The Modulation Transfer Function of the Human Visual System at Selected Spectral Frequencies

George L. Ayers
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by

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Photographic Science 4

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The Modulation Transfer Function of the human visual system has been determined with a sinusoidal test target, by measuring the threshold contrast as a function of spatial frequency, for monochromatic light of constant average luminance. Data were obtained for a broad band range and wavelengths of 538 and 617 nm.

It is shown that a maximum MTF occurs at frequencies between 20 - 30 cycles/mm on the retina and that this sensitivity decreases for both lower and higher frequencies. Small but discrete differences appear in the curves for broad-band radiation and the green and red filtration at the photopic luminances.
INTRODUCTION

The usefulness of describing the human visual system by the principle of modulation transfer function was realized by Westheimer\textsuperscript{26} in 1959. He termed this measure of the eyes ability to distinguish fine detail modulated in a sinusoidal fashion the "Contrast Sensitivity" of the eye. Fringes were created directly on the retina of the eye by an apparatus based on Young's double slit interference method. This gave a system free from defocussing of the optics or aberrations. The light source however, was not coherent and problems arose in the interpretation of data in the photopic regions. This investigation yielded data based on quantitative description with direct measurements of a variable frequency sinusoidal pattern at threshold luminances.

A similar paper\textsuperscript{4} (Campbell and Green, 1965) updated methodology and used a split beam of a neon-helium laser (632.8 nm) to produce an image directly on the retina without involving the optical system of the eye. This also gave a measurement of the RETINA-BRAIN resolving power of interference patterns modulated sinusoidally.

Recognition of this pattern as an actual grating was found to be difficult. Campbell and Green describe it as that of "a scintilating area brighter than the surrounding field and also desaturated in colour compared to the rest of the field. It is presumably due to beating between the periodic fringes and the regular pattern of the retinal mosaic". This effect occurred at high spacial frequencies.

In the course of a sub-experiment these investigators were concerned with the resolving power of the visual system and the
effect wavelength would induce on the shape of the contrast sensitivity curve. Filters chosen in conjunction with the spectral emission of the oscilloscope phosphor (used to create the sine-wave patterns) gave a blue and orange test field (480 and 600 nm). Inspection of the resulting curves showed no differences in the shape of the two curves.

Campbell and Gubisch (1966) using a double pass technique studied the effect of pupil aperture and fundal qualities on the line spread function. Calculations transforming the line or point spread functions into modulation transfer data require two major assumptions concerning the optical system. These assumptions however, are only partially satisfied by the eye. The first is ISOPLANASIA. Isoplanasias ia fulfilled at the fundal areas but at off-axis portions loses this because of retinal curvature and to some extent on small foveal impressions or pits. This precipitates marked errors in line spread distributions since only the average values can be calculated. These errors can be large when M.T.F. is calculated from image distributions of small targets.

Secondly in the transformation from spread function to M.T.F. symmetry in the light distribution must be maintained. However, for astigmatized or decentred optical systems it would be unrealistic to make this supposition.

"On the other hand, the light distribution of straight lines or grids may be derived with a good all-over accuracy".

Further reading suggests that the majority of experiments used either a broad band analysis (white light) or a region corresponding to maximum eye sensitivity.

Few investigations have been completed in the determination
of how the visual system responds to different spectral frequencies.\textsuperscript{4, 24, 25}

Schlaer, Smith and Chase\textsuperscript{24} (1942) determined the visual acuity at two restricted spectral regions (670 and 490 nm) in order to gain maximal separation of the rod and cone functions. The first test target used was a broken circle (C) with the break equal to the width of the line forming the circle and one-fifth its outside diameter and the second field was a grating having opaque and transparent bars of equal widths. It was found that the red light data which represents relatively pure cone vision fell on a single continuous curve. Blue light data on the other hand fell into two distinct groups. Values below a certain luminance value (0.03 photons) represented rod vision and those immediately above combined the rod and cone vision to produce an effect of superadditivity of the mixture. This area produced a higher response in terms of visual acuity.

These investigators emphasized three major limiting factors of visual acuity. The primary factor is pupil size. Since the variance of pupil diameter causes marked variance in visual acuity especially in the longer wavelength radiation careful consideration must be given to this factor. Schlaer, Smith and Chase maintain that a pupil diameter of 3mm is sufficient to transmit the zero order spectrum of the test grating plus at least one first order spectrum and also give maximal acuity data. Secondly, inhomogeneity of the light source creates chromatic fringes in the image. Finally it is theorized that under certain conditions, the diameter of the foveal cones may constitute a limiting factor if the geometric retinal image is in fact smaller than the actual cone diameter.

(5)
In 1965 Van Nes and Bouman 25 studied the effect of wavelength and luminance of the visual modulation transfer. Data was obtained for three values of monochromatic light (450, 525, 650 nm) of constant average luminance. Threshold modulation was defined to be the average of the "grating just visible" and "no grating visible" luminances. The results obtained were for the right eye of one subject who was 3 diopters myopic. The target itself was viewed by a chemically accommodated eye through an artificial pupil and external optically system comprised of five elements.

Van Nes and Bouman found "there is little differences at photopic luminances in the modulation transfer function curves for the red, green and blue wavelengths.

However, it is left to the reader to interpret any differences in the data curve functions. It would seem reasonable in most instances to make decisions about and predict differences in curves based on the fact that they are drawn separately yet quite closely together. The authors have employed no statistical analysis in organizing the data to clarify or repudiate conclusions they have extracted from data obtained experimentally. Quantitative methods were employed to obtain the data which was subsequently subjectively analyzed for the presentation.

Again in this region of experimentation there has been no estimation of "between" and "within" subject variation. Certainly there must be some observer error involved and a calculated statistical analysis would present this information clearly to the experimenter.

It is the intention of this investigation to treat the raw
data in a statistical manner in order to clarify and substantiate the conclusions drawn. It is felt that an analysis of variance technique coupled with observer replication would yield a valuable estimate to both curve functions and within subject variability. This technique would also allow investigation of between observer variability.

Many of the previous investigators involved atropinization of the eye with the addition of an artificial pupil and external optical systems.\(^3, 4, 5, k8, 24, 25, 27\) It must be recognized however, that the human visual system which has been chemically accommodated and with external apertures does not necessarily conform in any known manner with the eye under actual viewing conditions. Depalma and Lowry recognized this fact\(^16, 17\) and theorized that since pupil diameter versus luminance functions have been extensively investigated\(^6, 19, 23\) a stringent control of mean luminance value in the system would afford a similar control of pupil (aperture) diameter. This control does not take into account several major pupillary reactions which must be considered if no chemical influence is involved.\(^15\) The pupil reacts to near vision causing a contraction of the pupil which is associated in some manner with the convergence of the eyes and accommodation of the lens. Spontaneous thoughts or emotions elicited by stimuli either by the apparatus in the experiment itself or consequentially cause pupillary dilatation. Spontaneous or reactive changes in the level of consciousness or neurologically speaking changes in the degree of cortico-thalamo-hypothalamic activity affect the pupillary reflex dilatation. It increases with emotional stimuli and decreases with fatigue by increasing or decreasing the sympathetic impulses which reach the dilator pupillae muscles in
the iris.

Pupillary movements can also be caused by an intentional short closing of the eyelids. This Lid-Closure reflex consists of a short contraction and then redilatation.

Finally, there exists apparently spontaneous oscillation of the pupil under steady conditions of illumination which have no direct liaison with any other reactions. When the eyes are exposed to long-lasting light stimulation the pupils contract, then redilate partially and begin to oscillate. In dim illumination as for threshold readings the pupils become quite large and quiet as they would be in darkness. As the intensity of the stimulation is increased the mean diameter of the pupil becomes smaller and the rate of oscillation increases accordingly.

It would appear then that there are two alternatives for eliminating the interference of pupillary oscillation. The first would involve a pre-experimental investigation to test the hypothesis that there is no insignificant variation of pupil diameter for the observer under the experimental conditions. This would involve sophisticated and expensive apparatus and cannot be employed in this particular investigation.

The second method involves the dilation of the pupil chemically. This can be achieved with only a minimal affect on accommodation by using a mydriatic drug. Each observer would have to be individually tested as to the exact effect the drug would propagate. This method, although using an artificial pupil for exact control of pupil response would eliminate external pieces of optical apparatus.

It may be argued that we now have created an unnatural viewing condition which bears little semblance to real-life
conditions. However, control over pupil size must be carefully maintained either by an appropriate apparatus included in the instrumentation to maintain a running control or by removing the psychological and physiological incongruities from the system.

In this respect a more accurate study of the viewing conditions can be estimated. There will be no need to speculate what the effects will be if external optics are added to the system to maintain focus for the chemically dilated pupil. The fact that any optics between the object space and image space must degrade the sinusoidal light distribution is a major factor which cannot be disregarded as has been done in many investigations.

It is felt that the latter course of action would yield the most consistent results but it involves constant medical attention during the process. For this reason past data gathered by other experiments \(6, 19, 23\) must be relied on to supply adequate information of pupil size and conditions.
The modulation transfer function of a transilluminated system is defined as the contrast ratio at the modulation of the output to that of the modulation of the input of a sinusoidally distributed target. This approach is widely applied in the photographic industry to the response of a receiving layer (the emulsion) or the light dispersion characteristics of an optical system. Provided there is linearity in the system any number of component parts can be deduced from sufficient knowledge of the aggregate. Another fundamental advantage of using a sine-wave target is that the modulation remains sinusoidal even when imaged by a poorly focussed or imperfect optical system.

In this type of physical arrangement a measurement is made of the output magnitude for a constant input magnitude of variable frequency. In this context it is difficult to correlate the purely physical system to a psychophysical visual system. Although the input values are physical measurements of the light modulation of sine-wave test target, the output values can by no means be described with this extreme accuracy since it is a quantity which does not permit observation in the physical sense.

During this investigation the response variable for the output will be the reciprocal of threshold contrast or modulation transfer function. In order to assume the linearity needed for mathematical manipulation of the function certain conditions need be clarified. One major supposition is that the internal noise level of the visual system is a constant value. It will therefore, be assumed in this paper that if the recognition of
high spacial frequency targets is limited by an internal noise source that the noise level is independent of the different frequencies and the output contrast of threshold measurement is constant. Therefore, the contrast loss in passing through the apparatus and visual system is the reciprocal of the THRESHOLD CONTRAST at the input end. Consequently the reciprocal of contrast threshold is defined by the same parameters as modulation transfer function and can be substituted for it as the function plotted against spacial frequency.

The concept that \((\text{THRESHOLD CONTRAST})^{-1}\) is a good first order approximation of modulation transfer has been further substantiated in a communication with Mr. J.J. DePalma (Kodak Research Laboratories, June 19, 1968).
OBJECTIVES

PART I

To test the hypothesis that the modulation transfer function (reciprocal of contrast threshold) as generated by a sinusoidal target of diminishing spatial frequency on the human visual system changes as a function of spectral frequency.
1. Microdensitometer technique was used to determine the maximum transmittance, $T_{max}$, and minimum transmittance, $T_{min}$.

The method will follow closely that of Deperlu et al. and Leddy, C.M. (1962) which made use of the following quantities:

- $L_{max}$ = maximum luminance of test object at zero retinal
- $L_{min}$ = minimum luminance of test object at zero retinal
- $L_{max}$ = maximum transmittance of test target
- $L_{min}$ = minimum transmittance of test target
- $L = $ luminance
- $V_0 = $ special frequency of test target cycle
- $V_1 = $ special frequency of retina
- $M = $ magnification
- $P_0 = $ object distance (mm)
- $P_1 = $ effective image distance (mm)
- $P_2 = $ filtration (mm)
- $P_{VL} = $ viewing luminance

Resolution

Each Fixation Point of $F_{2A1}$ has $R \cdot C_{11}$

Each Fixation Point of $F_{2B1}$ has $R \cdot C_{11}$

Each Fixation Point of $F_{2C1}$ has $R \cdot C_{11}$

Analysis of Variance

Conclusion

Figure 1

(13)
EXPERIMENTAL METHOD

1. Microdensitometer traces are made of the sinusoidal test target at each spatial frequency to determine the maximum transmittance $T_{\text{max}}$ and minimum transmittance $T_{\text{min}}$.

The method will follow closely that of Depalma, J.J. and Lowry, E.M. (1962) which made use of the following quantities.

- $B_{\text{max}}$ = maximum luminance in test object at threshold
- $B_{\text{min}}$ = minimum luminance in test object at threshold
- $T_{\text{max}}$ = maximum transmittance in test target
- $T_{\text{min}}$ = minimum transmittance in test target
- $B_o$ = luminance of test target
- $V_o$ = spatial frequency of test target cycles/mm
- $V_r$ = spatial frequency of retina
- $M$ = magnification
- $P_o$ = object distance (mm)
- $P_1$ = effective image distance (mm)
- $F_2$ = filtration (nm)
- $B_{VL}$ = veiling luminance
SCHEMATIC OF MTF INSTRUMENTATION

M₁  Beam Splitting Mirror
M₂  Front Surface Mirror
H   Integrating Box
L   Tungsten Light Source (300 watts)
O₁, O₂ Opal Glass Diffusing Screens
F₁  Test Filters
F₂  Neutral Density Filters
T   Sinusoidal Test Targets with viewing aperture included

Figure 2
(15)
The test targets are inserted in the finish lucite assembly of the integrating cone (fig 2). Deadpaint or as to be evenly illuminated in the 200 candle power range. The binocular observation distance is fixed at 10 inches from the viewing post or 14 inches from the sinusoidal target. Instead of 2 fixed position xenon controlled light sources, a single 300 watt, moveable tungsten filament illuminates the target. System components consist of 3 front surface mirrors mounted at 45 degree angles \( X_1 \), opal glass screens \( O_1 \), \( O_2 \), a set of filters \( F_1 \), \( F_2 \). The opal glass forms a uniformly illuminated background, eliminating the filament image on the transilluminated target \( T \) and the veiling luminance surround. Filters \( F_1 \) consist of a Wratten No 58, Green and Wratten No. 25 red as well as a broad band analysis while \( F_2 \) consists of a series of graduated neutral density filters used as needed. The target frequencies vary from a source 3/8 c/m to 6.0 c/mm.

The target size will be 1 inch in length by 1/2 cm, width and the veiling luminance will provide a surround of 25 cm square. The surround will be of the same spectral content as the target.

The observer views the target and fixation point through the veiling luminance, an opal glass diffusing screen, filters, and a beam splitting mirror \( M_1 \). The purpose of the veiling luminance is to provide a control of the surround content at a fixed level for each test target and to provide a means by which the contrast can be varied.

The only optics in the way of the object space as seen by the observer is the partially transmitting mirror \( M_1 \). This
The test targets are inserted in the front filter assembly of the integrating cone (fig 2) designed so as to be evenly illuminated in the 200 candle power range. The binocular observation distance is fixed at 2 inches from the viewing post or 14 inches from the sinusoid target. Instead of 2 fixed position reostat controlled light sources, a single 300 watt, moveable tungsten filament illuminates the target. System components consist of 3 front surface mirrors mounted at 45 degree angles \( (M_2) \), opal glass screens \( (O_1, O_2) \) and a set of filters \( (F_1, F_2) \). The opal glass forms a uniformly illuminated background, eliminating the filament image on the transilluminated target \( (T) \) and the veiling luminance surround. Filters \( F_1 \) consist of a Wratten No 58., Green and Wratten No. 25 red as well as a broad band analysis while \( F_2 \) consists of a series of graduated neutral density filters used as needed. The target frequencies vary from a coarse 3/8 c/m to 6.0 c/mm.

The target size will be 1 m. in length by 1/2 cm. width and the veiling luminance will provide a surround of 2.54 cm square. The surround will be of the same spectral content as the target.

The observer views the target and fixation point through the veiling luminance, an opal glass diffusing screen, filters, and a beam splitting mirror \( (M_1) \). The purpose of the veiling luminance is to provide a control of the surround content at a fixed level for each test target and to provide a means by which the contrast can be varied.

The only optics in the way of the object space as seen by the observer is the partially transmitting mirror \( (M_1) \). This
obstacle can be mathematically removed from the system once its MTF value is determined.

In making a threshold observation, the carriage of the moveable filament is placed so as to give the test target the maximum contrast and visibility. The rooms lights are turned off and the subject is required to wait 60 seconds before the test target is illuminated. When the apparatus is switched on the subject views a test target with both eyes with the surround and vieling luminance at a minimum brightness. The carriage is then slowly moved forward to increase the vieling luminance and reducing the target to threshold detectibility. The filters are the removed.

When a threshold setting has been accomplished, photometer readings are made of the vieling luminance BV₂ and the cone luminance B₀.

The modulation transfer is described as

\[ MFF = \frac{B₀T_{\text{max}} + B₀T_{\text{min}} + 2BVL}{B₀T_{\text{max}} - B₀T_{\text{min}}} \]

In investigating the effect of the MTF, it is most usefully expressed as a function of spatial frequency on the retina, \( V_r \). The spatial frequency on the retina is computed from the spatial frequency in the test object by the following relationship:

\[ V_r = V_o \cdot \frac{1}{M} = \frac{P_o}{P_I} \]

In calculating \( V_r \) for each test object and for each viewing situation, the usually accepted value of 17 mm was used as the effective image distance PI. This is the distance from the second nodal point of the eye lens to the retina.
RESULTS

All results are for binocular vision of four observers, each having individual eye characteristics. Figures 3 - 6 give the response of each observer to the test conditions for broad-band radiation as well as green (538 nm) and red (617 nm) filtration. The horizontal axis has been mathematically remodelled to read in retinal spatial frequency rather than that of the target frequency.

The three parameters all produce a maximum in sensitivity or minimal threshold at about 20 - 30 cycles/mm ($V_m$). For photopic luminances, thresholds for spatial frequencies smaller or greater than $V_m$ are higher.

Figures 7 - 9 show the response of each observer for each filtration level. All curves take the same general shape but are displaced according to the specific observer characteristics.
KLEIN - 14 AUGUST

SPATIAL FREQUENCY - RETINA

MYOPIC RIGHT = 1.75 + 2.50 AXIS 10
LEFT = 1.75

PUPIL DIAMETER 3.4 mm average

Figure 3
Figure 4
Figure 5

McELROY - 12 AUGUST

Spatial Frequency - Retina

Myopic Right = 4.00
Left = 2.75
ROAD-BAND ANALYSIS
1 - KLEIN
2 - MORETON
3 - McELROY
4 - SOUTHWELL

Figure 7
Missing Page
RED FILTER - No. 25
1 - KLEIN
2 - MORETON
3 - McELROY
4 - SOUTHWELL

Figure 9
CONCLUSIONS

It has been shown that, using the Contrast Threshold criterion, the Modulation Transfer is a function of spatial frequency and spectral content and has a maximum sensitivity at about 20 - 30 cycles/mm. From this maximum MTF, the sensitivity to the sinusoidal test target decreases for spatial frequencies of both higher and lower content. This relationship was maintained by all wavelengths tested. This maximum response surrounded by a decreasing response suggests the interaction of two distinct mechanisms. This could be explained by assuming a low-pass component associated with the optics of the eye lens, ocular media, pupil diameter, and the retinal mosaic diffusion. By experimentation Flamant has determined that the high-pass component of the visual system appears to be intimately related to the inhibitory processes taking place from the retinal mosaic to the brain. This is composed of a complexity of interrelated mechanisms; neural, chemical, electrical, and psychological.

There is a small but distinct degradation of the observer MTF as the spectral band is shifted from the bare filament to green to red. This can partially be explained by realizing that the retina is a thin sheet of interconnected nerve cells, including a mosaic of photoreceptive rod and cone cells. The cones function in daylight or photopic conditions and have a peak sensitivity to radiation of about 560 nm while at 617 they have a much lower response. The retinal surface around the fovea is composed almost entirely of cones and so the response of the eye in this area is completely dependent on the cones. This, combined with the possible interaction of pupillary diffraction would cause the response in the red region to be lower.
APPENDIX

OBSERVERS

1. Miss Jo Ann Klein  
   Age 20  
   Myopic Right - 1.75 + 2.50 Axis 10  
   Left - 1.75

2. Mr. Wayne Moreton  
   Age 22

3. Miss Louise McElroy  
   Age 19  
   Myopic Right - 4.00  
   Left - 2.75

4. Miss Janet Southwell  
   Age 19  
   Myopic Right - 5.50 + 0.50 Axis 90  
   Left 4.00 + 1.00 Axis 8.0

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<td>95.4</td>
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PUPIL SIZE

\[
\frac{1.5}{\pi} \times 10.8 = 5.15 \text{ Trolands}
\]

According to Lowenstein, O., and Lowenfeld, I.E., 5.15 Trolands would give a pupil diameter of 3.4 mm. This would of course be only the average pupil diameter with oscillations continually occurring.
The blue filter was not used since it caused defocussing problems with the optics of the eye.

SAMPLE CALCULATION SHEETS - SEE figures 10, 11.

Only two runs for each observer could be made in the time limits placed upon completion. Each run consisted of 120 pieces of information and lasted for two to two and one half hours. For this reason the analysis of variance technique was not employed. The instrumentation and observer error varied with the wavelengths of light used and with the sinusoidal target. An averaging technique was employed in order to plot the final curves.

Figure 12 shows an average MTF for broad band, green and red filtration for all the observers. If enough measurements had been carried out this would be the standard MTF response curves for the average visual system.

An interesting side experiment undertaken substantiates the fact that a given color looks brighter if its surroundings are its complimentary colour. The Wratten No 58 and No 25 filters were again matched in luminous transmittance and then the red filter was placed in the target assembly and the No 58 was placed in the beam of the vieling luminance. This gave a target of green and red bars surrounded by a green field. When the red bars disappeared threshold was assumed. Fig 13 graphs the results. Contrast enhancement seems
to be directly related with the general importance of border effects in perception. Additional experimentation in this particular area may lead to an enhancement of high altitude aerial instrumentation visibility.

Time did not permit the use of the MTF data reduction for the beam splitting mirror. Additional work should be done to eliminate this entirely from the data.
SAMPLE
VISUAL MTF RECORD SHEET

OBSERVER ___________________   AGE _______

DATE _______________ 19_   P_o __________

TEST NUMBER ___________  ND FILTER __________

VIEWER LIMITATIONS AND REMARKS

____________________________________________________________________________

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OBSERVATION CONDITIONS

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FIGURE 10

George L. Ayers
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ADDITIONAL COMMENTS

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George L. Ayers

Date
A - RED TARGET ON GREEN SURROUND
B - GREEN TARGET ON RED SURROUND

RELATIVE PERCENT MODULATION

SPATIAL FREQUENCY - RETINA

FIGURE 13
REFERENCES


11. HECT and MINTZ, (1939) Visibility of single lines of various luminances and the retinal basis of visual resolution. J. Gen. Physiol (22) pps. 593-612.

23. SHLAER, S., (1937) Relation between visual acuity and illumination. J. Gen Physiol (21) pps. 165-188.

ADDITIONAL RELATED LITERATURE


B. HUBBARD, R; KROPF, A; Molecular isomers in vision Sci. Amer. Vol 216, No 6 June 1967 pps. 64-76.


