COMMUNICATIONS

MEASUREMENTS OF VISUAL ACUITY*

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(1) INTRODUCTION

THE ability to detect detail is so important an attribute of the eyes that many measurements of visual acuity have been made. The most extensive and most quoted work is that of Lythgoe (1932); but the range of luminances which he could study was limited, and he concerned himself only with the effect of one background size, namely the whole visual field.

In the investigations described in this paper, luminances of test object up to 10,000 ft. L. have been used and the effect of different sizes of background has been explored. Some experiments on coloured test objects have also been made.

(2) FACTORS AFFECTING VISUAL ACUITY

The visual acuity is a measure of the eye's ability to discriminate detail. It is expressed as the reciprocal of the angular subtense, in minutes of arc, of the separation that can just be detected between two objects. The ability to detect detail depends on the nature of the object and on the eye; the visual acuity depends also on the criterion for successful detection that is used. Of these three factors the nature of the detail (including the method of presentation), as well as the criterion for detection can be completely determined by the experimenter. The eye, however, forms part of a complex nervous system and the subjective image is affected by many physical and mental factors. Some of these are understood and may be kept constant during an experiment; but the majority are fluctuating continuously and large variations in visual acuity occur in any observer. Hence, any measured visual acuity is only true for the instant of measurement and consequently many observations must be made to obtain a useful average result.

The effect upon visual acuity of the nature of the test object, criterion of detection, and eye receptor mechanism are briefly discussed below, since a consideration of these effects determines the conditions of the tests and experimental technique. This discussion is by no means complete and shows only a few results of other workers in relation to the present series of tests.

Test Object.—This usually consists of some fine detail which has to be discovered

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with respect to an easily seen reference object. Many test objects have been devised, the most common being the Landolt broken circle, parallel bar gratings, and the Snellen test chart. In the first series of experiments a dark Landolt broken circle on a light background was employed, and in the experiments with colour contrast a coloured test object and surround were used. The advantage of this type of test object is that it provides a "point" rather than a "line" object. The relative dimensions and shape of the broken circle are shown in Fig. 1. It could

FIG. 1.—Dimensions of Landolt broken circle.

rotate about its centre so that the gap was presented at any of eight points of the compass and the subject had to detect the position of the gap. The detail to be detected was, therefore, given by the size of the gap: the reciprocal of the angular subtense of the gap gave the corresponding visual acuity. The subtense of the gap in the broken circle at the observers' eyes ranged between $1/3$ and 2 min. of arc.

The broken circle was always presented on a small white field subtending 0.5° at the observer's eye. This small field is referred to below as the "central field".

Contrast of the Test Object.—The majority of workers have used a relatively high contrast between the test object and its immediate background. This is convenient, as it seems that visual acuity does not vary rapidly with contrast between the test object and its immediate background provided this contrast is fairly large. This contention is indirectly supported by Smyth (1947) in his reports on the visibility of road traffic signs. Although the exact effect of contrast upon visual acuity has not been determined, Weston (1945) has investigated the relation between the "visual performance" of an observer and illumination for various contrasts.

In order to eliminate effects due to contrast sensitivity and to secure results comparable with previous work a high contrast test object was used in the experiments described in this paper. The Appendix describes how the test object was made.

Luminance Distribution in the Field of View.—The luminance pattern of the field of view can be considered to consist of two areas, the "central field" and the "surround". An infinite variety of luminance patterns occurs in the surrounds encountered in normal life, but in a controlled experiment simple backgrounds are more convenient. Lythgoe considered three different luminance distributions: a total surround, a dark surround, and glare sources at one side of the direction of vision; he showed that the surround exerts a considerable influence upon the visual acuity of an observer.

The purpose of the present series of tests was to investigate the effect of a symmetrical surround: first, the effect of the size of the surround when at the same luminance as the central field, and secondly the effect of the luminance of the surround for various luminances of the central field.

When the test object is black, as in Lythgoe's experiments and those described in Section 5 of this paper, the luminance of the central field is a major factor in determining whether or not the detail can be detected. This direct effect of luminance upon visual acuity has been investigated by König (1897),

Lythgoe (1932), Shlaer (1937), and others. The experiments described in this paper extend this relationship to high luminances.

Colour.—The effect of various coloured backgrounds to a neutral test object has been studied by König (1903), Roaf (1930), and Shlaer, Smith, and Chase (1942), for example. In general there appears to be little difference between coloured and white backgrounds of equal luminance.

A coloured test object viewed on a coloured background presents a colour contrast as well as a luminance contrast, and as so many visual tasks in practice involve coloured surfaces it is surprising that little is known about these conditions. Interesting difficulties arise when acuity tests are made in small areas of colour, as described below.

Movement of Test Object.—This greatly affects the detection of its detail. A low velocity may improve the subject's performance, but as the velocity is increased the detail is soon rendered indistinguishable. In the experiments described in this paper the test object was stationary while being observed. It was rotated at high speed between observations thus making the gap invisible.

Criterion for Detection of Detail.—The criterion for assuming that the observer can perceive the detail presented will considerably modify the visual acuity assigned to him. For example the standard of performance needed in most practical work is that the detail should be detected every time. However, as soon as the observer's performance rises above that due to chance, he is in fact detecting the detail to some extent. The conditions required to attain 100 per cent. perfection differ widely from those needed for a performance just a little better than that which may be achieved by chance. Lythgoe has shown that the performance curve obtained in this type of experiment helps to resolve the difficulty of the choice of criteria. A typical curve is given in Fig. 2, which shows how the performance of the observer, in trying to detect the detail of the test object, increases from chance to a maximum of 100 per cent. as the conditions of the test are eased. The curve is sigmoid, typical of this type of sensory test. The criterion of chance and 100 per cent. performance are difficult to determine as the curve is asymptotic to the horizontal at these points; also, many experimental observations are required to define these portions of the graph. The most easily obtained portion of the curve lies near the point of inflexion in the region of 50 per cent. correct observations.

This usually only requires three or four observational points to define its position, and the criterion adopted by Lythgoe of 50 per cent. correct observations together with an allowance for chance was used for most of the tests. The correction for chance observations was applied as follows: suppose the observer to be seeing 50 per cent. of the test exposures correctly. Since there are eight possible positions for the gap in the Landolt broken circle, he will score one-eighth of the remainder by chance.

FIG. 2.—Typical performance curve.

If, therefore, the observer's true criterion were 50 per cent., his score would be:

$$50 + \frac{50}{8} = 56.25 \text{ per cent. correct observations.}$$

Similarly, if his true criterion were 80 per cent., his score would be:

$$80 + \frac{20}{8} = 82.5 \text{ per cent.}$$

Some tests were made at this higher performance since it is closer to the requirements of practical conditions.

Receptor Mechanism.—The eye and brain, and the nervous connexions between them cannot be held constant: their performance will vary from moment to moment and day to day, so that an observer presented with a given visual task on different occasions will give responses which vary. The extent of such variations will depend upon the observer and the severity of the task. Some observers are more than usually consistent in this type of experiment and it is more convenient to use a small group of such consistent observers than a larger group of less consistent observers.

Observations in a particular set of conditions must be repeated sufficiently often to get a fair average result: and the conditions of experiment must be precisely repeatable. One of the physical factors which can be controlled is the state of adaptation of the subject. He must be allowed the necessary time to adapt to the prevailing luminance level of the test. In these experiments tests were begun at normal luminances, where possible, and these were then gradually altered to the extreme levels.

The distance between observer and test object also has some effect on the acuity of the observer. Shlaer, Smith, and Chase (1942) have pointed out that an alteration in the distance of a test object does not bring about an exactly corresponding change in the retinal image, because the posterior nodal distance of the eye alters during accommodation and increases the size of the image on the retina as the test object is brought closer to the eye. Hartridge (1950) has calculated this effect, and it appears that it will only become appreciable at very close range. The apparatus used in the present tests displayed the test object at one metre from the observer and a difference in visual acuity of about 2 per cent. from that obtained at much larger distances might be expected.

FIG. 3.—Effect of speed of working upon performance.

of this type showed that the time factor had a marked effect on the results. The

Exposure Time of Test Object.—The time allowed for detecting the detail of the test object will affect the performance of the subject. To investigate the extent of this effect an experiment was made using a performance test devised by Weston (1945). Cards consisting of 256 printed Landolt broken circles, arranged with their gaps in any of eight possible positions, were presented before a subject who went through them marking off broken circles orientated in a particular direction. The time allowed to discover the detail of the test object was reduced, and the effect upon performance was noted. The relation between time and performance for one set of conditions is shown in Fig. 3. Several tests

more the observer is forced to "work against time" the poorer is the performance. To assist in obtaining consistent results and to confine the problem to measurements of acuity, therefore, the observer was allowed as long as he liked to make his judgement in the experiments described below.

(3) APPARATUS

Many ways of presenting the test object have been devised: they may be broadly divided into direct viewing and observation of an aerial image. The direct viewing method usually consists of showing the test object on a card at a certain distance from the observer. Thus a relatively large test object can be used and consequently small errors in its reproduction are unimportant. This has a disadvantage in that much space is required and the surround conditions cannot be easily altered.

In the second method an aerial image of the test object is formed by a lens system. This permits a short viewing distance to be used provided that the test object is accurately formed and allows a spotlight to illuminate the surround without illuminating the test object itself.

FIG. 4.—General arrangement of apparatus (side of booth removed).

FIG. 5.—Diagram of apparatus (plan).

In these experiments the second method was used. In the apparatus (Figs 4 and 5) a lamphouse illuminated a photographic transparency of a

Landolt broken circle. A lens formed an image of the transparency in a fixed plane. The lens and the slide were mounted on carriers running over a pair of scaled guide rails and so, by altering the position of the lens and slide relative to the fixed plane, a large range of image sizes could be produced. The image was formed in an aperture in the side of a booth and viewed by the subject sitting with his eyes at a distance of one metre. The subject viewed the test object binocularly with his eyes positioned at the correct distance by means of a head rest. This luminance pattern of the field of view was provided by white card discs mounted in the booth and illuminated by spotlights. The construction and checking of the apparatus and test object are described in the Appendix.

The transparency could be rotated at high speed about its centre. By depressing a button the subject could stop the rotation: the broken circle was then presented to the subject in one of eight possible positions, the test object remaining stationary as long as the button was depressed. Neither the subject nor the operator could influence this choice of position. The subject then informed the operator of the position in which he thought the gap appeared. By taking many such observations the subject's performance could be estimated.

This form of apparatus had several advantages. The size of the Landolt broken circle could be varied easily by means of the lens system, and the very small test objects, required for the higher visual acuities, could be accurately produced. The test object was always presented at the same distance from the eye, thus avoiding any alteration of the posterior nodal distance. Also, a factor which was very important for the present investigation, the test object could be easily incorporated into the various types of surround required by the experiment.

(4) EXPERIMENTAL TECHNIQUE

The observers employed in the tests were specially selected. A preliminary series of tests was carried out with a large group of subjects and the choice of subject was based upon two aspects of their performance. The criteria of selection were:

- (a) that the observer should be consistent in his readings;
- (b) that the absolute value of visual acuity obtained was approximately that of a person with average sight.

In the first experiments each subject made twenty observations, trying to determine the position of the gap in the test object for various luminance conditions, the size of the Landolt broken circle remaining the same. This test was repeated on five separate occasions for each observer and a mean taken. Then a graph was plotted of performance against luminance condition, and by using the criterion of 50 per cent. + chance (i.e. 56.25 per cent.) correct observations, it was possible to determine the luminance condition corresponding to the visual acuity.

After using this technique for some time it was found that the first few observations in each set of twenty were sometimes inconsistent with the rest. This was due to the subject taking a short time to settle down to the test; subsequently, therefore, the first few readings in each set were ignored. It also appeared that some reduction in the total number of one hundred readings taken by each observer would be possible and by taking a total of 65 observations on two separate occasions, consistent results were still obtained.

Altogether about 100,000 observations were made with neutral test objects and another 30,000 with coloured test objects.

The adaptation of the observer's vision to the luminance of the test will have a considerable effect upon performance. In the present experiments the observer was allowed as long as he required for adaptation, and where possible the tests were started at normal luminances before being gradually altered to the high or low values.

If two test conditions are to be compared and the two tests are made on separate occasions, then the continual fluctuations in the visual acuity of the observers tend to mask the difference existing between the two conditions. This was overcome by comparing the two test conditions directly in each experiment wherever possible, for, although values might fluctuate, the relation between the two conditions remained fairly constant. The apparatus was constructed, therefore, so that rapid changes in surround size and luminance level could be made.

Performance of Subject.—In general the subject was unaware of the correctness or otherwise of his performance. This was most noticeable at the lower performance levels where the subject often could not believe that he was detecting the gap at all. Several subjects found that at certain instants they could see the gap clearly although their average performance was quite low. Evidently, for some reason, the visual mechanism was in a state favourable to the reception and recognition of the image at that particular moment.

The time of observation of the test object was completely under the control of the subject. Most people took one to five seconds to make the judgement, the time required being longer as the task became more difficult. Although subjects had more confidence if the test started with easy conditions and was then made more difficult, it was found that their performance was the same if the test began with the harder tasks.

With tests of this type, which tend to be monotonous and yet require the full attention of the subject, it is possible for fatigue to affect the result. In order to reduce fatigue the tests were kept as short as possible, and usually lasted about half an hour. Separate experiments indicated that there was no appreciable reduction in performance during this period.

(5) EXPERIMENTS WITH BLACK AND WHITE TEST OBJECTS

(a) *Effect of Luminance and Size of Surround on Visual Acuity.*—The results of the experiments concerning the effects of luminance and size of surround are shown in Figs 6 and 7. For this investigation three surround sizes were used as well as the central field. These surrounds were circular discs subtending angles of about 120° , 38° , and 6° at the eyes, whilst the immediate background to the test object (or central field) subtended 0.5° .

FIG. 6.—Relation between visual acuity and luminance for various sizes of surround (luminance of surround same as that of central field).

FIG. 7.—Relation between visual acuity and size of surround for various luminances (luminance of surround same as that of central field).

In each case the surround was matched to the same luminance as the central field. The graphs show the relation between the luminance of surrounds of various sizes and the visual acuity.

At low luminances, of the order of 0.8 ft.L. , the size of the surround does not affect the visual acuity. At rather higher luminances the increase in surround from a background of 0.5° subtense to 6° gives improved visual acuity, but a further extension of the surround to 38° and 120° has progressively less effect. This tendency becomes more marked at higher luminance levels; although a considerable improvement in visual acuity occurs on increasing the surround from 0.5° to 6° , no significant change results from using the much larger surrounds of 38° and 120° . At luminances above about $1,000 \text{ ft.L.}$ the visual acuity for all surround sizes is reduced. Also the previous effect of the size of surround is to some extent reversed, and the 38° and 120° surrounds give rather poorer visual acuity than 6° .

Since the curves for surrounds of 38° and 120° are so alike up to $1,000 \text{ ft.L.}$, it appears that, provided the surround subtends more than about 38° , all

sizes of surrounding field give similar results. The values of visual acuity found with a 120° surround may, therefore, be assumed to hold for a 180° surround.

(b) *Effect of a Surround of Different Luminance from the Central Field.*—

Fig. 8 shows the result of tests with a 120° surround of different luminances from the central field. For a test object with a central field luminance of 1 ft.L., there is no change in visual acuity as the luminance of the surround is increased from darkness until the luminance of the surround exceeds that of the background, when a rapid fall occurs. With a 10 ft.L. central field luminance, visual acuity increases with the luminance of the surround until it reaches a maximum, when the two luminances are about equal, but a further increase results in a quick drop in visual acuity. The curves for central fields having luminances of 100, 1,000, and 10,000 ft.L. show this same general shape. It is noticeable, however, that, as the luminance of the central field increases, so the maximum visual acuity occurs with surrounds having rather lower luminances than the central field. These results are

FIG. 8.—Relation between visual acuity and luminance of surround for various central field luminances (120° surround to central field).

FIG. 9.—Relation between visual acuity and luminance of central field for various surround luminances (120° surround to central field).

plotted in a different manner in Fig. 9 and in this form may be compared with Fig. 6.

In these graphs at some points similar conditions occur but the indicated values of visual acuity are slightly different: this is because the two experiments were made on separate occasions and with different observers.

A further series of experiments with the intermediate surround of 6° showed that it gave similar results to those obtained with a 120° surround.

The comparison is shown in Fig. 10 for central fields having luminances of 10 and 100 ft./L. The smaller surround does not have such a large effect: also the rapid fall in visual acuity when the surround exceeds the central field luminance is not so marked as for the larger surround.

FIG. 10.—Relation between visual acuity and luminance for two sizes of surround.

1. Central field luminance 100 ft./L. with 120° surround.
2. Central field luminance 100 ft./L. with 6° surround.
3. Central field luminance 10 ft./L. with 120° surround.
4. Central field luminance 10 ft./L. with 6° surround.

FIG. 11.—Effect on results of different criteria of performance (38° surround).

(c) *Effect of Changing Criterion of Detection.*—All the results presented in the previous sections are based on a “50 per cent. + chance” criterion of performance; the reasons for choosing this level of performance have been discussed in Section 2. However, in practical seeing a higher criterion is of more interest and the relation between the “50 per cent. + chance” and a higher criterion was, therefore, investigated. Because of the difficulty of determining the end point of 100 per cent. correct observations a rather lower level was used. In Fig. 11 the effect of the luminance of a 38° surround upon visual acuity is shown for two levels of performance, “50 per cent. + chance” and “80 per cent. + chance”. Although the absolute values given by the higher criterion are quite different, the curves are similar in shape and show the same characteristics.

(d) *Variations in a Group of Subjects.*—The accuracy that could be obtained in the experiments was limited by the fluctuations in the performance of the subjects. The precautions to reduce these variations to a minimum by employing consistent observers have been described. Because of the large number of observations made it is impracticable to show the individual results of each observer on the graphs without confusion.

However, in order to show the spread in performance of the observers in a typical experiment, their results have been indicated in relation to the mean curve in Fig. 12, which shows the variation of visual acuity with the luminance of the central field. The spread in results of the four subjects in this test was typical of that encountered in all the experiments.

It is difficult to ensure that the ability of the subjects selected for the experiments does in fact represent an average performance. In order to find out how far the selected subjects deviated from the mean of a larger group, the visual acuity of 27 subjects was measured for three different luminance conditions. In the Table these results are compared with those obtained from the smaller set of observers used in the main experiments; the differences are small.

When tested with the Snellen chart the performance of the smaller groups of observers ranged between 6/4 and 6/9 (with glasses where worn): the average performance was slightly better than 6/6.

FIG. 12.—Spread of results for four observers.

TABLE
RESULTS IN SELECTED SUBJECTS COMPARED WITH LARGER GROUP

Luminance Condition	Ft.L.	Visual Acuity		
		27 Observers	3 Observers	4 Observers
0.5° background	0.8	1.35	1.4	1.35
38° surround	1,000	2.5	2.66	2.62
0.5° background	1,000	1.93	2.18	2.07
Average Age (yrs)	—	32	29	28

(e) *Results.*—Visual acuity at the lower levels of luminance has been determined by many experiments, the most important being those of Lythgoe (1932).

Fig. 13 (overleaf) shows the effect of luminance on acuity obtained by Lythgoe and in the present investigations. In Lythgoe's experiments the background (which was a full 180° field) was limited to a luminance of

FIG. 13.—Comparison of Lythgoe's results with present experiment.

Curves 1 and 2 were obtained in the present series of tests on different occasions. Curve 2 has been modified, by a dotted line, on the basis of results shown in Fig. 8 to accord with Lythgoe's test, the results of which are shown by curve 3.

results showed a continuous increase in acuity with increasing central field luminance: the present results, however, show that the increase of visual acuity does not continue indefinitely but reaches a maximum followed by a decrease. The region of falling visual acuity occurs at luminances only obtained in practice with light-coloured objects in bright sunlight, *i.e.* in the "glare region". This condition would be unlikely to occur with artificial lighting as at present practised.

This result applies not only to large surrounding fields, but is true of all field sizes (Fig. 6). In general there is an increase in acuity as the surround size is increased, although the major increase was achieved when the surround subtended 5° to 10° . Figs 6 and 8 show that the minimum surround size which will give nearly maximum acuity depends upon the surround luminance. However, in general, it would seem that a surround subtending 30° – 40° will give very nearly the highest attainable value of acuity for a given luminance condition. In addition the observers found this a comfortable condition for observations. The luminance of the surrounding field for maximum acuity is not critical for luminances below 100 ft.L., provided that the surround is not brighter than the central field. Fig. 14 (opposite) shows, however, that for central field luminance above 100 ft.L. the

38.1 ft.L. The surrounding and central fields were matched in luminance up to 38.1 ft.L. Above this level the surrounding field was darker than the central field and this condition is shown on the graph by a broken line.

Curves 1 and 2 in Fig. 13 were obtained in this series of experiments on different occasions, the surround size being 120° . Curve 2 has been modified on the basis of the results shown in Fig. 8 to accord with Lythgoe's reduced surround luminance and this is shown by a broken line. Having regard to the limitations of this type of experiment there is good agreement between Lythgoe's results and ours.

Because of the experimental limitations Lythgoe's

surrounding field must have a considerably lower luminance than that of the central field to secure maximum visual acuity.

All these results apply strictly only to a criterion of 50 per cent. chance of detecting the fine detail. Practical seeing demands a considerably higher chance of detection than this, but there are two pieces of evidence which suggest that the results may be applied to more practical conditions. These are:

(i) the tests made using an 80 per cent. criterion of detection,

(ii) a comparison with the results of Weston (1935).

The tests made with an 80 per cent. criterion gave curve shapes similar to those with a 50 per cent. criterion (Fig. 11). It appears, therefore, that altering the criterion will alter the absolute values of acuity recorded but will not materially alter the general relationships of acuity, luminance, and surround size.

The results of some of the measurements of "visual performance" recorded by Weston (1935), a compound of acuity, speed of working, and accuracy, are shown in Fig. 15 (overleaf), which also shows a plot of visual acuity against luminance obtained in the present experiments. The curve shapes are not very different, but to bring the absolute values reasonably close, the visual acuity values found in Weston's experiments must be multiplied by 4.5. This suggests that the general curve shapes of Weston's results are largely controlled by acuity, but that the absolute values are mainly determined by other factors such as speed of operation. Evidently, therefore, although the results given in the present paper show the relations between visual acuity and other factors, they cannot be used to compute absolute values of acuity in practical conditions since any practical problem of seeing will involve difficulties which will greatly reduce the effective visual acuity.

Conclusions.—By far the largest factor affecting visual acuity is the luminance of the small immediate background (some 6°) to the visual task.

By increasing the luminance of the background to the test object, relatively large increases in visual acuity can be secured up to the region of 100 ft.L. Beyond this luminance, visual acuity tends to remain constant and a definite

FIG. 14.—Luminance of surround for maximum visual acuity (120° surround).

FIG. 15.—Comparison of Weston's visual performance results with present experiment.

1. Present experiment.
2. Modified Weston's results.
3. Weston's results.

maximum is obtained at a high luminance level, the exact value of which depends upon the surround conditions. At luminances above about 1,000 ft.L. (which are only encountered in bright sunlight and on the surfaces of lighting fittings) there is an overall reduction in visual acuity for all surround conditions.

Visual acuity increases with the size and luminance of the surround, and a surround subtending some 30° or 40° at the eyes and having a luminance tending to be rather lower than the background to the test object will give the best performance under most conditions. There is a considerable reduction in visual acuity when the surround exceeds the background luminance to the task. Alterations in surround, in general, cause second order changes in visual acuity, and it is unnecessary to provide large surrounding fields to secure high acuity.

There is a widely held belief that to obtain good conditions for seeing, particularly in interiors, the diversity of luminance in the surroundings should be kept quite small and that large areas of the interior should have substantially the same luminance as the work area: this is an argument adduced by some exponents of "brightness engineering" who claim that this technique reduces glare and improves acuity. Whether or not glare is reduced, it is evident from the present work that large, bright surrounds do not improve acuity.

The maximum visual acuity which can be obtained at high luminance levels corresponds to the detection of details much smaller than are encountered even in such fine work as watchmaking, although it may be that our visual impression of a scene depends more on the appreciation of very small details than we realize. In ordinary work many other factors operate to affect the luminance needed for high visual efficiency. For example, the

element of speed in working, and the need for a higher accuracy than 1 in 2 correct, makes it desirable to have a higher luminance than shown by these experiments for the convenient resolving of a small object of any given size. Alternatively, it must be appreciated that although under the best conditions the observers in these experiments were able to detect detail much smaller than is encountered in normal work, they would not achieve these high values of acuity in "real" situations where many conditions might limit their visual performance, as in Weston's experiments.

It appears, however, that acuity plays a large part in determining the relation between "visual performance" and such factors as luminance so that relations which hold between acuities measured under different conditions may also be substantially true for "visual performance" under similar conditions.

(6) EXPERIMENTS WITH COLOURED TEST OBJECTS

(a) *Method of Experiment.*—A Landolt broken circle of one colour, upon a background of a different colour but of the same luminance, was used to determine the visual acuity due to colour contrast at various luminance levels.

The visual acuity of a subject with such a test object was found by the same method as that described for a black Landolt broken circle upon a white background. Since in this apparatus the actual test-object consists of a photographic transparency, a colour film could conveniently be used for the coloured test object. This places a considerable limitation on the colours and saturations obtainable and, although the colour contrast was intended to be red and green, the actual colours reproduced on the film tended to red-orange and green-blue respectively. These were, therefore, not spectral colours but colours similar to those obtainable with normal dyes and paints. The Appendix gives details of how the test object transparencies were made. Two transparencies were produced: one having a green Landolt broken circle upon a red background and another with a red Landolt broken circle upon a green background. Both these transparencies had been exposed so that the reproduced colours were of equal luminance.

Five subjects were selected as being consistent observers having average visual acuity. All gave normal results when tested with the Ishihara tests for colour blindness. With each of the two test objects, the visual acuity of each subject was determined over a wide range of luminances, using the methods described previously. A 38° surround was used for all tests and this was matched in colour and luminance with the background to the Landolt broken circle in both cases. As the colour film and the colour filters used on the spotlights illuminating the surround had a relatively low transmission, it was not possible to reach extremely high luminances.

(b) *Results.*—Fig. 16 shows the visual acuity obtained with a red-green colour contrast. Curve (2) gives the results for a green Landolt broken

circle upon a red background, and Curve (3) those for the opposite colour arrangement, both having a medium-sized surround matched in luminance and colour with the background. In Fig. 16 these results for colour contrast may be compared with

FIG. 16.—Visual acuity with Landolt broken circle (38° surround).

1. Black circle on white.
2. Green circle on red.
3. Red circle on green.

those for a black, high contrast, test object. Both of the curves for coloured test objects have characteristics similar to those for the neutral test object, in that visual acuity increases rapidly with luminance up to 100 ft.L., reaches a maximum value, and subsequently decreases at high luminances. The two-colour contrasts give similar results which are rather lower in magnitude than those obtained with a neutral test object.

Most subjects found that, as the luminance of surround and test object increased, the saturation of both the coloured surround and the background appeared to decrease, until they appeared almost white at the very high luminances.

The Landolt broken circle also appeared to undergo changes. As the luminance increases, in general visual acuity improves, and consequently the size of the Landolt broken circle required to test the subject decreases. This combined effect of increasing the luminance and decreasing the size of the test object appears to affect the two types of colour contrast differently. With the green Landolt broken circle upon a red background and surround, according to most subjects, the green appears to become darker at the higher visual acuities. However, with the red Landolt broken circle upon a green background, the subjects find it difficult to analyse the effect, which seems to be a tendency to make the red more prominent, and was variously described as an increase in the red luminance, or an increase in the red saturation.

The visual acuity obtained for the red-green colour contrast is quite high, but does not attain the values obtained with a high-contrast neutral test object for a given luminance and surround size. With "white" light

sources, however, in order to attain the same luminance with the coloured test object as with the neutral one, much higher illuminations were required. In the present experiment, the transmission of the colour transparency was of the order of 4 per cent. so that an illumination 25 times greater than that required for a black and white test object was needed to reach the same luminance. Under practical conditions a similar relation will occur. For example, the reflection factor of white paper is about 80 per cent. and that for red and green paper might be 15 per cent., thus requiring an illumination 5 times greater on the coloured surfaces to achieve the same luminance. As can be seen from Fig. 16, such a reduction in luminance when using a coloured surface with a low reflection factor will reduce visual acuity considerably. Nevertheless, comparatively high values of visual acuity have been obtained with a red-green colour contrast under the described conditions of measurement.

(c) *Validity of Results.*—It is important to stress the fact that these results strictly only apply to detecting detail in a Landolt broken circle corresponding to the indicated visual acuity, because of the visual changes that take place when the luminance of the test object and surround is raised and the size of the Landolt broken circle is reduced for measurements at high visual acuity values.

Although all observers found it difficult to analyse the changes that took place in the test object, in general the green Landolt broken circle appeared to become darker and the red broken circle more prominent: as a consequence an apparent brightness difference is added to the existing colour difference, increasing the contrast and probably increasing acuity.

The results obtained, therefore, do not record acuity due solely to a colour contrast. To obtain this information it would be necessary to re-adjust the relative luminances of the Landolt broken circle and background for each set of observations to ensure that the subjective impression of the observer was that circle and background were equally bright.

The technique adopted was to match the luminances of circle and background at ordinary luminance levels and to assume that this match held over the range of sizes and luminances explored. This method has, perhaps, more resemblance to practical conditions than has the other method.

The apparent change in the luminance of the Landolt broken circle in relation to that of its background might be due either to its decreasing size or to its increasing luminance. The effect of size was investigated in a subsidiary experiment in which a green Landolt broken circle upon a red background, at a fixed luminance, was viewed at various distances. It was found that as the subtense of the broken circle, at the observer, decreased, so it became darker with respect to the red. With the opposite colour arrangement, observers were unable to detect any definite change in appearance, but there might be a slight tendency for the red luminosity to increase.

This indicates that there is a change in luminosity as the size of the Landolt broken circle is reduced and a smaller image is produced upon the retina. The total subtense of the outside of the broken circle used in the present experiment varied from 7 to 4 minutes of arc, which corresponds to quite a small area on the fovea, and therefore the response of the subject depends upon the irregular colour vision of the central fovea.

The results show that the visual acuities attained with the two copies of colour contrast are of the same order, which implies that the effect upon visual acuity of irregular foveal colour vision may be smaller than might be thought from the appearance of the test object.

The colour vision of the central fovea has been investigated by Wright (1946), who determined the relative luminosity and hue discrimination curves for a field of 20' subtense. These curves differ from those obtained for a larger field of 2° subtense and show that the central fovea is tritanopic (or less sensitive to blue radiations). This would explain the differences in red-green luminosity, the green appearing darker than the red for small fields.

This change in luminosity as the field size is reduced has also been shown with an anomaloscope by Horner and Purslow (1947, 1948). In this investigation the amounts of red and green required to match a yellow were measured for fields subtending various sizes from 4° to about 12'. It was found that the amount was dependent on the viewing distance and that the ratio of red to green decreased steadily over this range of sizes. This again would indicate that the luminosity of green, with respect to red, decreases as the size of the field is reduced.

This effect greatly complicates the measurement of visual acuity for colour contrasts, for the measurement consists essentially of varying the size of a colour patch in the shape of a test character. As the determination of visual acuity at normal luminance depends on the ability of the subject to discern small detail in a coloured test character, it is impossible to increase the size of the character and so free it from any extraneous effects. It might be possible to devise a different technique for the measurement of visual acuity that would avoid this effect by allowing an increase in the size of the test character; this could be accomplished for example by changing the criterion of detection of the detail and introducing a speed factor. The results obtained in these conditions could be compared with similar experiments for neutral test objects. It is most necessary, however, to decide what practical conditions the experiment is to simulate and then to design the experiment accordingly.

The present results indicate the acuity to be expected when a small coloured object is viewed against a background of contrasting colour, where the two colours would appear equally bright in fairly large areas, and where the colour contrast is reasonably high for ordinary pigments.

It seems likely that in practice the value of colour as a means for securing high visual acuity will be appreciably lower than shown by these results.

SUMMARY

Using a black Landolt broken circle on a white ground as a test object, visual acuity was re-measured up to levels of luminance of 10,000 ft.L. with surrounds of various sizes. The values obtained by Lythgoe (1932) have thus been confirmed and extended. It is shown that acuity tends to decrease above 1,000 ft.L. and that a large surround is not necessary to high acuity.

Some tests on coloured Landolt broken circles are also described; difficulties of observation arose from changes in the apparent brightness of coloured test objects with size.

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APPENDIX

Apparatus.—The general arrangement is shown in Figs 4 and 5. In the lamp-house was a 500 watt projector lamp illuminating a sheet of opal glass which provided the bright background for the transparency of the Landolt broken circle. This transparency was mounted on an aluminium disk which could rotate about the axis of the broken circle on a ball-bearing race. The transparency was rotated by means of A.C. coils which formed an eddy current induction motor with the aluminium disk. The gap in the Landolt broken circle could, therefore, rotate to any angular position. Eight iron studs were mounted around the disk and when direct current was applied to another coil its poles drew in the nearest stud and stopped the rotation. The gap could, therefore, appear at random in any of eight positions, and the choice of position was entirely a matter of chance. The direct current was applied to this coil when the subject operated a push-button switch, and the test object then remained stationary as long as the button was depressed, so that the subject could view the test object for as long as he desired. The disk and transparency rotated at 150 r.p.m. and the position of the gap was undetectable at this speed. The lamp-house and transparency carrier were mounted upon a trolley running on two rails and provided with a scale. The projection lens was mounted on another trolley and formed an image of the Landolt broken circle in an aperture at the end of a booth; by altering the relative positions of the lens and transparency with respect to this aperture it was possible

to obtain a large range of image sizes. Fig. 17 shows the projection lens and transparency carrier mounted upon their trolleys. The subject sat with his eyes positioned by means of a head rest so that they were one metre away from the aperture. The aperture in which the test object was shown subtended a total included angle of 0.5° at the observer's eye and this formed the background to the test object. Three additional surrounds subtended angles of 6° , 38° , and 120° respectively. The 6° and 38° surrounds were provided by white disks surrounding the aperture and were illuminated by tungsten lamp spotlights in the booth. The 120° surround was provided by a translucent sheet mounted in front of the observer, lighted from behind either by a spotlight or, for the very high luminances, by high efficiency photographic lamps. The light output of the spotlamps and the lamphouse was under the control of the operator.

FIG. 17.—Transparency carrier and lens (close-up view).

Test Object Transparencies.—For the fairly short distances at which observations were made a very small Landolt broken circle was required. For a neutral test object the transparency was made photographically by copying a white ring on a black background and using the resulting negative of a black ring on a clear ground. An accurately drawn Landolt broken circle of about 2 in. diameter was thus reduced to one about 1.5 mm. in diameter on the negative. To do this accurately required a combination of camera and film capable of high contrast and resolution. Several combinations of films and developers were tried, and Kodak "Microfile" negative material was selected as having extremely fine grain and being capable of high contrast. The negative used for the projection transparency had a contrast of about 150:1. In the transparencies used the circle diameter was 0.17 cm. with a gap of 0.034 cm. The test objects used for the colour contrast experiments were made in a similar way. "Kodachrome" reversal colour film was used to reproduce a transparency of a small coloured Landolt broken circle upon a coloured background. Because the colours employed were red and green, effects of colour diffusion within the film gave some trouble, and a large number of test exposures had to be made in order to eliminate

this effect. The dyes used in colour films limit the range of colours obtainable, but they are probably as saturated as most of those found in ordinary pigments. The approximate chromaticity coordinates of the colours obtained were these:

Red	...	$x = 0.64$	$y = 0.36$
Green	...	$x = 0.28$	$y = 0.40$

The slides were selected so that the red and green were of equal luminance, as measured with a visual photometer equipped with suitable colour matching filters.

For copying the neutral and coloured test objects a 35 mm. "Contax" camera was used; a lens aperture of f8 gave a resolution of 80 lines per mm.

Checking the Apparatus.—The size of the gap in the image of the Landolt broken circle was determined in two ways. In the first method, the nodal planes and focal length of the lens were found, so that the position of the lens and transparency gave various magnifications. The size of the gap in the transparency was found with a travelling microscope and the image sizes corresponding to the various magnifications were obtained. These calculated values were then checked by measuring the size of the gap in the image of the Landolt broken circle by two methods: directly with a travelling microscope, and indirectly by forming a magnified image. The differences between the calculated and measured values of gap sizes were about 1 per cent.

The luminances of the image and surround were measured with a portable visual photometer. Most of the luminance levels of the image were obtained by placing calibrated neutral filters in front of the lamphouse, finer control being effected by altering the voltage applied to the lamp. The luminance of the image did not vary with magnification.