The Subjective Sharpness of Simulated Television Images

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1. Introduction and Summary

OF the many factors which influence the quality of a television image, the one which is generally indicative of the value of the image and the cost of its transmission is the resolution, or sharpness. This resolution factor has always been reckoned in purely objective terms, such as the number of scanning lines, or the number of elemental areas in the image, or the width of the frequency band required for electrical transmission at a given rate. The subjective value of sharpness has not previously been considered. Some recent tests with a small group of observers, using out-of-focus motion pictures in a basic study of the visual requirements on images of limited resolution, have thrown new light on the evaluation of resolution and sharpness. The results appear of sufficient interest, particularly when interpreted in terms of television images, to warrant this presentation. We shall use the word *sharpness* in the sense of a subjective or psychological variable, with a strict technical significance in keeping with our experimental method, and we shall use the word *resolution* in the sense of an objective or physical variable.

We find that as images become sharper, their sharpness increases more and more slowly with respect to the objective factors. We find also that as images become sharper the need for equal resolution in all directions becomes less and less, and that with images of present television grade the tolerance for unequal horizontal and vertical resolutions is already remarkably wide. These conclusions are supported by our experiments with small-sized motion pictures viewed at a distance of 30 inches, about 4 times the picture height. It would not be safe to extrapolate the results of these experiments to the large-screen conditions of motion-picture theaters, because the visual acuity of the eye may be expected to increase with distance in the range in question,[1] and for other reasons.

2. Exposition of Method

Image sharpness is to be measured by subjective test, employing psychometric methods [2] which have been widely used in the measurement of other subjective values. Test images are to be projected onto a screen from 35 mm. motion picture film in such a way that the resolution of the image can readily be varied over a substantial range, and with provision for making the horizontal resolution different from the vertical. The use of motion pictures instead of actual television images permits sharpness to be studied independently of other factors, and facilitates the experimental procedure.

The relationship between the television image and the motion picture which simulates it will be determined on the basis of their subjective equality in sharpness. For that purpose, a television image reproduced by an apparatus * of known characteristics is to be compared with a projected out-of-focus motion picture of the same scene, under the same conditions of size, viewing distance, brightness and color. (The motion picture will in general be superior in the rendition of tone values and in respect to flicker, and will of course not show the scanning line structure of the television image or any of the degradations commonly encountered in electrical transmission.) When the two images are judged to be equally sharp by the median one of a group of observers, the size of the figure of confusion of the motion picture is to be taken as the measure of the resolution of the compared television image.

The figure of confusion of the motion picture is that small area of the projected image over which the light from any point in the film is spread. Every point produces its own figure of confusion, of proportionate brightness, and the overlapping of the figures in every direction accounts for the loss of sharpness. When the projection lens is "in focus," the figure of confusion is a minimum one set by the aberrations of the optical system and by diffraction effects. As the lens is moved away from the "in focus" position, the figure of confusion becomes larger and assumes the shape of the aperture stop of the projection lens. If the illumination of the aperture stop is uniform, this larger figure of confusion is a well-defined area of uniform brightness. We used a rectangular aperture stop, at the projection lens, whose height and width could be varied reciprocally so as to maintain constant area of opening, and we used a calibrated microscope to measure the departure of the lens from the "in focus" position. Thus we could produce images of various degrees of sharpness and of unequal horizontal and vertical resolutions.

This method of specifying the resolution of an image in terms of the size of the figure of confusion affords an important advantage. It avoids the necessity for postulating any particular relation between the resolution and the spatial distribution of brightness values about

* The television apparatus comprised a mechanical film scanner and an electronic reproducing tube designed specifically for television. A description of it is given in reference 9.

originally abrupt edges in the image. The variety of such relations assumed by others[3, 4, 5, 6, 7] has led to a variety of conclusions with respect to resolution in television. We find subjective comparison of images to yield results of fairly small dispersion.

Let us consider now the measurement of sharpness in subjective terms. Here we find no familiar units of measurement, no scales or meters. We find no agreement as to the meaning of a statement that one image looks twice as sharp as another. We can say of two images only that (*a*) one image looks sharper than the other, or (*b*) the two images look equally sharp. When the images are quite different, there will be agreement by a number of observers that the one image is the sharper. When the images are not different in sharpness, there may be some judgments that one of them is the sharper, but these will be counterbalanced in the long run by an equal number of judgments that the other is the sharper. When the images are only slightly different in sharpness, an observer may reverse his judgment from time to time on repeated trials, and he may sometimes disagree with the judgment of another observer. It is within this region of small sharpness differences, in the interval of uncertain judgments where the observer is sometimes right and sometimes wrong with respect to the known objective difference, that it becomes possible to set up, on a statistical basis, a significant quantitative measure of sharpness difference.

Suppose that in judging two images of almost equal sharpness the observers have been instructed to designate either one or the other of the images as the sharper; that is, a judgment of "equally sharp" is not to be permitted for the present. An observer who discerns no difference in sharpness is thus compelled to guess which image is sharper, and his guess is as likely to be right as it is to be wrong, with respect to the known objective difference. Suppose, further, that the sharpness difference has been made so small that only 75 per cent of the judgments turn out to be right, the remaining 25 per cent being wrong. On the basis that these wrong judgments are guesses, we must pair them off with an equal number of the right judgments, so that 50 per cent of the total are classed as guesses. The other 50 per cent are classed as real discriminations. (The pairing of an equal number of the right judgments with the wrong judgments goes back to the equal likelihood of right and wrong guesses; it affords the best estimate we can make of the number of guesses.) When real discrimination is thus evidenced in one half of the observations, that is, when 75 per cent of the judgments are right and 25 per cent of them are wrong, we shall designate the difference in resolution as the *difference limen*.*

* The term *limen* is frequently used in psychometry in lieu of older terms such as *just-noticeable-difference*, *threshold value*, *perceptible difference*, etc. It has the virtue

It is seen that the value of the limen is arrived at statistically, taking into account the variability of individual judgments. Smaller differences than the limen are not always imperceptible, nor are larger differences always perceptible.

The difference in sharpness, or in sensory response, which corresponds to a difference of one limen in resolution may be said to be one unit on the subjective scale of measurement. We shall designate this as a *liminal unit.** It will be understood that the word *liminal* has here a particular and precise significance, by reason of the one-to-one correspondence between the liminal unit and the statistically-derived value of the difference limen. A liminal unit of sharpness difference may be considered as the median of a number of values of sensory response to a difference of one limen in resolution.

3. Sharpness and Resolution

Figure 1 shows how we find the sharpness of an image to vary as the number of elemental areas in the image is changed. Sharpness is expressed in liminal units, based on measurements of the limen at four different values of resolution, indicated by the four pairs of points on the curve. Resolution is expressed as the number of figures of confusion in a rectangular field of view whose width is 4/3 of its height and which is viewed at a distance of 4 times its height.† This conventional field of view was chosen as typical of viewing conditions for motion pictures and television images. (The conventional field is 19° wide by 14° high.) The range of the curve in Fig. 1 may be stated very roughly as from 150-line to 600-line television images.

The significant feature of this curve is its rapidly decreasing slope with increasing sharpness. It shows that sharpness is by no means proportional to the number of elemental areas in the image, and demonstrates that the use of objective factors as indices of sharpness should be regarded with more than the usual amount of caution. It shows

that its meaning may be precisely defined in terms of the particular experimental method under consideration, without the extraneous significance which might attach to the more commonplace words.

* There seems to be no accepted name for such a unit. Guilford[2] calls it simply "a unit of measurement on the psychological scale." In discussing the measurement of sensory differences which are equal to each other but not necessarily of liminal size, the terms "sensory value" and "scale value" have been used.

† We have used relative values here in order that our results might be applied to other images not too different in size from the small ones we actually used. Other values of aspect ratio in the neighborhood of 4 to 3, and other values of viewing distance in the neighborhood of 4 times the picture height, may be brought within the scope of our data on the assumption that the sharpness is the same if the solid angle subtended by the area of the figure of confusion is the same. For example, a square field of view containing 60 thousand figures of confusion, and viewed at 5 times its height, would be equal in sharpness to our conventional field containing 125 thousand figures of confusion $[125 = 60 \times 4/3 \times (5/4)^2]$.

that images of present television grade are well within a region of diminishing return with respect to resolution, a region, however, whose ultimate boundary is still well removed. (We estimate that the sharpest image our motion picture machine could project would be repre-

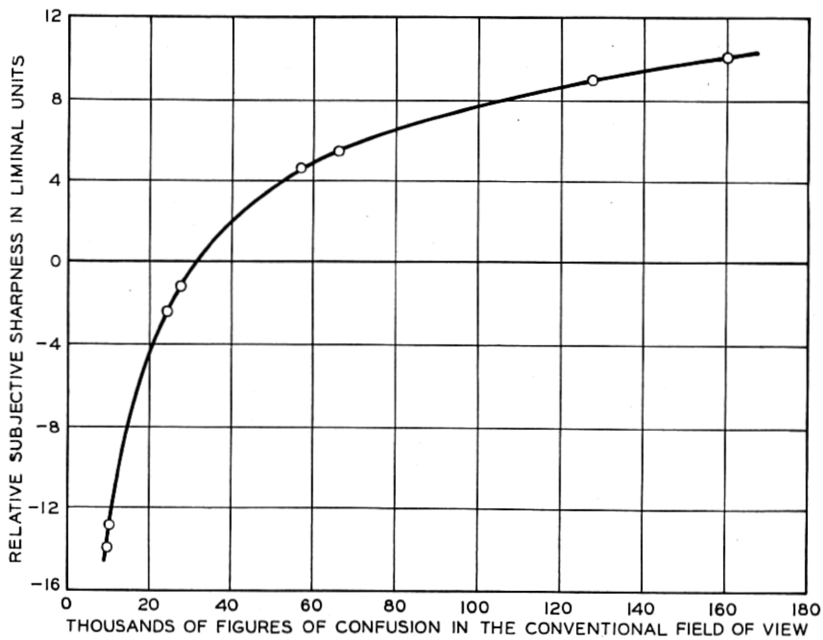


Fig. 1—Sharpness of small-sized motion pictures as a function of resolution. The conventional field of view is a rectangle whose height is 1/4 the viewing distance and whose width is 4/3 the height. Reference sharpness is approximately that of a 240-line, 24 frame per second, 806 kilocycle television image. Curve based on 1,080 observations at a viewing distance of 30 inches.

sented in Fig. 1 by a point in the neighborhood of + 18 units.) It must be remembered that the curve represents judgments made by trained observers under optimum conditions for distinguishing small differences, and that a change as small as one liminal unit, under the conditions of ordinary television viewing, would probably be largely unnoticed.

A better understanding of the meaning of this curve relating sharpness to resolution may be had by examining the experiment in detail. An individual observation was made when one of the observers, watching the projected image, caused the projection lens to be moved from a reference position to a neighboring one and reported which position he judged to yield the sharper image. The motion picture scene was a close-up of a fashion model turning slowly against a plain neutral background, and was repeated every quarter minute. The observer could have the lens moved whenever and as often as he wanted to before reporting, so that he soon acquired the habit of observing only the most critical portions of the scene. As soon as his report was recorded, completing that observation, he was shown a new pair of lens positions, the same reference one with a different neighboring one, and asked again to report which he judged to yield the sharper image.

We believe that there were no contaminating influences and that only the size of the figure of confusion was varied. No change in brightness or in magnification could be detected. A minute lateral shifting of the image, because of play in the focusing mount of the lens, was completely masked by the continual weave of the film in the gate and the natural motion of the model. Any significance of the position of the observer's control key was destroyed by reversing its connections from time to time, between observations, without the observer's knowledge. No tell-tale sound accompanied the small motion of the lens, and none of the operator's movements could be seen by the observer.

Each one of 15 observers made 84 separate observations of sharpness difference. Expressing the resolution in terms of the angle at the observer's eye subtended by the side of the square figure of confusion, there were four main reference values, namely 0.71, 1.1, 1.7 and 2.8 milliradians (1 milliradian is equal to 3.44 minutes of arc). At each of these reference values there were seven neighboring values, namely 0, 0.045, 0.090, 0.13, 0.18, 0.22 and 0.27 milliradians greater than the reference value. (The 0 in that set means that the reference value was shown against itself, or that the observer was asked to judge a null change; this was intended to keep him on his guard and alert, not to furnish primary data.) Each pair of values was presented to each observer three times, so that there were 45 observations on every pair. The pairs were presented in irregular order according to a schedule, the variation about one reference value being completed before going on to the next. The differences were set up on the basis of preliminary trials to include some which almost none of the observers could detect and some which almost all could. It was explained that some of the differences to be judged would probably be too small for discernment, and that a "no choice" response would be permitted whenever reasonable effort failed to establish a definite choice.

The primary data are shown in Fig. 2. Each point shows the proportion of the observations in which the variable image, which had the poorer resolution by reason of its larger figure of confusion, was nevertheless judged to be sharper than the reference image. Such a judg-

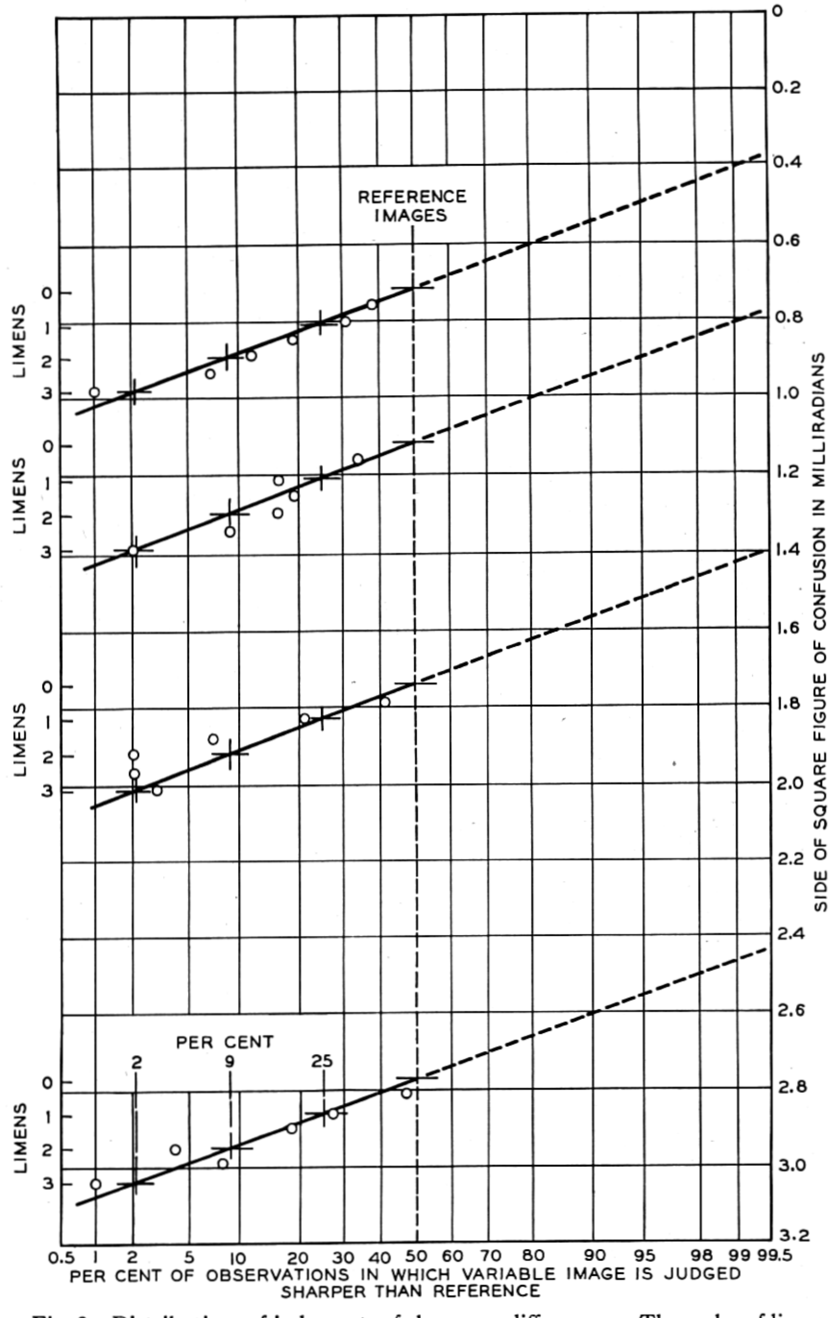


Fig. 2—Distributions of judgments of sharpness differences. The scales of limens denote subjectively-determined units, as explained in the text. Each point represents 45 observations of a small-sized motion picture at a viewing distance of 30 inches.

ment would, of course, be classed as wrong. All reported "no choice" judgments have been distributed equally between the "right" and "wrong" classes. It will be noticed that there was some discrimination at even the smallest change made, that is 0.045 milliradian, and that there was lack of complete discrimination at the largest change, that is 0.27 milliradian. The "no choice" judgments comprised 15 per cent of the total at the smallest change and only 2 per cent at the largest.

It is interesting to note that for the null changes the "no choice" judgments comprised only 17 per cent of the total, indicating either that the observers were reluctant to admit that they were guessing or that they were judging coincidental small changes in the film due to its bending in the gate or to its photographic processing. (We did observe, in establishing the lens position for sharpest focus, that film at the start of a reel required a slightly different lens setting from that at the end of the reel, and we ascribed it to the varying tension during projection, or to the varying degrees of curvature in storage on the reel.)

The four sets of points in Fig. 2 exhibit rather striking similarities. Each set may be fairly represented by a normal error curve (straight line on this arithmetic probability paper). We have drawn in four such normal curves, passing each one through the 50 per cent point at the null change and giving each a common slope. The appropriate value of slope was determined by inspection of an auxiliary plot in which the four reference values were superimposed and the four sets of points were plotted to a common ordinate scale of differences. These normal curves are considered to represent the data as well as any more elaborate relations that might have been used.

We varied the resolution only in the direction of decreasing it with respect to the reference values. We presume that had the variation been in the opposite direction the data would have been represented equally well by the same normal curves, which are accordingly extended in dotted lines.

In Fig. 2 we have indicated the magnitude of a difference of one limen by means of supplementary scales of ordinates. Since the four normal curves have a common slope, the difference limen turns out to have a constant value, 0.090 milliradian (0.3 minute of arc), independent of the size of the figure of confusion in the range from 0.71 to 2.8 milliradians. Why this should be so is a problem of physiological optics which is rather beyond the scope of this paper. The supplementary scales also serve to illustrate the meaning of differences two and three times as large as the difference limen. That is, a change in the side of the figure of confusion of 0.18 milliradian would be twice as large as the limen of 0.090 milliradian, and would result in wrong judgments in 9 per cent of the observations, corresponding to real discrimination in 82 per cent of them. Likewise a change of 0.27 milliradian would result in real discrimination in 96 per cent of the observations. Any change larger than about three times the limen would be discriminated in practically every instance, under the conditions of our experiment.

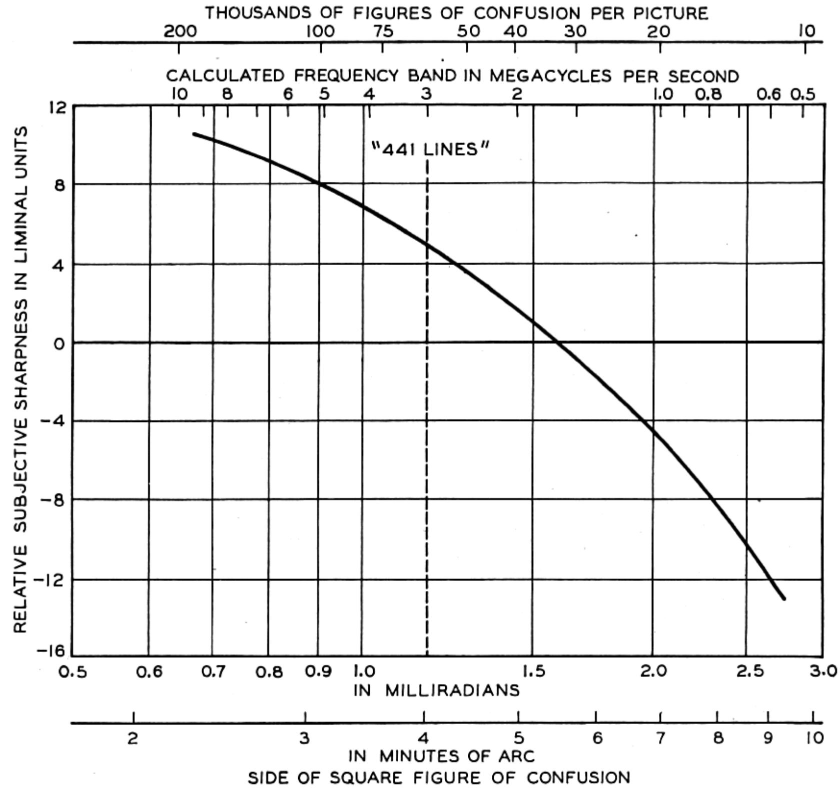


Fig. 3—Sharpness of small-sized motion pictures at a viewing distance of 30 inches. The frequency band is calculated on the basis of a 10-inch by $7\frac{1}{2}$-inch television picture, 30 frames per second, with 15 per cent horizontal and 7 per cent vertical blanking, under the condition of equal horizontal and vertical resolutions.

Figures 3 and 4 show the curve of Fig. 1 replotted in terms of some additional objective variables. A scale of nominal frequency band width required for transmission of the image signal over a video circuit has been worked out on the basis of our comparison of the out-of-focus motion picture with a television image of known characteristics. to be described in section 5. We see that in order to effect an increase in sharpness which would be practically always discriminated under our experimental conditions, that is, a change of three or four liminal units, the frequency band would have to be increased from say 2.5 megacycles to about 4.5 megacycles. To effect an additional increase of the same

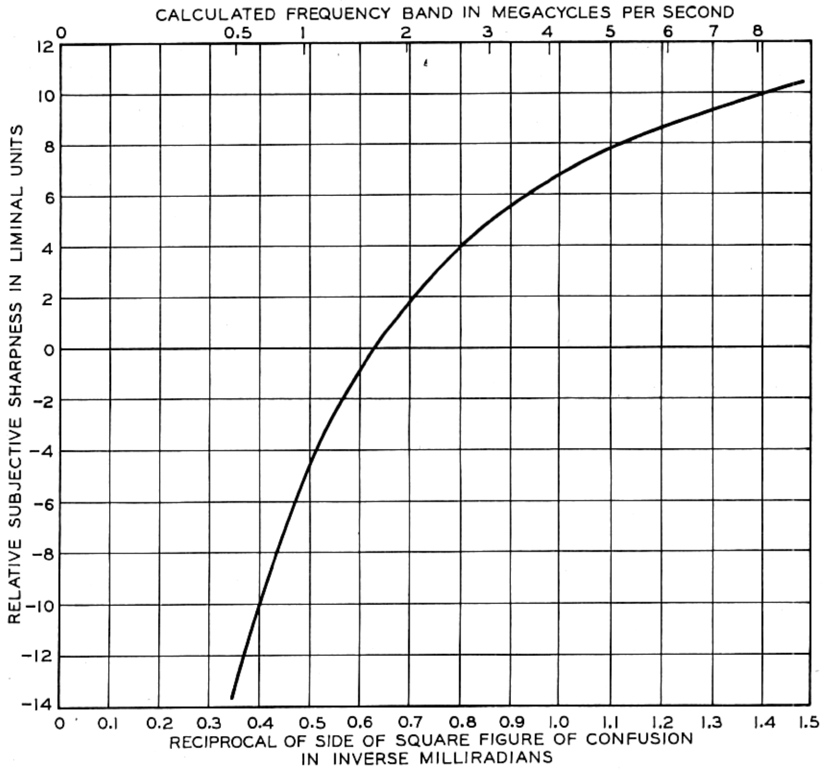


Fig. 4—Sharpness of small-sized motion pictures at a viewing distance of 30 inches. The frequency band is calculated on the same basis as in Fig. 3.

subjective amount would require that the frequency band be increased from 4.5 megacycles to about 10 megacycles. The diminishing return in sharpness is possibly better illustrated by the continually decreasing slope of the curve in Fig. 4, in which the abscissa is proportional to the square root of the frequency band, a factor which may perhaps be interpreted to represent roughly the cost of electrical transmission over a long system. We might infer from this curve that transmission costs are likely to increase faster than image sharpness, other things being equal.

4. Horizontal and Vertical Resolutions

The effect of unequal horizontal and vertical resolutions upon sharpness is shown in Fig. 5. The various rectangular figures of confusion, which were intercompared in a manner which will be described pres-

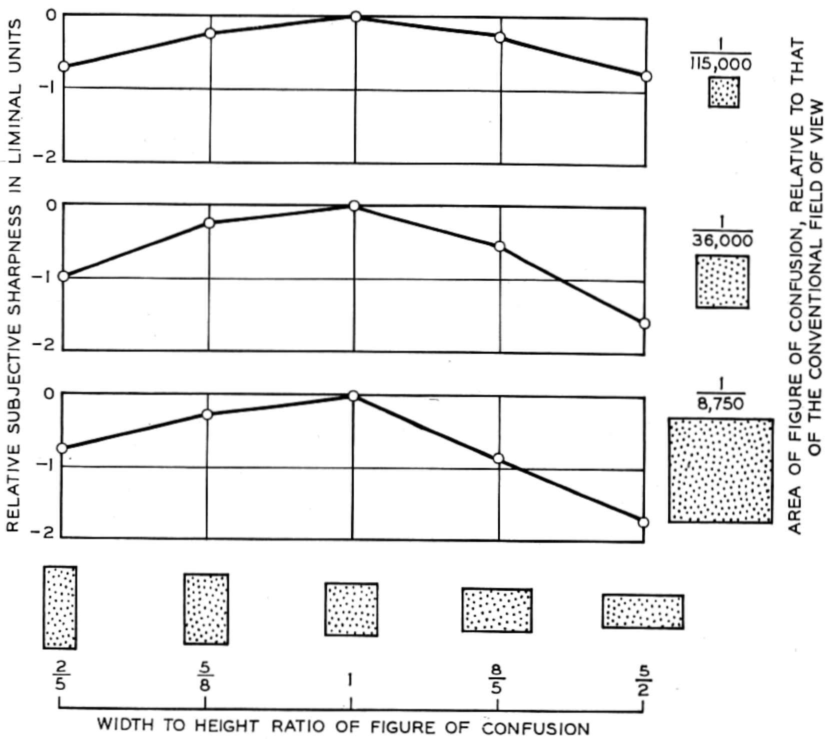


Fig. 5—Sharpness of small-sized motion pictures as a function of the relative values of horizontal and vertical resolutions. The conventional field of view is a rectangle whose height is 1/4 the viewing distance and whose width is 4/3 the height. Each point represents 150 observations at a viewing distance of 30 inches.

ently, are shown along the axis of abscissae, positioned according to the logarithm of the ratio of width to height, for the sake of symmetry. Three curves are shown, each for a different constant value of the area of the figure of confusion, which determines the sharpness for the central square shape (as in Fig. 1). At the right the relative areas are illustrated and specified in terms of the number of figures of confusion in the conventional field of view, whose width is 4/3 of its height and which is viewed at 4 times its height.

Sharpness, the subjective variable, is plotted along the axis of ordinates in liminal units. This unit denotes a difference in sharpness which corresponds to a difference of one limen in the shape of the figure of confusion. When two images, characterized by different shapes of figure of confusion, are judged by a number of observers, the proportion of the observations in which one image is said to be sharper than the other affords a significant measure of the evaluation of the difference between them. When 25 per cent of the observations show that shape *A* yields a sharper image than shape *B*, we say that shapes *A* and *B* are different by one limen, and that the image *A* is less sharp than the image *B* by one liminal unit. All "no choice" or "equally sharp" judgments are distributed equally between the judgments for *A* and those for *B*.

In order to evaluate other than unit differences, we have assumed that a normal error curve describes accurately enough the distribution of sharpness differences in liminal units. Thus, image *A* is less sharp than image *B* by two liminal units when it is reported to be sharper than image *B* in 9 per cent of the observations. The difference is three liminal units when it is reported to be sharper in 2 per cent of the observations. Any difference larger than about three liminal units would indicate practically complete agreement that the one image is less sharp than the other, under our experimental conditions. A distribution of this nature was found to hold for sharpness differences resulting from changes in the area of the figure of confusion, as shown in Fig. 2.

Each shape of figure of confusion was compared with each of the four other selected shapes, and the sharpness differences were expressed in liminal units by the procedure just discussed. A fifth difference, corresponding to a null change, or a shape compared with itself, was presumed to be zero. The average value of these five sharpness differences, averaged in liminal units, measured the relative sharpness of that particular shape with respect to the average sharpness of all five shapes, an unvarying reference. In Fig. 5, the sharpness scales have been shifted so that zero denotes the most preferred one of the shapes, which happened in each case to be the square.

The sharpness curves are found to be slightly skewed with respect to the logarithm of the width : height ratio, there being a small preference for figures of confusion whose long dimension is vertical rather than horizontal. This is believed to be the first evidence of an asymmetric requirement on resolution. It suggests the possibility that the square figure might not have been the most preferred, had we tested other shapes nearer to the square than the ones we did use. With a more searching experiment we might have found that the eye prefers resolution in the horizontal direction to be just a little better than in the vertical direction. Inasmuch as the effect is fairly small, and found only with the less sharp images, we shall leave it as another problem in physiological optics.

With an actual television image this small skewness would probably be reversed by the attendant coarsening of the scanning line structure. We do not know how much to allow for annoyance caused by visibility of the line structure. Taking our best estimate * of the height of the figure of confusion which would be equivalent in vertical resolution to a just noticeable pattern of scanning lines, we may say that for the uppermost curve in Fig. 5 the scanning line structure would not be noticeable except possibly for the shape marked 2/5. For the central curve the line structure would be noticeable for all shapes except possibly the one marked 5/2. It appears that the skewness and the line structure vanish together as the sharpness is increased.

Figure 5 demonstrates that equality of horizontal and vertical resolutions is a very uncritical requirement on the sharpness of an image, especially of a fairly sharp one. An image somewhat better than present television grade, exemplified by the uppermost curve in Fig. 5, shows a remarkably wide tolerance in this respect. Its figure of confusion could be three times as high as wide, or three times as wide as high, yet any intermediate shape between those two extremes would yield an equally sharp image to within one liminal unit. Under the ordinary conditions of television viewing the difference would be even less marked than that. This would imply that if the square figure of confusion simulates a television image of say 500 lines, then the number of lines could be changed to any value from about 300 to about 850 without altering the sharpness by as much as one liminal unit, under the condition, of course, that all the other pertinent factors, such as frequency band width and number of frames per second, remain unchanged.

The curves in Fig. 5 represent the averaged responses of fifteen observers each viewing five different motion picture scenes. Each one of the five selected shapes of figure of confusion was shown with each other one as a pair, a total of ten pairs. The observer was asked to identify which member of each pair he judged to yield the sharper image, or to report "no choice" if he judged them to be equally sharp. The pairs were scheduled in irregular order, and the observer could have the aperture shape shifted at will. The observers were instructed to consider the whole image area without undue regard for some features to the neglect of others.

* Engstrom [8] estimates that the scanning line structure becomes just noticeable when the spacing of the lines subtends an angle of 2 minutes at the observer's eye. In section 5 we show that the equivalent figure of confusion has a height 1.9 times as great as the spacing of the scanning lines.

5. Comparison of the Out-of-Focus Motion Pictures with a 240-Line Television Image of Known Characteristics

The motion picture machine was arranged to project out-of-focus pictures onto a screen set up beside the cathode ray receiving tube of a laboratory television apparatus [9] of excellent design. Duplicate films were run in the two machines, and the images were made equal in size and approximately equal in color and brightness. Special low-pass filters in the video circuit limited the frequency band without transient distortion, and permitted the trial of three different band widths. The conclusion was reached that the nominal band width of the video circuit, expressed in cycles per frame period, was equal to 1.3 times the number of figures of confusion in the frame area.

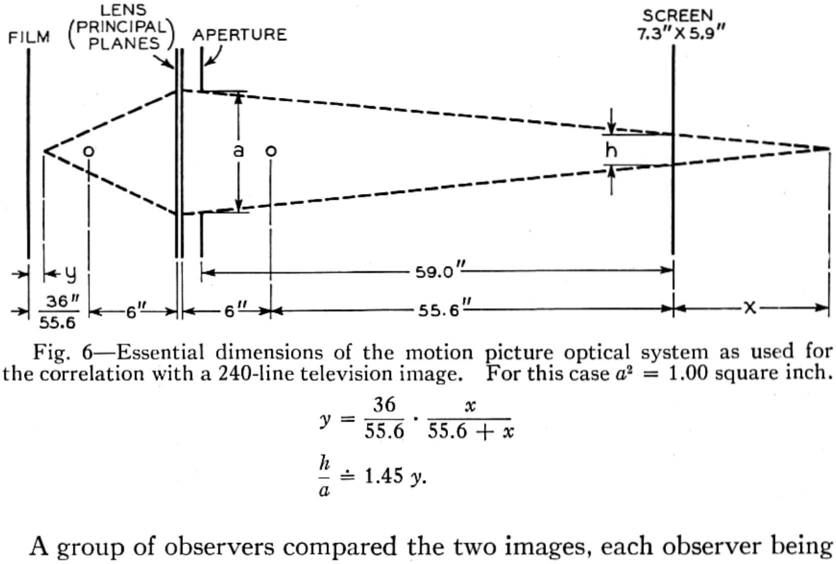


Fig. 6—Essential dimensions of the motion picture optical system as used for the correlation with a 240-line television image. For this case $a^2 = 1.00$ square inch.

$$y = \frac{36}{55.6} \cdot \frac{x}{55.6 + x}$$

$$\frac{h}{a} \doteq 1.45\, y.$$

A group of observers compared the two images, each observer being allowed to adjust the focus of the projection lens until he judged the images to be equal in sharpness. The distribution of lens positions, in terms of microscope scale divisions, was found to follow a normal error curve fairly well, and the median value for the group was used in computing the sizes of the figure of confusion. The external aperture shape was always square.

Since the television film scanner had been designed without regard for the unused space between frames on sound film, it became necessary to modify some of the dimensions of the out-of-focus projection system in order to make the two images equal in size. Figure 6 shows the modified dimensions. Comparison with Fig. 7, which gives the dimensions used in the main experiments, will show that the magnification was reduced from 12 to 9.3, the area of the external aperture was increased from 0.49 square inch to 1.00 square inch, and the aperture was mounted 2.6 inches instead of 1.3 inches from the principal planes of the projection lens.

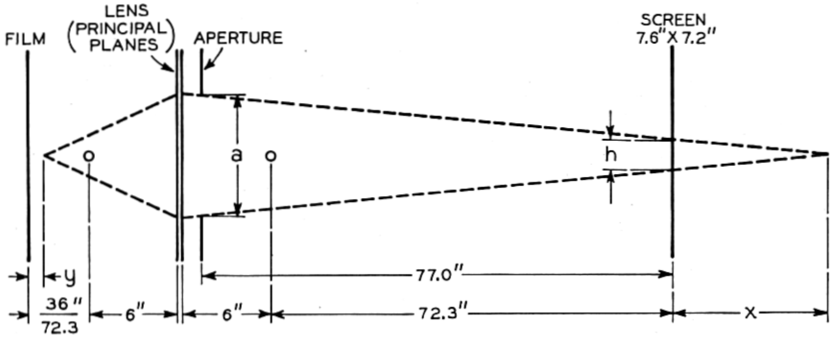


Fig. 7—Essential dimensions of the motion picture optical system as used for the subjective sharpness tests. For this case $a^2 = 0.49$ square inch.

$$y = \frac{36}{72.3} \cdot \frac{x}{72.3 + x}$$

$$\frac{h}{a} \doteq 1.88\, y.$$

The television apparatus was designed for 240 lines, 24 frames per second, and a width : height ratio of 7 : 6. Actually 20 per cent of the frame time was consumed in scanning the blank space between sound film frames, and 10 per cent of the line time was used up by the return sweep in the receiver. The television image, which was the same size as the projected motion picture, was 5.6 inches high. This dimension was 20 per cent less than the height of the entire 240-line field including the blank portion, which was, therefore, 6.9 inches. The width of the entire field including return trace was 6.9 × 7/6 or 8.1 inches, and the width of the television image was 10 per cent less than this, or 7.3 inches. Thus, the total area transmitted per frame period was 6.9 × 8.1 or 56 square inches; the useful image area was 5.6 × 7.3 or 41 square inches.

The three amplitude-frequency characteristics used in the video circuit are shown in Fig. 8. Curve *A* is for two square scanning apertures in tandem, one transmitting and one receiving, each having the height of one scanning line. No electrical band limitation was effective in this case. Curves *B* and *C* are for the addition of each of two special low-pass filters which were carefully phase-equalized and designed for gradual cut-off. In each case the nominal band width was taken to be the same as that for the aperture effect alone, namely, the frequency at which the loss is 7.8 decibels greater than at low frequency. The addition of a low-pass filter could thus be considered

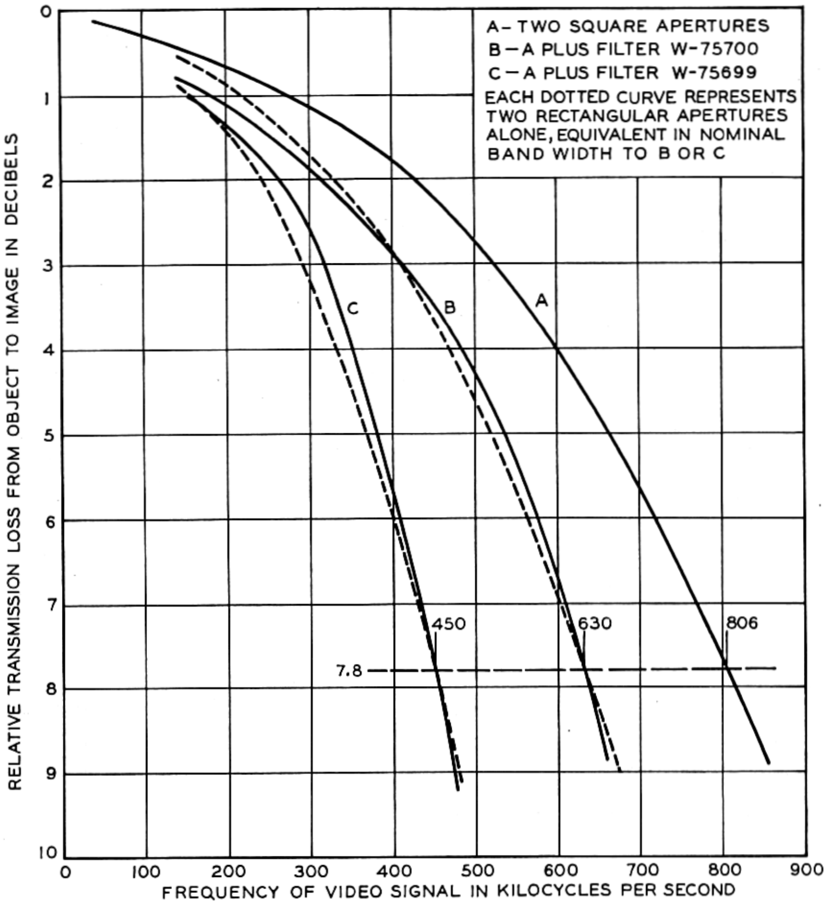


Fig. 8—Amplitude-frequency characteristics of the television system used for correlating the motion picture projection with a television image.

equivalent to an increase in the length of each of the scanning apertures in the ratio of the nominal band widths, as illustrated by the dotted curves.

The results of the comparison were as follows. The number of figures of confusion in the area of the frame was reckoned by dividing the entire area of the television frame, including the blank portion and the return trace, by the observed area of one figure of confusion of the equally sharp motion picture. The number of cycles per frame period was the nominal band width of the video circuit, in cycles per second, divided by the number of frames per second, or 24.

	Case A	Case B	Case C
Figures of confusion per frame	22,400	18,900	14,800
Cycles per frame period	33,600	26,200	18,800
Ratio	1.50	1.38	1.27

The ratio in Case A was suspected to be too large because of unaccounted-for small defects in the film scanner which degraded the image sharpness more than was indicated by the aperture effect alone. The difference in ratio between Cases B and C was no larger than the measured probable error of each set of observations. Making allowance for these things, we concluded that the ratio between the number of cycles per frame period and the number of figures of confusion per frame area had been found to be 1.3.

This factor 1.3 gave us a basis for calculating the television aperture loss in the direction normal to the scanning lines, and enabled us to compute the nominal video frequency band required to yield an image having equal horizontal and vertical resolutions.

The stepped nature of the brightness variation across the scanning lines of a television image, in contrast to its continuous nature along the lines, gives rise to the requirement that for equal resolution in the two directions the scanning apertures must be longer in the scanning direction than they are across it. The extent of this departure from squareness has been estimated (see references 3 to 7) at from 1.2 to 1.9, mostly on theoretical grounds. Our comparison of a television image of known characteristics with a controlled out-of-focus motion picture furnished a subjective measurement of the effect which yielded the value 1.4 for the ratio of width to height of the scanning apertures for equal resolution. We take width to mean the dimension along the scanning lines, and height to mean the dimension normal to them.

We found that the nominal video band width of a television signal, in cycles per frame period, was 1.3 times the number of figures of confusion per frame area in the equally sharp motion picture. This meant that the area of each figure of confusion was 1.3 times as great as the area of one scanning line over a (scanned) length of one cycle. By the adopted definition of nominal video band width, the length of one cycle was just twice the length of each one of the pair of rectangular scanning apertures which were considered equivalent to the actual square apertures plus the filter. According to the scanning theory of Mertz and Gray,[4] the pair of apertures in tandem was equivalent, in frequency limitation, to a single aperture 1.35 times as long as either one of the pair. Taking the width of this single aperture (1.35 times the length of one half cycle) equal to the width of the figure of confusion, the height of the figure of confusion was calculated from its area to be 1.9 times the height of one scanning line or one scanning pitch. This was the measure by subjective comparison of the resolution across the scanning lines.

Under the condition of equal resolution along and across the scanning lines, the figure of confusion would have to be square and its width would then also be 1.9 times the scanning pitch. The width of each one of the pair of equivalent tandem scanning apertures would be 1.9/1.35 or 1.4 times the scanning pitch. That is, two rectangular scanning apertures, each 1 line high and 1.4 lines wide, used in tandem without electrical band limitation, would yield an image having equal resolution along and across the scanning lines.

The nominal frequency band associated with such scanning apertures is 1/1.4 times that associated with square apertures. That is, the nominal video frequency band, in cycles per frame period, required for equal horizontal and vertical resolution is 0.70 times one half the number of square scanning elements per frame area, reckoning a square scanning element as an area of height and width equal to the scanning pitch, or spacing between scanning lines.

For comparison with the value 0.70 which we have just found, the following values of nominal band width coefficient have been lifted from their contexts in the references:

(*a*)	Kell, Bedford and Trainer (1934)	0.64
(*b*)	Mertz and Gray (1934)	0.53
(*c*)	Wheeler and Loughren (1938)	0.71
(*d*)	Wilson (1938)	0.82
(*d*)	Kell, Bedford and Fredendall (1940)	0.85

Acknowledgment

This work has been done under the direction of Dr. P. Mertz and with the extensive assistance of Mr. T. R. D. Collins. To them, and to my other colleagues who have given of their time and counsel, I wish to extend my appreciation of their help.

APPENDIX

1. Determination of the Size of the Figures of Confusion

The image was put out of focus by moving the projection lens nearer to the film gate, throwing the plane of sharp focus beyond the viewing screen. Assuming for the moment that the optical imagery was perfect, each point of the film gave rise to a pyramidal volume of light whose base was the opening of the external aperture and whose apex was the point's image in the new focal plane beyond the screen. The intersection of this pyramid with the viewing screen was the geometrical figure of confusion for that point. The shape of the figure was geometrically similar to that of the aperture, and the side of the figure was to the corresponding side of the aperture as the distance from focal plane to screen was to the distance from focal plane to aperture.

The distance of the focal plane beyond the screen was related to the displacement of the lens from the "in focus" position by means of the simple lens formula, and this relation was verified by actual measurement of the distances. The geometrical area of the figure of confusion was thus known in terms of the lens displacement, as shown in Fig. 9.

Efforts to check this relationship by direct measurement of the dimensions of the figure of confusion in the plane of the screen were nullified by the aberrations of the optical system, especially by the residual chromatic aberration. A comparison method was therefore devised in which the out-of-focus image of a very thin vertical slit was compared with an actual slit in the plane of the screen. In the film gate was placed a glass plate bearing a sputtered layer of gold with a razor-blade scratch not wider than 0.0001 inch in selected portions. In the plane of the screen was placed a back-lighted slit made by cementing the two halves of a cut piece of thin black paper onto a piece of translucent white paper. This slit had sharp, parallel edges and uniform brightness over its width, which was easily made as small as 0.005 inch. A set of these slits was prepared, ranging in width up to 0.100 inch, and each one was observed, without optical aid, close beside the projected out-of-focus image of the scratch in the gold film. The apparent brightnesses were equalized by means of neutral-tint filters behind the paper slit.

The ranges of values of lens displacement and of external aperture shape which were used in the experiments were tested in this way, by adjusting the out-of-focus images to subjective equality with the sharp-edged slits. In every case the measured width of the comparison slit turned out to be about 15 per cent less than the calculated geometrical width of the projected image. This seeming a not unreasonable measure of the effect of the aberrations, it was adopted as a factor for converting geometrical sizes into subjective sizes of the figures of confusion.

Figure 9 shows both the calculated geometrical area and the observed subjective area of the figure of confusion in terms of the displacement

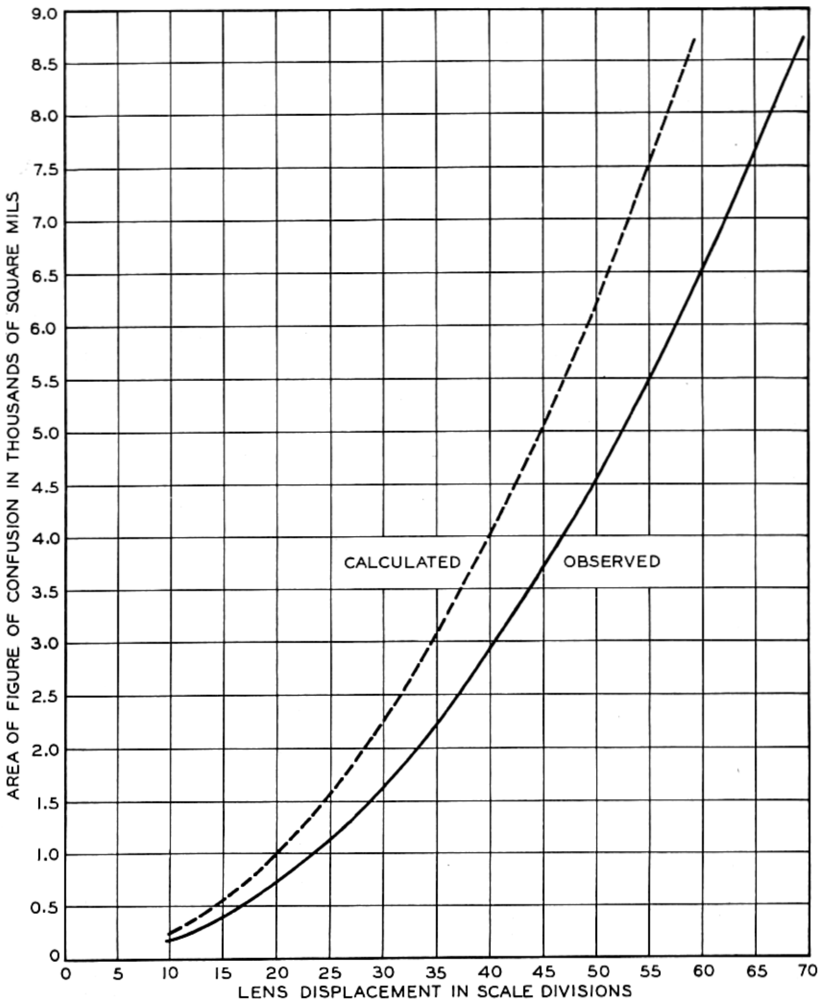


Fig. 9—Calibration curve for the motion picture optical system as used for the subjective sharpness tests.

of the lens from its sharp focus position. The lens displacement is expressed in microscope scale divisions, the working variable. Figure 7 shows the dimensions of the optical system.

2. Equipment and Conditions of the Experiment

Light Source

A ground glass screen ½ inch behind the film, illuminated by a 1,000-watt projection lamp and double condensing lens system. This served to break up the image of the lamp filament which otherwise would have been formed near the principal planes of the projection lens and would have destroyed the uniformity of illumination within the figures of confusion of the out-of-focus image on the screen. The screen brightness was about 10 foot-lamberts with the projector running without film.

Projection Machine

Acme Portable, with two-bladed shutter. There was no provision for reproducing the sound track. The screen image, in sharp focus, was said by competent judges to represent very good motion picture projection practice.

Projection Lens

Bausch and Lomb Series "0", 6.00-inch focus. There was fitted over the lens barrel a brass ring with an extremely sharp turned edge to serve as an index for the measurement of lens displacement. The lens could be set to the nearest 0.0003 inch by means of the focusing mechanism. The image was put out of focus by moving the lens toward the film. At sharp focus the linear magnification was 12 times.

Measuring Microscope

Mounted rigidly on the frame of the projector, and fixed with respect to the film gate. The micrometer scale was focused on the index mark on the barrel of the projection lens. A lens displacement of 0.060 inch caused the index to traverse 50 divisions of the scale.

External Aperture

An adjustable black paper mask mounted $1\frac{1}{3}$ inches from the principal planes of the lens, on the screen side. The opening was rectangular, with sides horizontal and vertical, of constant area 0.49 square inch. The ratio of height to width could be varied continuously from 2.5 to 0.40 without changing the area. The opening was uniformly filled with light under all conditions.

Viewing Screen

White Bristol board, 7.2 inches high by 7.6 inches wide (the image size of an available television receiver to be used for comparison). The screen was hung at the back of a black-velvet-lined box 18 inches high, 22 inches wide and 12 inches deep. The viewing distance was always 30 inches.

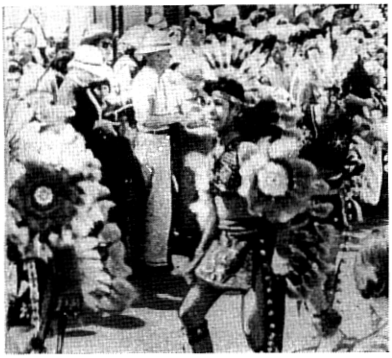
The viewing room was completely darkened except for a little stray light from the projection machine.

Scene 1

Scene 2

Scene 3

Scene 4



Scene 5

Fig. 10

Scene 1 reproduced by courtesy of Loucks & Norling.
Scenes 2 and 3 reproduced by courtesy of Fox Movietone News.
Scenes 4 and 5 reproduced by courtesy of Paramount News.

The Observers

The observers were almost all Laboratories engineers associated with television research and transmission problems. The average observer devoted about one hour to the experiment on unequal horizontal and vertical resolutions, and about three hours (in two sessions) to the experiment on small differences in resolution. Each observer was carefully instructed with regard to the purpose and the mechanism of the experiments, and was allowed to examine trial pictures to see clearly the effects of changing the shape and size of the figure of confusion.

Motion Picture Film

Standard 35 mm. black-and-white sound film on safety base. The area projected onto the screen was 0.600 inch high by 0.633 inch wide.

For the experiment on unequal horizontal and vertical resolutions, five different scenes were used. Sample frames from them are shown in Fig. 10. For the experiment on small resolution differences, Scene 3 was selected as the most suitable on the basis of photographic excellence and picture content, and this alone was used. Each of the scenes was about one quarter of a minute in length, and was shown repeatedly. Brief descriptions follow:

Scene 1: A country-side landscape, with trees and fields. A center of interest is the tall steeple of a white church on the distant hillside. A concrete highway flanked by a white fence carries cars into and out of the picture. There is no fast motion.

Scene 2: A full-length view of a girl modeling an evening dress moving slowly against a dark, fluted backdrop. A large vase of flowers is a secondary center of interest.

Scene 3: A close-up view of a girl modeling a hat, turning slowly against a plain, neutral background.

Scene 4: A street scene of an Indian parade, with a background of store windows and signs. The parade moves rather rapidly, and there is some motion among the by-standers.

Scene 5: A closer view of some of the Indians in the parade. There is much fine detail in the costumes, and the motion is rapid.

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