E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 12.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -5.29527 116.95780

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Table 6b. SQRI Computation for Color GE Light Valve Displayed Through Pancake Window (Vertical MTF; MTF Normalized)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	1.0000	.0000	-.2481E+00	.7640E+02
2.6180	.9796	412.6381	-.5778E+00	.9551E+02
5.2359	.9490	314.4123	-.9101E+00	.1046E+03
7.8539	.9082	205.1057	-.1204E+01	.1097E+03
10.4719	.8776	136.3541	-.1473E+01	.1129E+03
13.0898	.8163	92.6575	-.1746E+01	.1149E+03
15.7078	.7347	62.8229	-.2025E+01	.1162E+03
18.3258	.6224	42.0119	-.2310E+01	.1171E+03
20.9437	.4898	27.6593	-.2599E+01	.1176E+03
23.5617	.3265	17.9557	-.2894E+01	.1179E+03
26.1797	.1531	11.5190	-.3171E+01	.1180E+03
28.7976	.0714	7.3172	-.3403E+01	.1181E+03
31.4156	.0408	4.6100	-.3585E+01	.1181E+03
34.0336	.0204	2.8843	-.3727E+01	.1181E+03
36.6515	.0102	1.7939	-.3838E+01	.1181E+03
39.2695	.0000	1.1100	-.3925E+01	.1181E+03
41.8875	.0000	.6838	-.3989E+01	.1181E+03
44.5054	.0000	.4196	-.4037E+01	.1181E+03
47.1234	.0000	.2566	-.4072E+01	.1181E+03
49.7414	.0000	.1564	-.4098E+01	.1181E+03
52.3593	.0000	.0951	-.4108E+01	.1181E+03

NUMBER OF RASTER LINES = 1024
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 12.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 53.61596
J- AND J = -4.10786 118.14520

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

Below the tabular values in Tables 1 through 6 are the display parameters for the particular device. For example, in Table 1a the maximum number of raster lines was 1024; the viewing distance was 216 inches (i.e., 6 x the display device height of 36"); the display luminance used was 360 cd/m^2; u_{max} was 53.6 cycles/degree; and J- and J were -17.3 and 126.2, respectively.

Cumulative contributions to J- and J were denoted across spatial frequency bands to show how different bands were contributing to the overall image quality measure. Table 1a may again be used as an example. In Table 1a, J (column 5) is completely dominated by low spatial frequencies (by 10.4719 cycles/degree, J has reached 116.9); however, the (negative) contribution to image quality in J- reaches a maximum at approximately 20 cycles/degree and still shows a significant contribution at approximately 40 cycles/degree (5% or more of the total).

Conceptually, the greater weighting that the J- function places on spatial frequencies around 20 cycles/degree appears to be a desirable byproduct. However, it is not clear that we want information between 40 to 50 cycles/degree to significantly affect our image quality measure. The function J, on the other hand, heavily emphasizes information below 5 cycles/degree, but the contribution past 20 cycles/degree comprises less than 5% of J. Therefore, the two measures, J and J-, emphasize different bands of image information. Because of this difference in emphasis, the two measures may contradict each other in some instances. Consider, for example, two MTFs which have a crossover point at spatial frequency u_1. For all frequencies less than u_1, $MTF_1(u)$ is greater than $MTF_2(u)$; for frequencies greater than u_1, $MTF_1(u)$ is less than $MTF_2(u)$. By letting the shapes of the MTFs and the value of u_1 vary, it is not difficult to obtain values of J_1, J_2, J_1-, and J_2- for the two system MTFs such that:

$$J_1 > J_2 \qquad \text{but} \qquad J_1- \; < \; J_2-.$$

An example of this crossover phenomenon for the MTFs is given in Tables 3a and 6a. The J- quantity in Table 6a shows a 4-jnd improvement over J- from Table 3a, but J from Table 3a shows a 17-jnd improvement over J from Table 6a. It should be noted that the MTFs from the devices in Table 3a (36" CRT face) and Table 6a (monochrome light valve through the pancake window) are not normalized and have a crossover point around 10 cycles/degree. When the two MTFs are normalized (Tables 3b and 6b), there is no longer a crossover of MTFs. The J and J- values will not conflict with one another unless there is a crossover of the MTFs. However, given that the trends in the J and J- measures can theoretically contradict one another, the measures lose some of their robustness.

The effect of changes in display luminance on J- was simulated using the theoretical Gaussian MTF generated from Equation 19 (i.e., $MTF(u) = exp(-(3.14 \times d \times u)^2/12)$ in Barten (1987). For a spot size of 1 mm, a pixel size of .3 mm, 400 raster lines, and a viewing distance of 500 mm, the relationship between luminance (expressed in cd/m^2), and J- and J was as follows:

Luminance (cd/m^2)	J-	J
1	-5.23	93.77
10	-8.22	111.34
30	-9.61	117.38
70	-10.51	120.97
150	-11.12	123.25
250	-11.41	124.30

No attempt was made to modify the display MTF as a function of luminance level in the data above.

As previously mentioned, the trend in J- values computed above is contrary to what would be intuitively expected. Image quality should certainly increase as we increase display luminance without compensation in the display MTF. The quantity J increases in an asymptotic fashion. For human vision, contrast sensitivity reaches an asymptotic level somewhere between 150 and 250 cd/m^2. In the simulated data, we also see that both quantities J and J- are approaching asymptotic levels for these display luminances. A one-unit change in J or J- is equivalent to a jnd. Thus, increasing the luminance from 1 to 10 nits results in an 18-jnd increase in image quality, whereas increasing luminance from 70 to 150 nits results in only a 2-jnd increase in image quality when we use J as our measure. These results, as predicted by the model, would be testable through empirical investigation.

Peak luminance values given for the 36" Thomas CRT were (a) 400 to 500 foot-lamberts from the CRT itself and (b) 4 to 5 foot-lamberts from the pancake window. Peak luminance of the color light valve through a projection screen with a gain of 1.75 (for rear projection) was 51 foot-lamberts for front projection and 88 foot-lamberts for rear projection. Peak luminance values for the color light valve projected through the pancake window ranged from 2.4 to 3.5 foot-lamberts across measurements. With the monochrome light valve, peak luminance through a rear-projection screen with a 1.75 gain was 189 foot-lamberts. A peak luminance of between 8 and 10 foot-lamberts was measured through the pancake window. No luminance values were supplied for the monochrome light valve through a front-projection screen.

The CRT was capable of providing greater resolution than the 1024 lines by 1000 pixels/line resolution at which the devices were tested. However, additional modifications would have been required to drive it at its full capability of 2000 lines by 1000 pixels/line. Manufacturer specifications for the Color Light Valve, PJ5155C1, give a minimum of 750 TV lines for horizontal resolution and 650 TV lines for vertical resolution. These two values yield the number of television lines at which the MTF falls below 10%. No values were mentioned for the monocnrome light valve.

The upper limit for spatial frequency integration proves to be an important consideration. The integrations in both Equations (6) and (7) use the maximum spatial frequency from the display, u_{max}, as the upper limit of integration. The contribution to J at high spatial frequencies will be zero when the system MTF is also zero. However, as the system MTF falls to zero, the value of J- becomes dependent on the quantity $(CSF(u))^{1/2}/u$. This quantity decreases as spatial frequency increases, but still contributes in a negative fashion to the J- measure at high spatial frequencies (e.g., 30-50 cycles/degree).

As is the case with light valve systems, a system may be driven at a higher rate than that to which it is capable of responding. In the case of the light valves, this means that, for example, even though the system is driven at a 1000-line rate, its MTF drops to zero at 800 lines. In terms of the image quality measure, then, u_{max} would be taken to be 1000. Although the contribution to the J measure between 800 and 1000 lines would be zero, the contribution to J- between 800 and 1000 lines could be significant.

Theoretically, the negative contribution to J- between 800 and 1000 lines should be compared to the image quality of the ideal display (which would transmit information perfectly at all spatial frequencies where the human CSF is nonzero or at least somewhat significant). One of the problems is the continuous mathematical representation of the CSF from Equation (4). It approaches zero in a smooth manner for high spatial frequencies and thus extends much further than a true human CSF.

For practical purposes, then, it may be advisable to redefine u_{max}. Barten's (1987) article defines this as the video bandwidth limit of the television signal. Using this interpretation, u_{max} for the two light valves in this report will be 1024/2 in the vertical direction and 1000/2 in the horizontal direction. Manufacturer specifications set u_{max} for the CRT at 2000/2 in the vertical direction and 1000/2 in the horizontal direction. However, for the light valves, the manufacturer specifications state 650 vertical by 750 horizontal TV lines as the minimum number of lines over which a 10% contrast may be obtained. For purposes of computation in this report, u_{max} for the vertical dimension will be 1024/2 = 512 for the light valves and 2000/2 = 1000 for the CRT.

For device number 2, the color light valve projected onto the front-projection screen, J and J- measures were computed using u_{max} equal to both 1024/2 and 650/2. Results are shown in Table 2a (u_{max}= 1024/2) and Table 7 (u_{max}= 650/2).

Table 7. SQRI Computation for Color Light Valve Displayed on a Front-Projection Screen (Vertical MTF; 650 Raster Lines)

FREQUENCY CYCLES/DEG	MTF	CSF	Y(J-)	Y(J)
.0000	.9400	.0000	-.2711E+01	.7742E+02
2.6180	.9200	529.3783	-.3705E+01	.9947E+02
5.2359	.9100	491.6848	-.4323E+01	.1110E+03
7.8539	.8900	365.4897	-.4793E+01	.1179E+03
10.4719	.8600	262.7811	-.5206E+01	.1223E+03
13.0898	.8100	191.9336	-.5609E+01	.1253E+03
15.7078	.7400	142.3979	-.6013E+01	.1274E+03
18.3258	.6550	106.0217	-.6418E+01	.1288E+03
20.9437	.5600	78.5388	-.6821E+01	.1298E+03
23.5617	.4500	57.6795	-.7220E+01	.1305E+03
26.1797	.3300	41.9691	-.7607E+01	.1309E+03
28.7976	.2300	30.2739	-.7973E+01	.1312E+03
31.4156	.1300	21.6701	-.8307E+01	.1313E+03
34.0336	.0800	15.4077	-.8598E+01	.1314E+03

NUMBER OF RASTER LINES = 650
VIEWING DISTANCE IN INCHES = 216.00000
DISPLAY LUMINANCE (CD/M SQUARED) = 170.00000
MAXIMUM SPATIAL FREQUENCY (CYCLES/DEGREE) = 34.03357
J- AND J = -8.59828 131.43700

NOTE: Y(J-) AND Y(J) DENOTE CUMULATED APPROXIMATIONS TO J- AND J FOR THE SPATIAL FREQUENCY GIVEN.

The J- measure increased approximately 1 jnd (J- = -9.6 vs J- = -8.6) when the number of raster display lines decreased from 1024 to 650. As previously discussed, this result is as expected because the negative integrand is integrated up to a lower maximum spatial frequency. The J measure, as expected, went in the opposite direction a small amount, with J increasing from 131.4 to 131.5 jnd's when the upper resolution limit was from 650 to 1024 raster lines. Differences between Equations (6) and (7), the equations for J and J-, become quite evident when making comparisons at high spatial frequencies. The CSF shown in Equation (4) still evaluates to a value greater than 1 between 50 and 60 cycles/degree of visual angle for large display luminances. Assuming the system MTF is zero around 50 to 60 cycles/degree, the contribution to J or Equation (6) will be nil at these high frequencies. However, in computing J-, the square root of the human CSF is multiplied by the square root of the system MTF minus 1. Thus, at high frequencies where the system MTF is zero, the integrand in Equation (7) will be approximately (0 - 1) x CSF(u) = (0 - 1) x 1.5 = -1.5 around 55 cycles/degree. Thus, J- may be affected in an adverse manner by decreases of 1 to 2 jnd's at high spatial frequencies. The general point to be made is that the contribution to J is zero at all spatial frequencies where the system MTF is close to zero, but such is not the case for the computation of J-. That is, the choice of u_{max} as the theoretical limit on resolution or the spatial frequency where the system MTF falls below some contrast may figure significantly in the computations of J- but not J.

A second somewhat more practical problem associated with display rates also becomes evident here. Suppose we wish to compare two systems driven at differing rates (i.e., with different u_{max} values), and the two systems have identical MTFs but System One is driven at only half the rate of System Two. Thus, $u_{1max} = .5\ u_{2max}$. The fact that the MTFs are equivalent for all frequencies less than u_{1max} but System Two is capable of presenting higher frequency information than System One would lead one to conclude that the image quality of System Two is better than the image quality of System One. However, Equation (7) will always yield J_1- greater than or equal to J_2-.

One such instance is shown in Table 8. In these two simulations, theoretical MTFs were generated from the Gaussian MTF equation using number of raster lines = 400 and viewing distance = 500 mm. For System A of Table 8, spot size and pixel diameter were set to 1 mm and .3 mm, respectively. For System B, spot size and pixel diameter were set to .5 mm and .5 mm, respectively. For these values, the maximum spatial frequency, u_{max}, is 14.54 cycles/degree for System A and 8.73 cycles/degree for System B. Thus, System A can produce nearly twice the spatial frequency of System B. The J value for System A is approximately the same as the J value for System B because most of the emphasis in the computation of J is at very low frequencies. However, the J- value for System A is approximately 9 jnd's worse than the J- value for System B--a significant decrement in image quality. System A is significantly better than System B because the MTF of System A is greater than or equal to the MTF of System B over all spatial frequencies. (In fact, the MTF of System A extends out approximately twice as far as the MTF of System B.)

Table 8. Simulated SQRI Computation

	System A	System B
Number of Raster Lines	400	400
Viewing Distance (mm)	500	500
Luminance (cd/m^2)	100	100
Spot Size (mm)	1	.5
Pixel Diameter (mm)	.3	.5
Maximum Spatial Frequency (cycles/degree)	14.54	8.73
J- (jnd's)	-10.83	-1.47
J (jnd's)	122.39	121.05

The above example indicates a need for caution when using Equation (7) to compare systems of unequal raster rates in the orientation of interest. The J- measure is useful for comparison of a specific display system with an "ideal" system which has the same raster or display capability and the same luminance output. Once again, however, use of Equation (6) in the example above would produce J values ordered as one might expect. That is, the system which is capable of displaying higher spatial frequencies would produce a larger J value, signifying better image quality (although the psychological implication of jnd's is still questionable).

V. RESULTS OF IMAGE QUALITY ANALYSIS FOR ASPT SAMPLED DEVICES

As stated previously, the display devices analyzed in Tables 1 through 6 (a and b) using the SQRI method were:

(1) monochrome light valve, front-screen projection, vertical MTF (Tables 1a and 1b);

(2) color light valve, front-screen projection, vertical MTF (Tables 2a and 2b);

(3) Thomas CRT at the CRT face, vertical MTF-sample 1 (Tables 3a and 3b);

(4) Thomas CRT at the CRT face, vertical MTF-sample 2 (Tables 4a and 4b);

(5) monochrome light valve, pancake window, vertical MTF (Tables 5a and 5b); and

(6) color light valve, pancake window, vertical MTF (Tables 6a and 6b).

For each of these devices, sample points representing a modulation depth curve were available. As mentioned previously, modulation depth was defined as $C_L = (L_{max} - L_{min})/(L_{max} + L_{min})$ for sampled spatial frequencies, where L_{max} and L_{min} denote maximum and minimum display luminance. Normalization of the computation above by the modulation depth at a spatial frequency of zero (i.e., the modulation depth using the peak display luminance and the display dark field luminance) is defined as the system MTF. Without this normalization, modulation depth at zero frequency will be less than 1.0. The normalized contrast curves now more closely resemble a standard MTF. Whether this transformation or division should be performed, however, is questionable, depending upon the use of the MTF.

Indeed, the classical definition and use of MTFs involve multiplying MTFs of cascaded components to denote the total amount of energy transmitted through the system at a given spatial frequency. These are systems where the input waveform and the output waveform are assumed to contain equal overall energy so that only a redistribution of energy over the variable of interest (two-dimensional space for our purposes) is occurring. If the display system neither adds nor subtracts energy from the input-output sequence, the value of the MTF at zero spatial frequency is 1.0, denoting this fact. When we employ the MTF in Barten's Equations (6) and (7) (as with most image quality measures), however, there are no theoretical assumptions available for linking his MTF to the traditional MTF in order to describe how systems filter energy at specific frequencies. In fact, in Equations (6) and (7) the minimum modulation depth--as determined by the CSF--is applied to the display modulation depth as a weighting at each spatial frequency. Normalization of the display MTF makes little sense in this context. Thus, the question of whether to normalize the relative contrast values is not predetermined by any assumptions.

In devices such as the CRT face, where luminance levels are much higher than those of the optics-limited light valves, overall dark luminance may be much brighter. This results in a lower modulation depth. In comparison, a pancake window, which transmits very little energy, has a much lower dark luminance and, as a result, may yield a higher modulation depth. As an example, consider the luminance and modulation depths for the three systems below.

System	Dark Luminance (nits)	Peak Luminance (nits)	Mod. Depth
1	100.0	1633.0	.88
2	.5	12.0	.92
3	2.0	34.0	.89

System 2 has the highest modulation depth, but because of its low luminance levels, it is likely to be the worst system for target identification purposes. System 3 also has greater modulation depth than System 1, but because of the overall luminance difference between the two systems, it would not be as good as System 1 for identifying detail within imagery. Extrapolating this argument based upon the modulation depth measure, we would find that System 2 might yield the largest J and J- values if we employed non-normalized modulation depth curves to play the role of the system MTF. Even though the luminance output from System 2 is much darker than that from System 1, System 2's modulation depth may dominate (i.e., be greater than that of System 1) at all spatial frequencies. The increased luminance of System 1 will cause the Contrast Sensitivity Function (CSF) associated with System 1 to dominate the CSF associated with System 2. The increase in the CSF associated with System 1, however, may not be sufficient to offset the loss in lower values associated with that system's MTF in the calculation of J and J-. Thus, for the purpose of estimating image quality, inclusion of display luminance indirectly through the CSF function is not enough. The display system MTF must also be characterized as a function of luminance.

Normalization of the system MTF does not solve the luminance-dependence problem. The source of the normalization problem involves both definition and measurement of modulation depth and MTF. From a Fourier perspective, an MTF is defined as the absolute value of the real and imaginary parts of the Fourier transform representing the device. In a linear systems framework, this system or "black box" MTF may be derived by taking the ratio of the absolute value of the input Fourier transform to the absolute value of the output Fourier transform. Snyder (1985) defines the MTF as the modulation depth out of the system divided by the modulation depth into the system. The normalization procedure used on the modulation depth data in the present study calls for normalizing all modulation depths (measured at differing spatial frequencies) by modulation depth at a frequency as close as possible to zero. This value is assumed to be approximately the modulation depth into the system. Modulation into the system can be considered using either voltage or digital-to-analog codes (DACs) as the input to the system.

DAC values control voltages which directly determine, for example, electron gun or lamp intensity into the display system. DAC values may be directly measured, but the relationship between the DAC values and output luminance is typically a nonlinear gamma function. The gamma function itself can be estimated by measuring the luminance out of the system relative to the DAC values put into the system.

Because of the ambiguities in these relationships, the present data will be analyzed with and without normalization of the display modulation depth curves, more as an exercise to show existing problems in image quality metrics. J- and J quantities were calculated for the six devices with and without normalization of the MTFs. The resulting values are given in Table 9.

Employing basic technical knowledge of the six display systems, we would most likely rate the image quality of the six display devices as follows. First, we would expect image quality for the two Thomas CRT samples (devices number 3 and 4) to be highest. The CRT face includes more lines of resolution, and luminance levels are much higher (1633 nits) than for other devices. Next, we would expect the monochrome and color light valves projected onto the front-projection screen (devices number 1 and 2) to be approximately equal in terms of image quality. The monochrome light valve yielded about 2.5 times the luminance of the color light valve on the front-projection screen (360 nits versus 170 nits). Because the focusing of the color light valve involves overlaying three primary colors (red-green-blue), it might also be expected that the monochrome light valve would focus at least as well as the color light valve. These two factors, then, led us to intuitively conclude that the monochrome light valve should provide better image quality (gray shades only) than the color light valve projected onto a front-projection screen. Lastly, the monochrome and color light valves projected through the pancake windows (devices number 5 and 6) were expected to be the worst displays in terms of image quality. Luminance is drastically reduced when displayed through the pancake windows. Using the same reasoning as with the front-projection screen, we might expect the monochrome light valve to provide better image quality (gray shades only) than the color light valve when both are projected through the pancake window.

Although the rationale used here appears quite reasonable, it does not take into account the physical size of the display area, which may prove to be quite important in observer ratings of image quality. The display data used in this report were normalized so that the images from the different devices subtended the same physical area. However, a major function of the light valves is that they are able to project the image onto a large display area. Westerink and Roufs (1988) found that images which subtend larger areas are judged as better in quality. This finding is reasonable in light of the hypothesis that stimulation of peripheral channels of vision can provide the viewer with a more realistic sensation. None of the image quality metrics currently in use are capable of accounting for this finding because the observer subsystem is considered only with respect to foveal contrast sensitivity data. Although light valves may be used to project over large display areas, this results in a loss of brightness and resolution. Current image quality metrics will show reduced image quality due to loss of brightness and resolution but cannot show the countering effect of the increased display area on perceived image quality. Because the display areas for the comparison of the six devices under discussion were standardized, the additional benefit of image

Table 9. Results of the SQRI and MTFA Analysis for Six Displays

Device	Lum (cd/m^2)	Non-Normalized MTF J-	J	MTFA	Normalized MTF J-	J	MTFA
1	360	-17.3	126.2	12.85	-11.9	131.6	13.99
2	170	-9.6	131.5	20.40	-5.5	135.6	21.74
3	1633	-9.1	133.9	40.47	-.3	142.8	46.81
4	1633	-9.4	133.7	37.49	-.6	142.5	43.19
5	33	-14.9	116.2	18.49	-4.3	126.8	18.87
6	12	-5.3	117.0	17.81	-4.1	118.1	21.41

1. Monochrome Light Valve; Front-Screen Projection
2. Color Light Valve; Front-Screen Projection
3. Thomas CRT at the CRT Face; Sample number 1
4. Thomas CRT at the CRT Face; Sample number 2
5. Monochrome Light Valve; Pancake Window
6. Color Light Valve; Pancake Window

quality due to the increased display size area for light valve devices is not reflected by these metrics.

In addition to rank-ordering the image quality of the six display devices based upon their technical attributes, a more traditional method would be to compare the modulation depth curves (or normalized MTFs). Figures 6 and 7 permit a comparison of unnormalized modulation depths (Figure 6) with normalized modulation depths or MTFs (Figure 7) for the six devices. The unnormalized modulation depth curves in Figure 6 exhibit a great deal of ambiguity. Although curves 3 and 4 completely dominate curve 5 (i.e., have greater modulation at all spatial frequencies) and curves 2 and 6 completely dominate curve 1, curves 1, 2, and 6 exhibit a crossover with curves 3, 4, and 5 at 10 cycles/degree or less. Inherent in these curves is the modulation depth problem previously discussed. That is, curves 3 and 4 represent modulation depth for the CRT face. The dark and peak luminances at the CRT face are most likely much greater than those for the other devices. As shown in the previous example, this increase in overall luminance may yield lower modulation depths at zero frequency. Thus, even though the modulation depth for the CRT face is lower than that for three of the four other devices, it is likely that the perceived image quality for the high luminance devices is still better than the image quality for the other devices.

Given this ambiguity alone, it would seem useful to normalize the MTF curves. The normalization process, however, is a double-edged sword. For example, consider two display devices which are equal in all respects except that the unnormalized MTF of one device may dominate the MTF of the other device at all frequencies. Mathematically, we can express this as

$$MTF_1(u) = C \times MTF_2(u),$$

where u is spatial frequency and $C > 1$ is a multiplicative constant. This equation says that the modulation depth of device number 1 always dominates (i.e., is greater than) the modulation depth of device number 2 at all spatial frequencies by a factor of C. If we normalize both of these MTF curves by their modulation depth at zero spatial frequency, the new relationship will be

$$MTF_1(u) = MTF_2(u).$$

If all other factors are equal, domination of the (unnormalized) MTF can be equated with an increase in image quality as predicted by any of the currently used image quality metrics. However, after normalization of the MTFs, the two devices would appear identical to any of the currently used image quality metrics. From this example, then, we can see that use of either the unnormalized or the normalized display MTF may be questionable. For the purpose of illustration, though, it will prove useful to compare the use of normalized versus unnormalized MTFs.

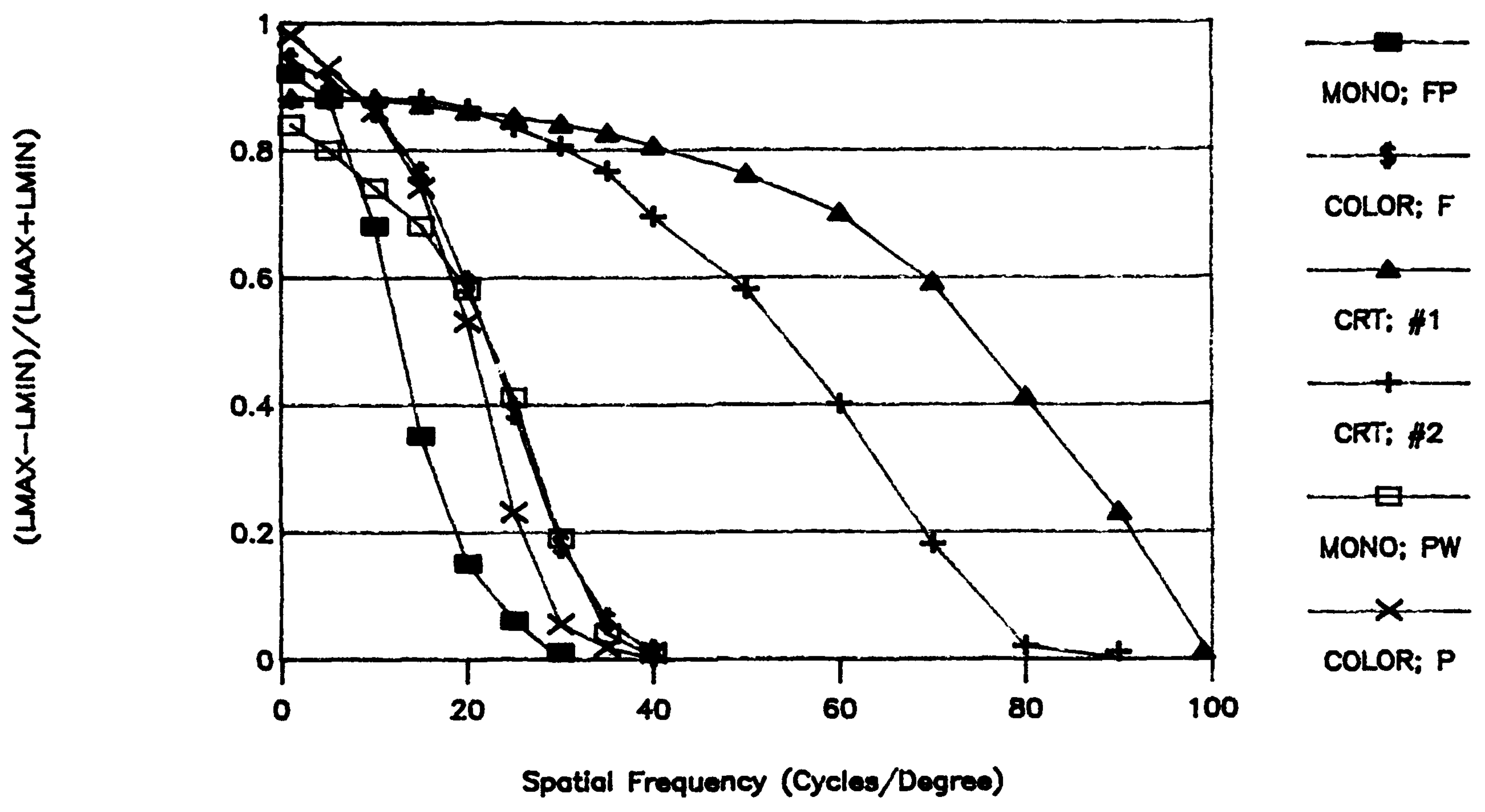

Figure 6. Unnormalized Modulation Depth Curves for Six ASPT Display Devices.

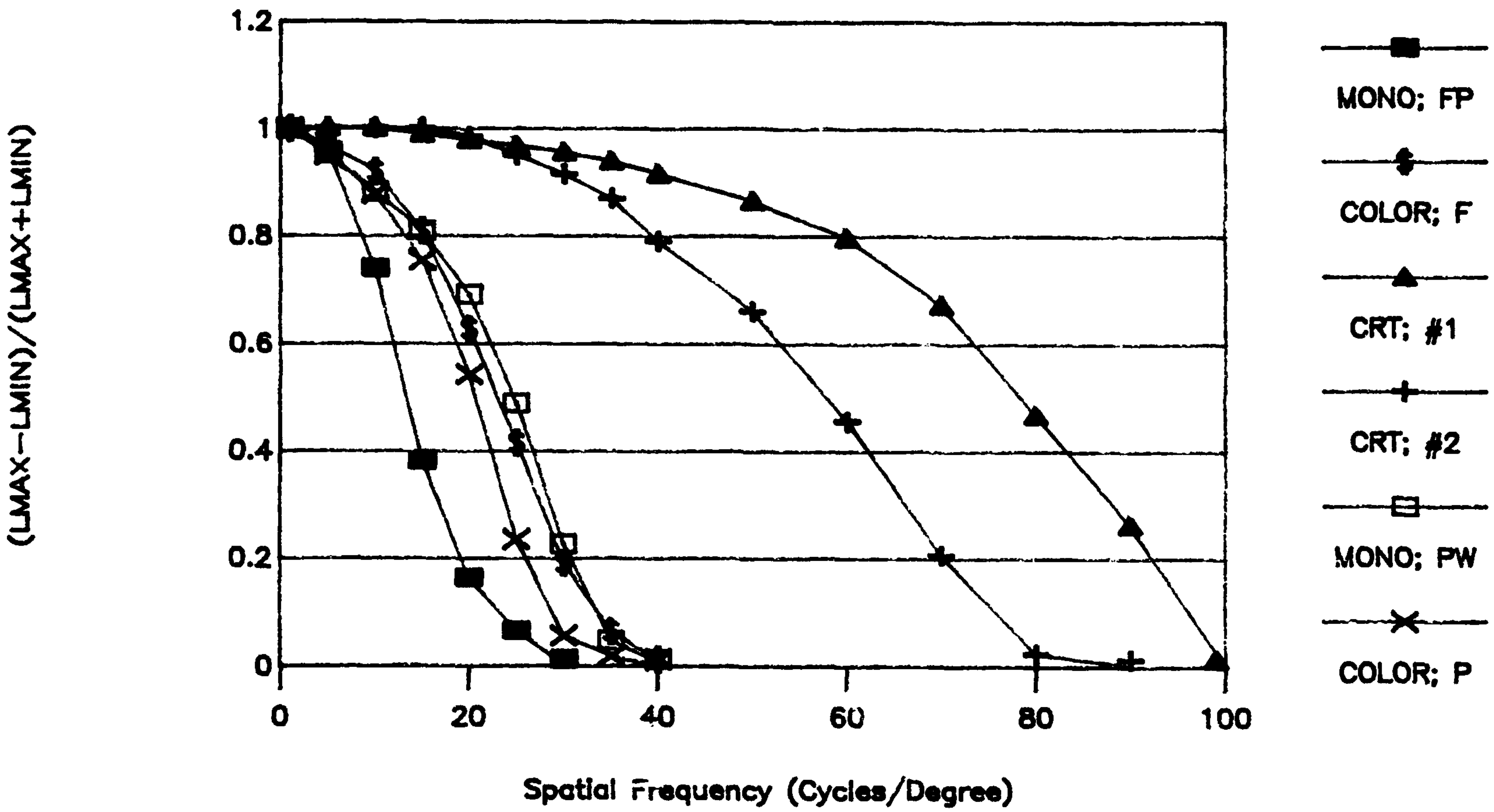

Figure 7. Normalized Modulation Depth Curves for Six ASPT Display Devices.

Figure 7 shows the normalized modulation depth or MTF curves for the six devices. Examination of the MTF curves from Figure 7 as decision criteria suggests that:

(1) the image quality of device number 3 is better than that of each of the devices;

(2) the image quality of device number 4 is better than that of numbers 1, 2, 5, and 6;

(3) the image quality of devices number 2 and number 6 is better than that of numbers 1 and 5;

(4) the image quality of device number 5 is better than that of device number 1; and

(5) image quality differences between devices number 2 and number 6 are insignificant.

One basic difference between the ranking of image quality based on technical attributes and use of the MTF to rank-order the image quality of the six devices may be noted. Intuitively, we expected the focusing of the monochrome light valve to be better than that of the color light valves for both front-projection screens and pancake windows. The normalized MTF curves exhibit only one distinct difference between the monochrome and color light valves. Namely, the MTF of the monochrome light valve projected onto the front-projection screen is noticeably worse than both (a) the MTF of the color light valve projection onto the projection screen and the pancake window, and (b) the MTF of the monochrome light valve projected onto the pancake window.

Table 10 shows the relationship between image quality rank-orderings using (a) the technical attributes approach, (b) the relationship between normalized MTF curves only, (c) the J measure from the SQRI method for the unnormalized (U) and normalized (N) modulation depth curves, and (d) the MTFA measure for both unnormalized (U) and normalized (N) modulation depth curves.

Table 10. Display Ranking Methods

Device number	Tech. ranking	Normalized MTF ranking	J Ranking (U	vs N)	MTFA (U	vs N)
1	3	6	6	4	6	6
2	4	3	4	3	3	3
3	1	1	2	1	1	1
4	1	2	3	2	2	2
5	5	5	5	5	4	5
6	6	3	1	6	5	4

It is clear that the SQRI (J ranking) and MTFA metrics for device number 1, the monochrome light valve on the front-projection screen, contradict the common sense technical rankings. This finding can be attributed in part to the sample MTF curves associated with device number 1 (see Figures 6 and 7). Logically, we would expect the monochrome light valve to project through the front-projection screen at least as well as through the pancake window. As mentioned previously, the MTF carries no information concerning display luminance. The fact that luminance output for device number 1 is 30 times that for device number 6 clearly has an effect on image quality comparison.

The J ranking (unnormalized MTF) of device number 6 as the best display device also points out an obvious shortcoming in this SQRI metric. From Figure 6, we see that device number 6, the color light valve projected through the pancake window, has a higher modulation at a very low spatial frequency than do the other devices; but its modulation quickly drops off shortly thereafter. The tendency of the SQRI metric to emphasize low spatial frequency information is the cause of this ranking error. Clearly, the overemphasis of low spatial frequency information relative to mid- and high-frequency information can be detrimental. In contrast, the MTFA weights all spatial frequency information equally. As mentioned earlier, the MTFA correlates highly with use of the display MTF alone.

For system procurement purposes, data available typically include luminance output, raster line resolution, and possibly some form of engineering MTF evaluation. Display systems engineers must incorporate this information in some rational fashion in the decision-making process. The SQRI method is an attempt to incorporate the same data in a precise, quantitative formula. However, as shown in this analysis, the J measure will tend to overemphasize the importance of low spatial frequencies, and the J- measure contains a number of inadequacies. Although luminance is incorporated into the SQRI metric through the observer CSF function, this factor will typically affect only high spatial frequencies. In the J measure, though, we have seen that contributions in bands above 10 to 15 cycles per degree of visual angle have an insignificant influence on the final value. Hence, we conclude that the J measure will not respond adequately to luminance display differences.

Concomitant with this insensitivity to fluctuations in display parameters at high spatial frequencies, the J measure is also insensitive to changes in resolution. Tables 1a-6b show that accumulation in the J measure is insignificant at frequencies greater than 20 cycles per degree of visual angle. Thus, from an SQRI point of view, displays with parameters equal to those employed in this section but with upper spatial frequency cutoffs of 20 cycles per degree would be defined as nearly equivalent in image quality to the corresponding devices actually used here.

The MTFA, with its equal weighting scheme along the spatial frequency axis, will be more sensitive than the SQRI method to factors affecting changes at high spatial frequencies. However, the sensitivity of the MTFA to a change in display luminance from 10 to 100 cd/m^2 (see Figure 5) is still not as large as we would desire. As mentioned previously, though, the MTF curve would also change for luminances of 10 versus 100 cd/m^2, and we do not know the luminance values used in the measurement of the MTF in Figure 5.

In the next section, the SQRI metric is used in the image quality comparison of two General Electric Light Valves. We have omitted MTFA in the next section as the MTFA correlates highly with the area under the display MTF, and rank-orderings of this area may be approximated through examination of the MTF curves.

VI. SQRI ANALYSIS OF GENERAL ELECTRIC SINGLE AND MULTIPLE LIGHT VALVES

In addition to the ASPT display devices, Howard (1989) more recently conducted a thorough analysis of the General Electric single and multiple light valves used in the Advanced Visual Technology System (AVTS) at the Air Force Human Resources Laboratory (AFHRL) at Williams AFB, Arizona. Although Howard (1989) provides a more thorough explanation of the differences between these two projection systems, a short explanation is provided here. First, the maximum luminance of the MLV is approximately five times that of the SLV (585 cd/m^2 versus 114 cd/m^2). Secondly, the control of the red, green, and blue primaries for the MLV can be accomplished in a more independent manner than for the SLV. These differences led to the a priori conclusion that the MLV would yield better image quality than would the SLV as an image projection device.

Modulation depth data collected for the two systems were presented in Figure 3. Figure 3 contains individual data points for the SLV and the MLV in both the vertical and horizontal directions. Both systems projected 768 raster lines by 1024 pixels/raster lines onto a back-projection screen. For an assumed observer distance of 10 feet and a display projection area of approximately 3 by 4 feet, the maximum spatial frequency was approximately 38 cycles/degree of visual angle. In Figure 3, the data between 19 and 38 cycles/degree were not measured directly but were interpolated from samples obtained at 10, 13, 19 and 38 cycles/degree. The interpolated values were obtained by fitting a decaying exponential through these four data points. Although the modulation depth values at 10, 13, and 19 cycles/degree were directly measured, the modulation depth at 38 cycles/degree was estimated from the spot size of a single pixel.

This interpolation across such a large range of spatial frequencies may easily result in estimation errors. For example, if a linear interpolation scheme was used between 19 and 38 cycles/degree, f_c for both 10 cd/m^2 and 100 cd/m^2 would be approximately 28 and 33 cycles/degree, respectively. Though it is likely that exponential decay interpolation represents the best method of interpolation in this instance, more measurements (direct method, see Beaton, 1988) or more computations (indirect method, see Beaton, 1988) would be required to determine which estimate (linear or exponential decay) is more appropriate. In addition, it was found by comparison that use of a linear interpolation scheme, resulting in greater modulation depth over the interpolated range, had little effect on the calculated J value from the SQRI metric (< 1-jnd change). As mentioned in the previous section, this insensitivity is due to the decrease in weighting along the spatial frequency axis as spatial frequency increases.

Figure 3 shows that the modulation depths of the MLV dominate those of the SLV at lower frequencies. From the average observer luminance-dependent CSFs for the SLV and MLV shown in Figure 8, we see that contrast sensitivity for the MLV (average luminance = 297 cd/m^2) always dominates contrast sensitivity for the SLV (average luminance = 62 cd/m^2) due to the greater output luminance characteristics of the MLV. Of course, though we would expect greater luminance to indicate better image quality if all other factors are equal, the J- measure always contradicts this finding.

Figure 9 shows the same modulation depth curves as Figure 3 but normalized by the modulation depth at zero frequency. For Howard's data, modulation depth at zero frequency was estimated by letting the larger luminance be the maximum output measured for the display when all pixel elements are turned on, and letting the minimum luminance be the dark field when all DAC values are set to zero. As a result, there is a loss of dominance for the normalized MLV modulation depths at low frequencies. This loss of dominance at low frequencies constitutes one of the problems noted earlier and provides insight in this instance where we note the loss of information in comparing the two systems.

Table 11 presents the results of applying the SQRI method to the MTF data for the SLV and MLV projection systems. As might be expected, the J- measure for the MLV data yields a significant improvement over the J- measure for the SLV with the unnormalized data. However, these J- results are reversed when the modulation depth curves are normalized, although the reversal is quite small. Thus, after normalizing the modulation depth curves, the J- measure indicates that the SLV provides better image quality than the MLV. Normalization of the modulation depth curves in this instance yields clearly erroneous results. For the J measure, the MLV data yielded better image quality for both unnormalized and normalized data, although the improvement in the unnormalized case was decidedly more significant.

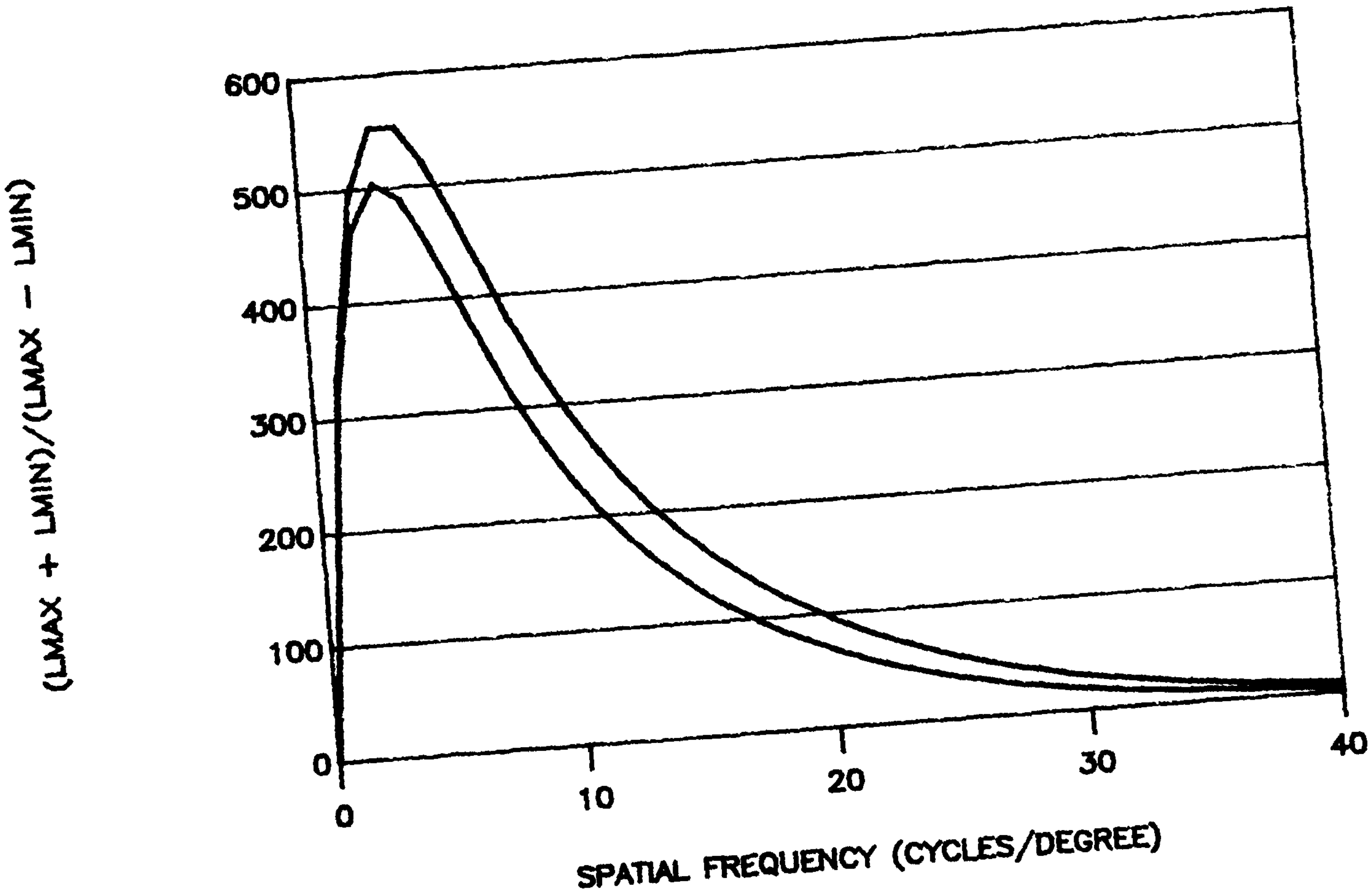

Figure 8. Observer Contrast Sensitivity Curves for Single Light Valve (62 cd/m^2) and Multiple Light Valve (297 cd/m^2).

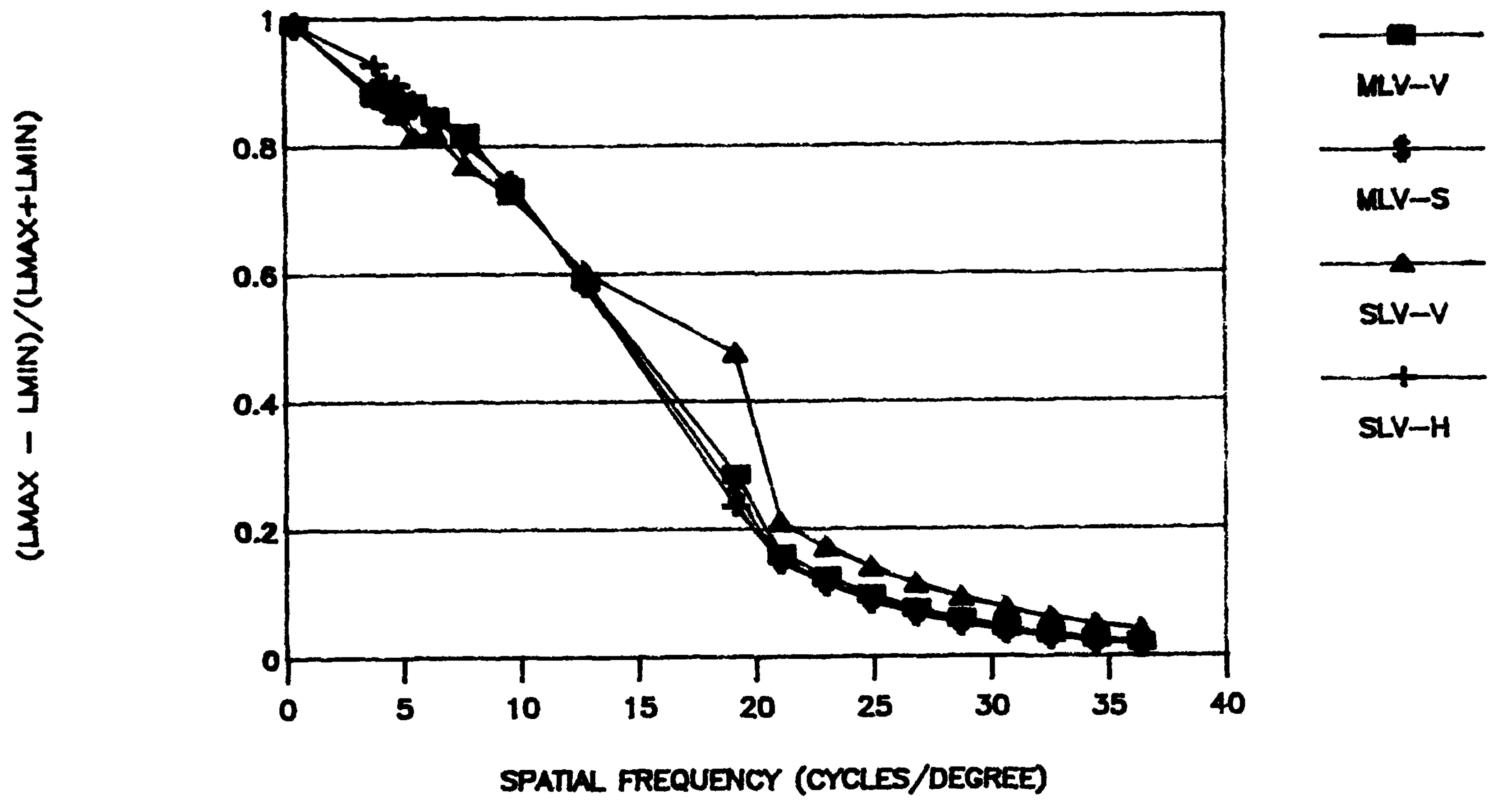

Figure 9. Normalized Howard (1989) Single and Multiple Light (SLV & MLV) Modulation Depth Curves in Vertical and Horizontal Directions.

Table 11. SQRI and MTFA Estimates for the Single Light Valve (SLV) and Multiple Light Valve (MLV)

Device	Background Luminance (cd/m2)	MTF Non-Normalized J-	MTF Non-Normalized J	MTF Normalized J-	MTF Normalized J
SLV, Vertical MTF	62	-71.6	649.3	-9.5	711.4
SLV, Horizontal MTF	62	-71.7	649.1	-9.6	711.2
MLV, Vertical MTF	297	-22.1	706.4	-11.6	716.8
MLV, Horizontal MTF	297	-22.2	706.3	-11.7	716.7

As with the data from the projection systems presented in the previous section, it was also desirable to see which spatial frequencies made major contributions to the J- and J measures with the SLV and MLV data. Figures 10 and 11 show the accumulation of J-and J, respectively, for both unnormalized and normalized MTFs and both vertical and horizontal resolution. In both figures, the vertical and horizontal curves for each device directly coincide.

In Figures 10 and 11, the accumulated value at any point always represents the respective function, J- or J, integrated to the next abscissa point beyond the current one. For example, in Figure 10, J- for the MLV (vertical and horizontal) is approximately -11 jnd's for a spatial frequency of zero. The -11 jnd's represent the J- value integrated from zero frequency to 3.83 cycles/degree. For the J- measure, approximately 50% of the final value is represented by the frequency spectrum at or below 3.83 cycles/degree. For the J measure (see Figure 11), approximately 90% of the final J value is represented by the frequency spectrum at or below 3.83 cycles/degree. This finding indicates, once again, that these measures are very insensitive to changes in the MTF and the CSF occurring in higher frequency ranges. It is unlikely that this insensitivity is reflected in the human process of rating image quality.

The sensitivity of the J- and J measures to the modulation depth and CSF functions at low frequencies also presents a problem for collecting the data. For example, the number of sampling points and the interpolation used to connect sampling points for low-frequency components can have a significant effect on the resulting J- and J measures. The individual data points in Figures 3 and 9 were connected by a straight line except for those in the tail of the curves between 19 and 36 cycles/degree, which were

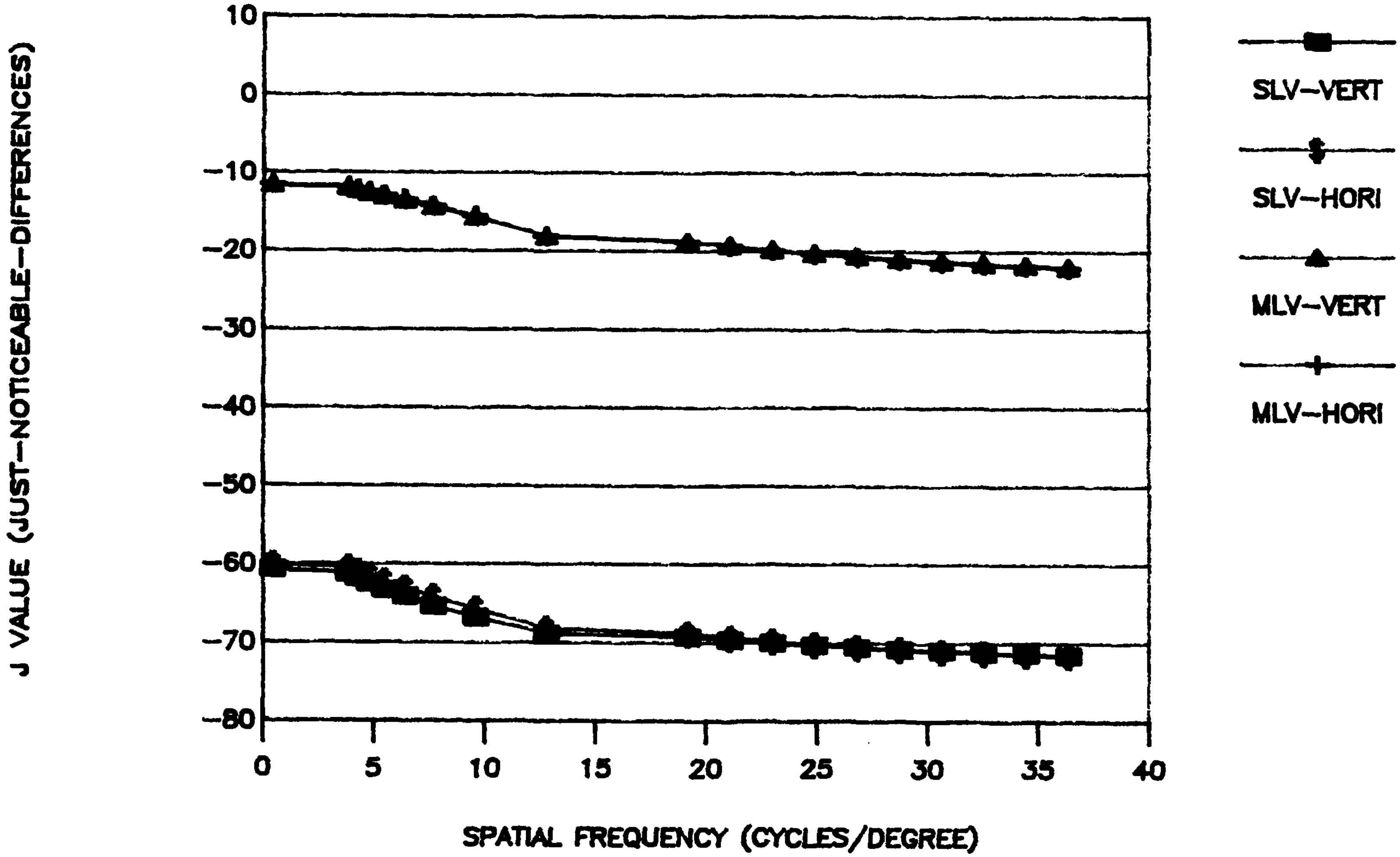

Figure 10. Cumulation of the J- Measure Over Spatial Frequency.

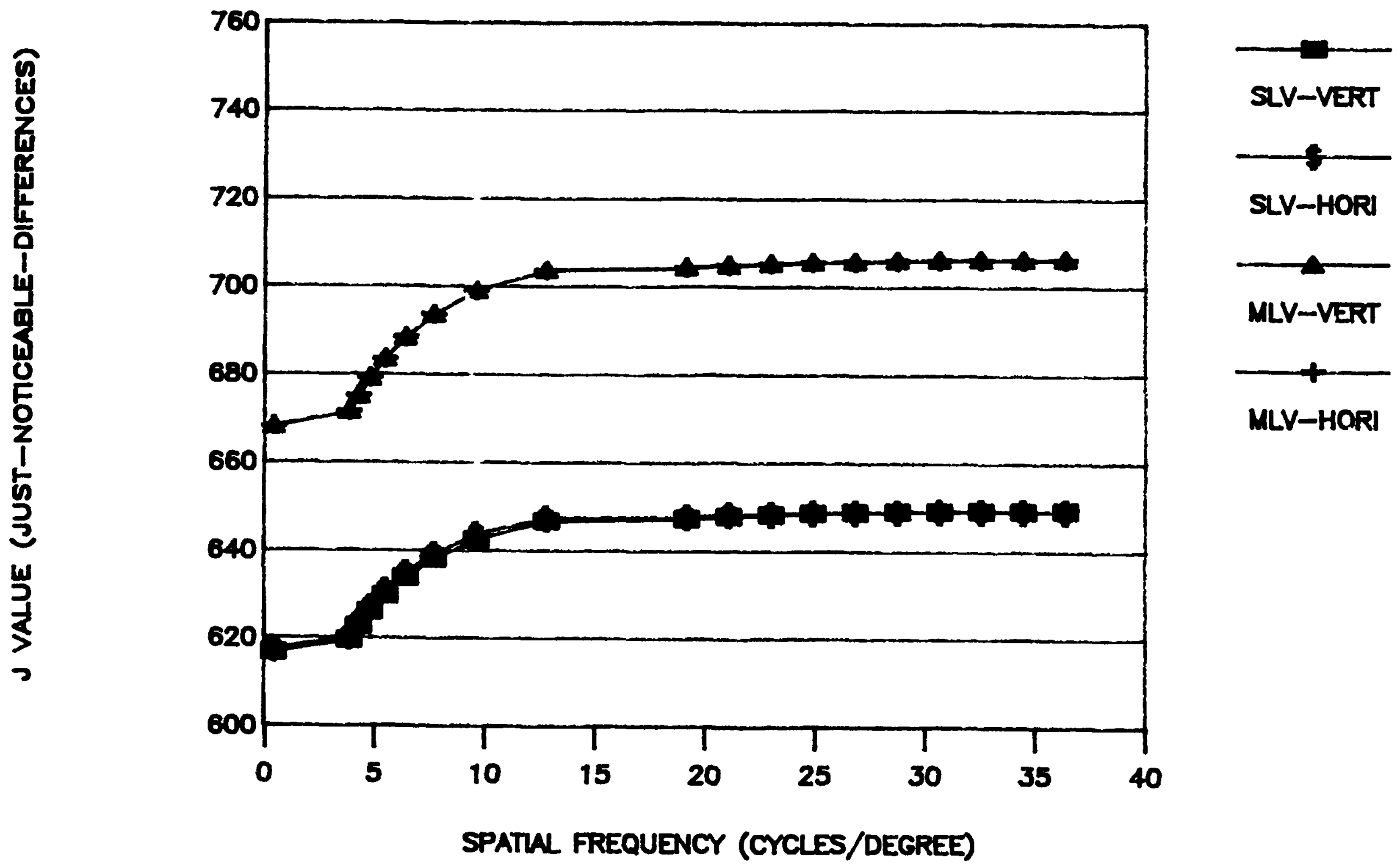

Figure 11. Cumulation of the J Measure Over Spatial Frequency.

obtained by exponential decay interpolation. The numerical integration used to compute J- and J was the trapezoid method based upon linear interpolation between individual data points. We found that by changing the interpolation method between a frequency of zero and 3.83 cycles/degree for the modulation depth data, a difference of greater than 1 jnd resulted in the J- measure. Because the empirical collection of the modulation depth data can hardly be considered a precise process in most instances, it is likely that the J- and J measures may be sensitive to sampling errors made in the data collection process at low frequencies.

In order that we might examine the effects of MTF sampling more carefully, we made small perturbations to the sample MTF data points and recorded the changes in the SQRI metrics. For this analysis, we chose modulation depth sampling points from the MLV for vertical resolution and created two new data sets by altering the first five modulation depth data points. The first five MTF sampling points for the empirical data were: .971, .852, .847, .841, and .840. In order to lower image quality, we lowered these values to .960, .840, .840, .840, and .835 for the first data set. In order to raise image quality, we raised the initial values to .98, .86, .85, .85, and .845 for the second data set. The resulting J- and J values for the original and altered MTF curves were as follows:

	Original MTF	Lowered MTF	Raised MTF
J-	-22.1	-25.9	-18.9
J	706.4	702.5	709.5

Lowering or raising five of the sample MTF points by less than 1% led to changes of more than 3 jnd's for J and J-. Errors of this magnitude or larger for single points in the sampled MTF are quite common. However, errors of the same bias (positive or negative) for five sampled points would be less likely, but they could occur due to errors in focusing the photometer or due to directional properties of display luminance as measured from the photometer.

VII. CONCLUSIONS

The image quality of a display system is determined by a number of components which combine in an interactive fashion. The primary factors considered in this report were display luminance, modulation transfer function (or some measure of display contrast capability as a function of spatial frequency for the device), and resolution capability in terms of, for example, number of raster lines and pixels per raster line. Although these factors will account for a majority of the variability in determining static, achromatic display quality, other factors not considered in this report include temporal and color properties, and nonlinear factors in display imaging.

Two image quality metrics explored in this report were the MTFA and the SQRI metrics. Results obtained by the MTFA method correlate highly with the area under the display MTF metric. The MTFA metric does, however, make a subtractive compensation from image quality at the high spatial frequency end of the spectrum when the display modulation is not above the visual threshold for the observer. The SQRI measure developed by Barten (1987) combines the display information differently than the MTFA and results obtained do not necessarily correlate well with the area under the display MTF.

Barten's SQRI metric contains two measures, J and J-, which were shown to be related to one another by a factor considered to be the J measure of an ideal display device. That is, J- denotes image quality relative to an ideal display (ideal in terms of the fact that the MTF equals 1.0 at all spatial frequencies or the display passes all spatial frequencies without any degradation in energy). From the analyses in this report it was found that:

(1) Barten's J- measure of image quality decreases with increases in display luminance--contrary to what should happen to image quality when display luminance is included as a factor.

(2) Systems employing different display resolutions or, for example, number of raster lines or pixels cannot be compared using the J- measure. Systems with greater resolution in terms of number of lines will have a worse J- estimate when all other display factors are equal. This is contrary to what an image quality measure should yield.

(3) The use of unnormalized and normalized MTF curves can be problematic to image quality metrics in general.

(4) The emphasis that the J- and J measures place on low spatial frequency information does not appear to correlate well with the human cognitive process of image quality interpretation. Such emphasis on low spatial frequency information also appears to make the measures overly sensitive to small precision errors in the data collection process and insensitive to changes in display luminance or resolution.

The conceptual explanation of findings (1) and (2) with respect to the mathematical formulation of J- is that although the image quality of a real system improves with increments in luminance and display line resolution, the ideal system (i.e., one which passes all spatial frequencies perfectly) improves more with such improvements in the display parameters. The J- measure reacted incorrectly to changes in display luminance and resolution, whereas Barten's J measure responded in the correct direction to improvements in display luminance and resolution but, as (4) points out, was highly insensitive to changes in these factors. Because luminance and resolution play more of a role in the high-frequency end of the calculations, the J measure greatly underestimates the contribution of luminance and resolution to overall image quality because of the relative emphasis on effects occurring at low spatial frequencies. Small improvements in modulation depth at low frequencies tended to cancel out any effects occurring at high spatial frequencies in the overall determination of the J measure. By normalizing the MTF curves in the first analysis section, the J measure was able to perform better in that modulation differences at very low frequencies were effectively cancelled. This made high spatial frequency effects associated with display luminance and resolution more noticeable in the SQRI metric. Under these normalized conditions, the incorporation of display luminance and display line resolution into the J measure allowed the SQRI metric to "rearrange" the rank-order predictions of the MTF curves. As shown in the previous section, though, normalization of the single and multiple light valve MTFs made them less discriminable for use in the J measure of the SQRI metric.

Another feature of the SQRI metric was that a change of one unit in measurement denoted a psychological just noticeable difference (jnd). From the simulations performed in this report, however, it is unclear whether a one-unit change in J signifies a psychological jnd. Only psychophysical experiments will reject or support this notion concerning Barten's SQRI method.

One of the major points that surfaced from this research concerns the use of the MTF curve. It is clear that for the same average display luminance, greater modulation depth implies a better quality display. However, examples provided in this report have shown that a display with a high dark field and peak luminance may have less modulation depth than a display with very low dark field and peak luminance values. Image quality metrics will treat the increase in modulation as an improvement in image quality, but intuitively we know that the display with greater luminance but decreased modulation will yield better image quality. Normalization of the MTF curve results in a loss of absolute information concerning modulation depth. As shown in this report, normalization of modulation depth curves can cause reversals in the image quality measure.

In addition to these factors, it is clear that the MTF curves are functions of display luminance. For any single display, a number of MTF curves may be generated as a function of luminance. The MTF curve may improve or worsen with increases in luminance, depending on other components within the system. The fact that these MTF curves can be measured for different display luminances introduces more ambiguity into the process by which we determine image quality.

Maximum luminance values for display systems used in the first section of this report varied from 33 cd/m^2 to 1633 cd/m^2. As shown, modulation at low luminance levels may in many instances be greater than modulation at higher luminance levels due to normalization of the difference in target and background luminance by twice the average luminance. For this reason, low-frequency modulation depth values of the different systems were found to be reversed from what was logically expected in some instances. Normalization of the MTF curves artificially removed these unexpected reversals. However, this type of correction mechanism is misleading because, in some cases, normalization erases important MTF information pertinent to display comparisons.

Because the display MTF has always been a primary driver in determining image quality, the ambiguity resulting from generating these MTFs, through either the direct or the indirect method, is disturbing. Use of any image quality metric cannot be justified until some type of MTF standardization is agreed upon. Once this problem is solved, the fact will remain that little psychophysical work has been applied to generating image quality metrics. Currently, Carlson and Cohen's (1980) summation of jnd's across the seven spatial frequency channels represents the majority of work along these lines. Experiments which simulate a variety of display MTFs by artificially filtering images and subsequently measuring observer preferences or detectable difference thresholds would be useful for getting a qualitative feeling for what denotes a significant difference in MTFs. For example, MTFs with the same amount of total area under the curve but emphasizing differing amounts of modulation depth at higher frequencies could be compared through filtered imagery for preference and threshold detection tasks.

Most likely the determination of significant differences in MTFs will be task-dependent. That is, image quality based on performance of detection, recognition, and identification tasks might require one weighting scheme of spatial frequency-based information while image quality based on observer preferences for imagery might require another. This hypothesis could be tested by presenting filtered images to observers in performance and preference tasks.

As mentioned earlier, color and motion were not addressed in the present analyses. These two factors are critical to some aspects of image quality but have yet to be integrated with brightness, contrast, and resolution in a quantitative formulation of image quality. Color space reproduction in visual displays is a well-studied phenomenon (e.g., Wyszecki & Stiles, 1982). From an image quality viewpoint, color will be a major contributor to observer preferences. From a performance viewpoint, however, color appears to serve as an attention-orienting mechanism. Observers can quickly orient their attention to areas in a display which are color-coded, and efficient use of such coding can be quite useful in those tasks which require quick reactions. The attention-orienting value of color, however, is not an issue for basic detection, recognition, and identification performance tasks unless stimuli are color-coded.

It is clear that color perception directly interacts with display brightness. Interaction of color with contrast and resolution is not as straightforward, though. Probably one of the major drawbacks to including color along with the parameters of brightness, contrast, and resolution in observer preference studies is that the manipulation of color reproduction quality is not naturally a unidimensional manipulation, as is the case with the other parameters. For example, with brightness we simply increase display luminance to produce better image quality.

Perceived motion for visual displays depends on the display update rate, the refractory period of the material creating the image (e.g., phosphor, plasma), and the computational mechanism used for translating the image in space on successive presentations. The application of these components to image quality determination is quite complex and task-dependent. For example, by lowering the phosphor decay rate (i.e., using slow phosphors), brightness and contrast may be increased through temporal summation. However, the slow phosphors used in older versions of Army night-vision goggles caused excessive blurring when these devices, designed for slow-moving vehicles, were modified for use in helicopters. Representation of the temporal domain in human neural circuitry will add greatly to the complexity required of image quality metrics.

Neglecting the issues of color and motion, we return to a static, achromatic view of image quality. In this report, we have evidenced how the SQRI and MTFA metrics can be used to obtain reasonable rank-order correlations with more empirical image quality measures. At a deeper level of analysis, though, the ambiguities in the display MTFs become more apparent. The metrics, while correlating on an ordinal level with changes in physical parameters, fail to register the significance of changes in factors such as overall luminance and resolution. In the present report, we stress the importance of having a metric which integrates physical parameters in such a way that the relative importance of these parameters to image quality is characterized in the metric.

It is doubtful that the currently devised metrics could withstand the large variety of testing and analyses to which an image quality metric must be amenable. Thus, although the current metrics presented here have their shortcomings, modification of these metrics based upon new psychophysical experiments is the most logical route for improved image quality metrics.

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