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DEFINITION OF VISUAL ACUITY*

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It is well known that different types of test object will give different measures of acuity in terms of the size of the angle subtended at an observer's eye by the critical detail in the test object. Acuity of an average observer may vary from 1″ arc, the thickness of a single black line just discernible on a white background, to about 1′ arc, the size of a gap in a black ring viewed on a white background. Other objects may give values between these two extremes, but in general, acuity is considered to be defined by the broken ring type of test object, rather than by the presence of a single thin line.

A grating pattern is frequently used to measure the acuity of the eye or the resolving power of a lens system or photographic process. The definition of what is considered to be the fine detail in this pattern is not, however, always clearly stated. It may be defined as the width of one single black line, or of one single space between the lines, or it may be defined as one pattern width, the width of one black line plus one white space.

In the measurement of visual acuity the definition of one line width is frequently used (*e.g.* Pirenne, 1948; Hecht, 1931; Bartly, 1941). The resolving power of lenses (Houstoun, 1930) and film resolution (Mees, 1942) tend to be defined in terms of the pattern width of the grating. Schlafly (1951) states fairly clearly that the film industry uses the pattern width, whilst the television industry uses the single line element width.

Because it is not always clearly stated which definition of fine detail of a grating pattern is being used, and because of the existence of the two different definitions, confusion is apt to arise as to which definition is intended in any particular context.

In view of this confusion, it was decided first of all to make a subjective comparison between grating patterns and the broken ring pattern in order to determine a method of defining the grating pattern detail, so that acuity measured on it would be the same as acuity measured on the broken ring pattern under normal conditions of observation. Since television images are superimposed upon a grating pattern or raster, an attempt was then made to apply the result to television systems.

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Experimental Procedure

Measurements of visual acuity were made, using the three types of high-contrast test object (Fig. 1):

(*a*) A broken black ring, in which the width of the line defining the ring and the size of the gap taken as the detail were each one-fifth of the total size of the object.

(*b*) A three-bar pattern, in which the detail, taken as the width of each bar or each gap, was one-fifth of the total length or breadth of the object.

(*c*) A grating pattern 3½" (89 mm.) in diameter, the detail being taken as the width of one black or one white line.

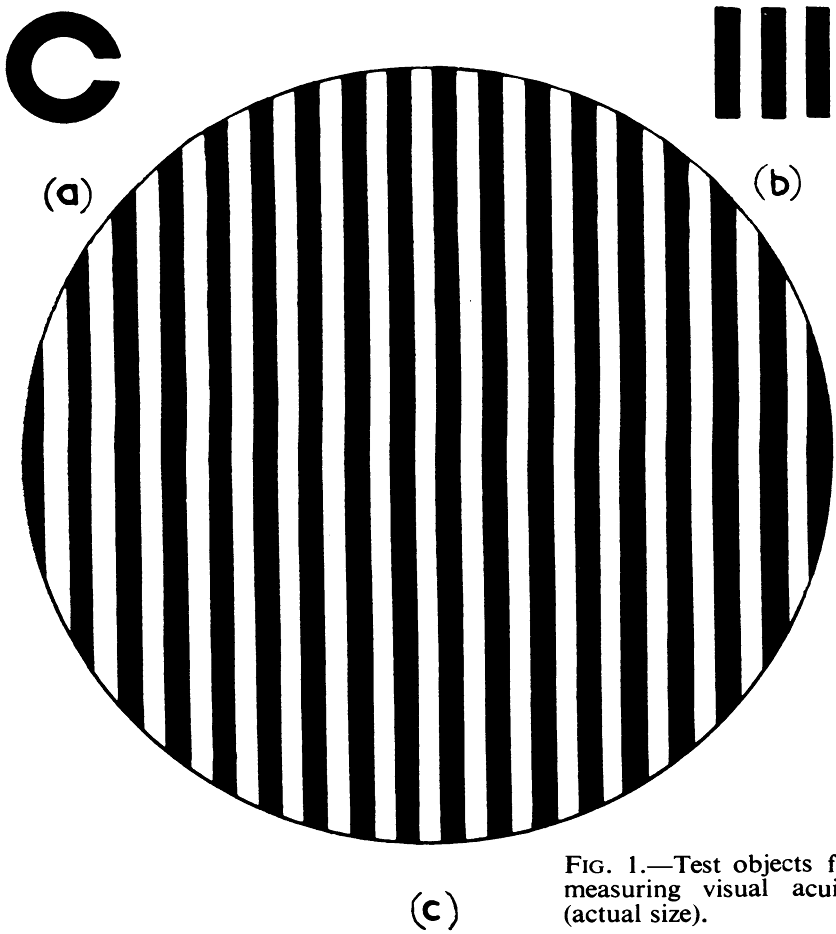

FIG. 1.—Test objects for measuring visual acuity (actual size).

The measurements were made on twenty subjects with normal vision or fully corrected defective vision. Each test object was displayed in turn on a cream coloured wall, illuminated to 40–50 foot-lamberts. The subject stood at appropriate distances from the wall, so that the test object detail subtended 1′, 0.8′, 0.6′, 0.5′, 0.45′, and 0.4′ arc at his eye; but for most of the measurements the object was viewed through a mirror to obtain the necessary distance. As all three objects had to be viewed through the same mirror, the results should be strictly comparable, although the absolute values of acuity might be influenced by imperfections of the mirror. After these measurements had been completed, the influence of the mirror was checked by repeating one set of measurements in a slightly larger room so that the effect of the mirror could be assessed. The angle subtended by the test objects at the subject's eye in this case was 0.7′ arc. It was found that the mirror had no influence upon the results.

In the first place all three objects were displayed in two alternative positions. In the case of Objects *b* and *c* (Fig. 1) the bars could be either vertical or horizontal, and in the case of Object *a* the gap was placed either uppermost or to one side of the centre. These alternative orientations were displayed ten times in random order for each object, and the subject stated the orientation. In the case of pure guesswork, therefore, 50 per cent. of the guesses should be correct.

In the second series of tests, the broken ring was displayed with the gap occurring above, below, or to the right or leftof the centre, so that only on 25 per cent. of the occasions would the answer be correct in the case of pure guesswork.

Results

The results of these observations are summarized in Table I.

TABLE I

PERCENTAGE CORRECT ANSWERS GIVEN IN TEN OBSERVATIONS OF EACH TEST OBJECT BY TWENTY SUBJECTS

Min. Arc Subtense	Ring		Bar	Grating
	(2-choice)	(4-choice)	(2-choice)	(2-choice)
1′	100	99	100	100
0.8′	99	96	92	100
0.7′	96	—	79	98
0.6′	84	79	57	100
0.5′	66	51	54	93
0.45′	—	—	—	88
0.4′	—	—	—	87

Somewhere between the point at which the orientation of an object is given correctly all the time, and the point at which the percentage of correct answers can be attributed to pure guesswork when one object is not seen at all, there must be a point at which one object is partially seen, and can be considered to be at the limit of resolution of the eye. It is conventional in statistics to consider that if an event occurs when the probability is 20 : 1 against it occurring by chance, then the occurrence may be regarded as significant. This convention has been applied to the results of the present investigation. The 20 : 1 probability level occurs, in the case where two possible alternatives exist, when 80 per cent. of the answers are correct, and, in the case where four possible alternatives exist, when 55 per cent. of the answers are correct. The values of acuity in terms of minutes of arc subtended by the test object's detail, interpolated at these levels, are listed in Table II (overleaf).

The four curves that can be drawn from the values given in Table I and which were used to interpolate the 20 : 1 probability levels have been normalized and are shown thus in Fig. 2 (overleaf). The limits of the three curves where two possibilities of orientation were presented lie between 100

TABLE II

SIZE OF DETAIL AT WHICH A SIGNIFICANTLY CORRECT NUMBER OF ANSWERS IS GIVEN

Test Object	Size of Detail	Definition of Detail
Ring (2-choice)	0.58′ arc } Mean 0.54′	Gap width
Ring (4-choice)	0.51′ arc } Mean 0.54′	Gap width
Bar (2-choice)	0.71′ arc	One white line width
Grating (2-choice)	0.39′ arc	One white line width

(certainty) and 50 (guesswork), and the limits of the fourth curve (where four possibilities of orientation were presented) lie between 100 and 25. By normalizing these curves, their limits have been made 100 and 0, so that they may all be compared, and Fig. 2 shows that the two experiments using the broken ring type of test object have yielded very similar results. The effect of having two choices (gap above or right of centre) or of having four choices (gap above, below, right, or left of centre) has not, therefore, influenced the results to any appreciable extent.

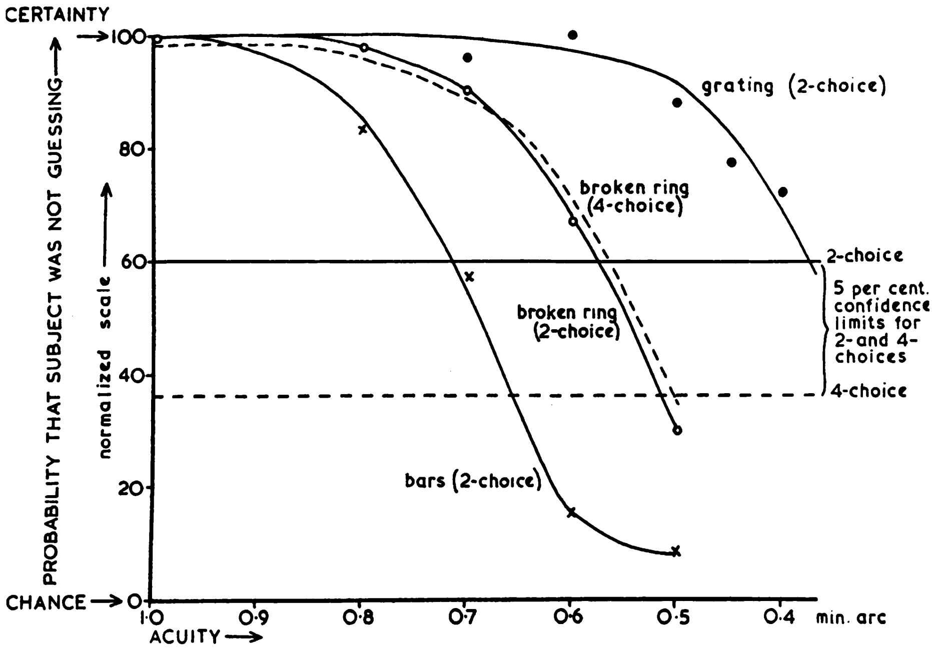

FIG. 2.—Dependence of acuity on test object with which it is measured.

Conclusions

General.—From the values obtained at the significant level of probability, the threshold of vision for the conditions stated can be assumed to occur when the angle subtended at a subject's eye by the gap in a broken ring is 0.54′ arc, the width of one bar in a three-bar pattern is 0.71′ arc, and the width of one single line in a grating pattern is 0.39′ arc.

In order to make a three-bar pattern as easy to see as a broken ring pattern, therefore, it is necessary to make the width of one black bar approximately four-thirds the width of the gap in the ring. In order to equate the grating pattern to the broken ring in visibility, the width of one black line should be approximately three quarters the gap in the ring. This means that, if acuity is defined by means of the gap in a broken ring, the width of grating pattern necessary to obtain similar results of acuity will be one-and-a-half times that of the gap in the ring.

Acuity to pictures, as distinct from geometrical patterns, has been measured by other workers, and it has been found that blurring of an out-of-focus picture could be detected for approximately 0.5′ arc subtended by one single element of black or of white. The method by which they arrived at their results was different from that used in the present series of experiments, but, assuming that comparison is permissible, acuity to pictures appears to be almost identical to the Broken Ring Test. This is less than acuity to a grating pattern, in the ratio of 4 : 3 approximately (acuity to pictures 0.54′ arc, to grating 0.4′ arc.)

Application to Television.—It is of interest to apply this result to the case of a television picture in which the scanning raster is in the form of a grating pattern.

The definition of a television channel was measured by placing a Cobb-Moss high contrast test pattern, B.S. 1613 (Fig. 3), in front of the camera, and noting by direct visual observation the minimum pattern size resolved by the system. Although in a more general pattern of random brightnesses very low contrasts will occur which set a limit to the resolution, it was considered that a high contrast test object should be used. This reduces ambiguity as to the exact contrast value and is in line with practice in the fields of photography, lens design, and visual acuity measurements, where it is recognized that a high contrast object is resolved when it is reproduced at a very greatly reduced contrast, in circumstances such that a low contrast object would not be resolved at all after a corresponding amount of degradation. Although the fall in television camera response at high scanning velocities will influence the results, the choice of a high contrast test object will render the final image less dependent upon this deficiency of camera response. Furthermore, this type of test pattern seemed a reasonable compromise between the two classic types of test signal: a continuous grating pattern on the one hand and a single bar (of light or darkness as the case may be) on the other.

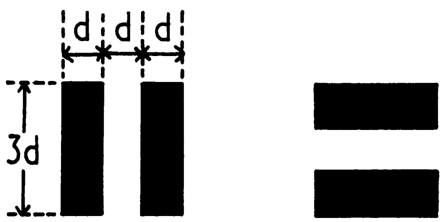

FIG. 3.—Cobb-Moss test pattern for testing vertical and horizontal resolution.

In the B.B.C. television system, using a 3 mc/s bandwidth and 405 lines, a picture is completely scanned in 1/25th of a second by means of two downward traversals or frames, each of $202\frac{1}{2}$ lines and 1/50th of a second duration. The lines constituting one such frame are arranged to lie between the lines of the other frame so as to give good picture detail (Blumlein, 1939). If the 405 lines were scanned in sequence and a 405–line frame made up in 1/50th of a second, a bandwidth of 6 mc/s would be needed to broadcast the picture. By interlacing two half-pictures, the frame repetition rate of 50 per second is maintained and the bandwidth needed for transmission is reduced by half. Reduction of frame repetition rate would make the pictures appear to flicker.

The results of this investigation are considered first in relation to the case of sequential scanning, when a 6 mc/s bandwidth is considered necessary in order to yield equal horizontal and vertical definition. The definition, or resolving power, along each line, is relatively easy to evaluate, but the definition down the picture frame will depend on the number of lines and also on the way the lines scan the original picture. If the lines exactly fit a pattern, it may be transmitted complete and undistorted, but the lines may fall exactly on the edges and the pattern will not be resolved at all. If the lines do not exactly fit a pattern, beat patterns and spurious effects will result, so that vertical definition becomes statistical in nature. By moving the test pattern relative to the camera scanning lines, this statistical effect was observed visually, and the results are shown in Fig. 4, both for the sequential and for the interlaced scanning. It should be borne in mind that although the system is nominally 405 lines, 20 of these lines are blacked out whilst the scanning spot is returning to the beginning of a frame, so that the resolution is in fact derived from 385 active lines. Taking the pattern size which was transmitted for 50 per cent. of the time as being the size of detail representative of vertical definition, this was found to be 377 elements per picture height, when sequentially scanned. By close visual inspection, the horizontal definition was observed to be 438 elements in a picture width equal to picture height. The picture can, therefore, be considered to be astigmatic, in the proportions of 377 : 438. The smallest picture element is 1/438 of the picture height. The size of a line element is 1/770 of the picture height, because there are 385 active lines and 385 black interspaces, making a grating of 770 elements.

The distances at which the acuity parameters of the television picture are at the threshold of visibility may now be considered. If an element of detail of the same dimensions as a raster line has the same visibility as the raster itself, then the ratio of the distance at which the finest detail transmitted is just visible to that at which the raster is just visible will be 770/438. It has been shown above, however, that a grating pattern will be visible at four-thirds the distance at which detail of similar dimensions, but of the subjective or broken ring type, will be visible. The distance at which the finest picture detail transmitted by the system is just visible, therefore, is $3/4 \times (770/438)$ or 1·3 times as great as the distance at which the raster is at the threshold of visibility.

Thus the picture detail can still be appreciated when the line structure is not visible, and from this point of view 405 sequential lines transmitted through about 6 mc/s would appear to be ample. It has been demonstrated, however, that the picture is astigmatic and requires either a slight reduction of bandwidth or a slight increase in the number of lines to correct this fault, but Baldwin (1940) demonstrated that, in the case of a subjectively sharp picture, discrepancies between vertical and horizontal definition were not noticeable within quite wide limits, of the order of 3 : 1. He noted a slight bias in favour of having higher definition along the lines than down the raster. The 405-line sequential system would, therefore, appear to be ideal from this viewpoint.

Now consider the case of an interlaced, nominally 405–line system. Owing to such visual effects as " line-crawl " and " break-up " of the interlaced pair of frames, the visibility of the grating formed by the raster will become that of a 192½-line or 385-element grating, and not twice that number.

In the sequential case there are no such disrupting visual effects, and the grating is of 770 elements.

The horizontal picture definition was again found by direct observation to be 438 elements in a distance equal to picture height, but the vertical definition of a nominal 405-line raster appeared to be 317 elements (Fig. 4), when interlacing was used (it appeared to be 377 elements on a sequential raster).

The greatest distance at which picture detail can still be appreciated,

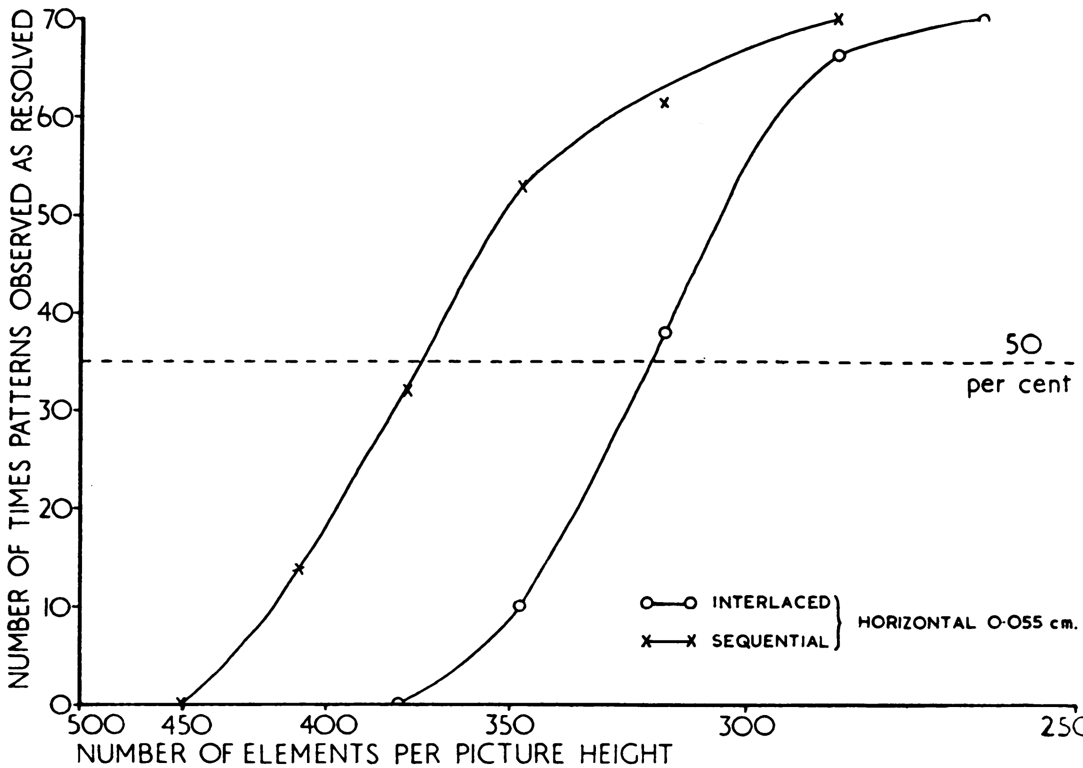

FIG. 4.—Vertical resolution of Cobb-Moss test pattern by variable definition channel.

therefore, remains dependent on the higher horizontal definition of the system, but the line structure can now be seen at twice the distance previously found, and the ratio of the distance at which picture detail is just visible to the distance at which the raster is just visible becomes 3/4 (385/438) or 0.66; that is, the line structure is visible long before the finest picture detail transmitted can be appreciated, and it would seem at first sight that more lines would be desirable for interlaced pictures through a 3 mc/s bandwidth. Also, the ratio of horizontal to vertical definition is 438/317, making the vertical definition only three-quarters of the horizontal definition in practice. This is a further indication that the number of lines used in the interlaced case is insufficient, and should be increased to something of the order of 405 $\sqrt{438/317}$, or 475 lines, although according to Baldwin's data this discrepancy in resolution is insignificant. The important point to be emphasized, however, when line interlace is utilized on the present standards, is that the lines will always be visible when full use is made of the available resolution of the system.

The number of pieces of picture detail that can be resolved both along the line and down the picture has been observed visually, and hence the total number of elements which are contained in the television picture has been counted. Thus the number of elements which are in fact transmitted in a 3 mc/s bandwidth is known. The bandwidth available can be distributed in varying proportions between providing the horizontal definition and providing the vertical definition by virtue of the line number. If the number of lines is decreased, vertical definition will decrease but horizontal definition will be increased, so that the elements will become tall rectangles. There will be a unique number of lines at which the elements will be square, and the picture will not be astigmatic. It can be shown, however, that the ratio of height to width of the elements, can never be adjusted to make the smallest picture-detail dimension more visible than the line-width, when the bandwidth is restricted to 3 mc/s and line interlace is used. For practical purposes, this can be extended to apply to all interlaced pictures irrespective of bandwidth.

The Cobb-Moss test pattern has been used to obtain independent values for the vertical and horizontal definition of a picture. In actual practice, the two types of definition are interdependent, and the two values of horizontal and vertical definition quoted for each example will need to be modified to give an average value of picture definition that probably lies between the two. In the first of the two examples given above, that is, the sequential case, this will have the effect of increasing the range of distance in which all picture-detail is visible and the line structure cannot be seen. This is because the detail would be taken as coarser than 438 elements per length equal to picture height. It will decrease the range in the second case, in which the line-break-up structure can be seen and the picture not fully appreciated. Contrast and distribution of brightnesses will also affect the result, and the final system resolution will depend on complex factors which cannot easily be handled.

The foregoing simplifications have been made in order to obtain some answer that it is hoped will indicate orders of magnitude. Many points have yet to be measured, such as the influence of the ratio of the widths of the black and white or the "duty factor" on the visibility of grating patterns. The chief drawback to the present television standard, however, appears to be due to the use of interlacing. If the limitations of interlacing could be overcome, the number of lines would appear to be satisfactory.

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