The Relation Between Illumination and Visual Efficiency — the Effect of brightness contrast.

By: H. S. Weston,

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REPORT No. 87

THE RELATION BETWEEN ILLUMINATION AND VISUAL EFFICIENCY—THE EFFECT OF BRIGHTNESS CONTRAST

by

H. C. WESTON

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THE RELATION BETWEEN ILLUMINATION AND VISUAL EFFICIENCY—THE EFFECT OF BRIGHTNESS CONTRAST

PREFACE

This report is the second of a series dealing with the effect of characteristics such as size, contrast and brightness—which are common to all visible objects—on the facility with which these objects can be seen. It describes investigations initiated as the result of a suggestion by Mr. A. W. Beuttell, that if the relationship could be ascertained between these characteristics for satisfactory visibility, then the illumination suitable for the performance of any industrial or other task ought to be capable of computation.

The first report, discussing the relationship between illumination and size of object, was published jointly by the Industrial Health Research Board and the Illumination Research Committee of the Department of Scientific and Industrial Research in 1935. The present report deals with the relationship between illumination and another variant of visual tasks, namely the contrast of brightness which differentiates details of the task object, or the object and its background.

The investigations described were made at the National Physical Laboratory by Mr. H. C. Weston, one of the Board's senior investigators. He has had the advice and co-operation of Dr. H. Buckley, of the Department of Scientific and Industrial Research, who has given most valuable help both with the experiments and with the presentation of their results. Acknowledgment is also due to Dr. Buckley for his supervision of the photometric observations involved, and of the necessary arrangements for lighting. The visual tasks were performed by members of the scientific staff of the National Physical Laboratory, to whom thanks are due for their interest and participation in this somewhat tedious work.

The Illumination Research Committee, under the aegis of which the investigations were carried out, was dissolved before a full report upon them could be made. In consequence, the report has been referred for consideration to the Physiological Committee of the Illuminating Engineering Society,* which includes a number of members of the former Illumination Research Committee, and of the Vision Committee of the Medical Research Council. Of these, Professor H. Hartridge, Mr. J. S. Dow and Dr. J. W. T. Walsh were respectively chairman and members of the sub-committee originally appointed

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by the Illumination Research Committee to direct and supervise the investigations, and thanks are due particularly to them for their continued interest in the work and their constructive criticism of the draft report.

The Board have been glad to accept the recommendation of this Committee to publish the report, for—not only in factories, but in offices, schools, homes and elsewhere—the importance of good lighting for health in its fullest sense cannot reasonably be doubted. One of the primary conditions of good lighting is an adequate amount of illumination, and it is in the determination of this that the data here presented are of interest and value.

Owing to the intervention of war, it has not yet been possible to complete the series of investigations originally contemplated in the hope of providing a scientific basis for a code of values of illumination for different classes of work. However, as soon as circumstances permit, it is hoped to undertake further work with this object in view.

INDUSTRIAL HEALTH RESEARCH BOARD OF THE
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30th December, 1944

THE RELATION BETWEEN ILLUMINATION AND VISUAL EFFICIENCY—THE EFFECT OF BRIGHTNESS CONTRAST

BY

H. C. WESTON, F.I.E.S.

CONTENTS

I. INTRODUCTION

A.—OBJECT OF INVESTIGATION

This report describes two of a series of investigations intended to test the value of a method, suggested by A. W. Beuttell, for determining the degree of illumination required for the efficient performance of any kind of work involving visual discrimination.

The method is "based on the proposition that the illumination required for any visual task, as compared with the simplest possible task, depends upon certain conditions adversely affecting its performance; that these conditions can be defined; and that if the relationship can be ascertained between each of the conditions and the illumination required to compensate for it, then the illumination suitable for the performance of the task ought to be capable of actual computation."*

*An Analytical Basis for a Lighting Code, by A. W. Beuttell. *Illuminating Engineer*, 1934, **27**, 5.

Among the more important of the conditions affecting the performance of a visual task are the apparent, or visual, size of the object viewed and the contrast between the latter and other juxtaposed objects. The effect of size on the illumination required when contrast is good has been shown in a previous publication,* and the present report is concerned with the effect of varying the degree of contrast presented by the task.

B.—Definition of "Contrast"

The term "contrast" is sometimes used with a special meaning,† but, as generally used, it means unlikeness, or difference, in things compared. Thus, contrast is presented when objects in juxtaposition differ in colour or brightness, or in both these characteristics, and the differentiation of objects by sight is fundamentally dependent on differences, or contrasts, of this kind. In this report only contrast due to difference in physical brightness is considered. This difference may be due to a difference in the amounts of light received by the objects or, as in the experiments to be described, to a difference in the reflection factors involved.

C.—Numerical Expression of Brightness Contrast

Physical brightness can be measured in terms of suitable units‡ so that the degree of contrast presented by objects which differ in brightness may be expressed numerically as a function of the photometric quantities involved. One function is the brightness difference (B_1-B_2); another is the ratio of the component brightnesses (B_1/B_2); and a third is the ratio of the brightness difference to the greater brightness $\left(\frac{B_1-B_2}{B_1}\right)$. The latter form may be termed the "relative brightness difference" or "relative brightness contrast".

The visual sense, in common with other special senses, appreciates relative rather than absolute differences in the stimuli to which it responds and, within a certain range of physical brightness, different pairs of juxtaposed brightnesses which have a common ratio *tend* to produce like sensations of contrast, whether their photometric values be low or high. Thus, the apparent contrast between contiguous surfaces having brightnesses of 1 and 10 equivalent foot-candles respectively, resembles that between other surfaces having brightnesses, e.g. of 10 and 100 e.f.c., although the sensory responses aroused by the component brightnesses of each pair are at different levels of intensity.

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* The Relation between Illumination and Industrial Efficiency: (1) The Effect of Size of Work. *Joint Report of the Industrial Health Research Board (Medical Research Council) and the Illumination Research Committee (Department of Scientific and Industrial Research).* H.M.S.O., 1935. (Out of print.)

† In physiological optics the term contrast has a special meaning. When two contiguous, or nearly contiguous, surfaces differing in colour or brightness are seen simultaneously, the stimulation of each retinal area involved modifies the sensation derived from the other. This reciprocal interaction is called "simultaneous contrast". Also, when a stimulus is applied to the retina the resulting sensation is followed by after-effects which modify the sensation due to succeeding stimuli. To this phenomenon the term "successive contrast" is applied. The alternative and more appropriate terms "spatial induction" and "successive induction" are now frequently used.

‡ The unit of brightness defined in the International Lighting Vocabulary (1938) is the Stilb. It is the brightness of a luminous source having an intensity of one candle per square centimetre of projected area. In this country it is usual to express the brightness of light sources in candles per unit area. One candle per square inch is the brightness of a source having unit luminous intensity (candle power) per square inch of radiating surface. In the case of illuminated surfaces, their brightness is a function of the illumination they receive and of their reflection factor. For such surfaces the unit of brightness commonly used is the foot-lambert or, as in this report, the equivalent foot-candle. One equivalent foot-candle (=1 foot-lambert=0·00214 candles per square inch) is the average brightness of a diffusing or matt surface which emits or reflects one lumen (unit of luminous flux) per square foot.

On the other hand, when the components of different pairs of unequal brightnesses are in different ratios they tend to excite different sensations of contrast, so that whether brightness contrasts appear "high" or "low", "strong" or "weak", depends chiefly on the relative rather than the absolute brightness difference involved. Thus, although it cannot be assumed that numerical expressions which are functions of stimulus intensities are proportional to the corresponding sensations, it is better to use a ratio than a difference for expressing contrasts numerically, and it is convenient to use the relative brightness difference $\left(\frac{B_1-B_2}{B_1}\right)$ for this purpose, so that the limits of contrast are zero and unity.

Since any brightness B is the product of the illumination and the reflection factor ρ of the illuminated surface, contrast can also be numerically expressed as $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ if the contrasting surfaces both receive the same illumination.

D.—Compensation for Difference in Contrast

If a brightness contrast is due to a difference in the reflection factors of contiguous parts of a uniformly illuminated surface, neither the ratio of the component brightnesses nor their relative brightness difference is affected if the illumination is changed. A change of illumination, however, changes the absolute brightness difference presented, and as it is known that the performance of visual tasks varies with illumination, it follows that it will also vary with brightness difference, since this is a function of illumination.

Having regard to this, Beuttell suggested, as a basis of research, that compensation for a difference in contrast, i.e., in $\left(\frac{B_1-B_2}{B_1}\right)$ or $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$, presented by otherwise similar tasks might be achieved by maintaining for each contrast a constant brightness difference. This can be done by choosing illuminations for different contrast tasks such that they are inversely proportional to the difference, of reflection factors involved.

Thus, if E were the satisfactory illumination for a task involving reflection factors ρ_1 and ρ_2, the equally satisfactory illumination E_1 for a task involving reflection factors ρ_3 and ρ_4 would, on this theory, be that which gave the same brightness difference. Since the brightness difference given by E is $E(\rho_1-\rho_2)$, and that given by E_1 is $E_1(\rho_3-\rho_4)$, the required value of E_1 would clearly be equal to $E\left(\frac{\rho_1-\rho_2}{\rho_3-\rho_4}\right)$.

The constant brightness difference obtained by this method applies only so long as a difference in the reflection factors involved is the only difference between the tasks. If the latter differ in size, the satisfactory illumination, and consequently the satisfactory brightness difference, will be different for each size, as shown in the report previously cited.

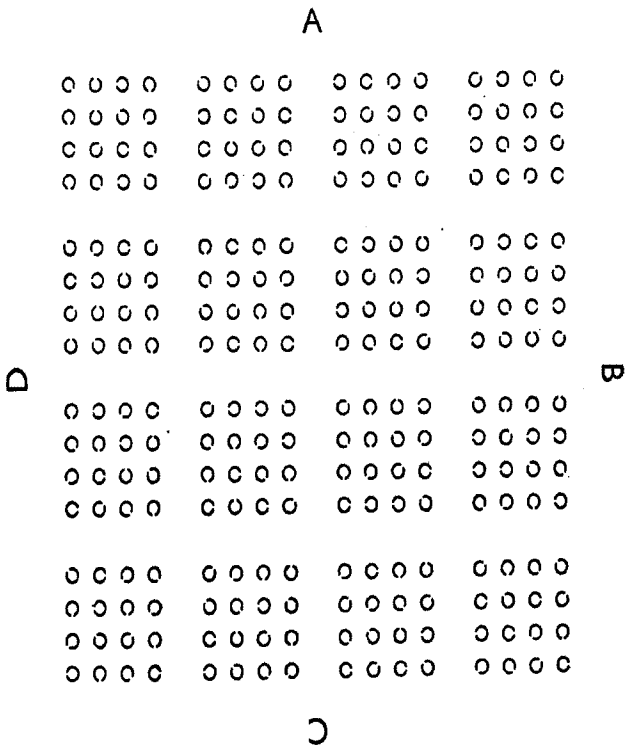
The investigations described in the present report were undertaken to determine the extent to which Beuttell's theory was borne out in practice or, in other words, to find out what degree of compensation could be obtained by changing the illumination so as to give equal brightness difference.

II. FIRST INVESTIGATION

A.—The Test Work

The investigation was carried out at the National Physical Laboratory fifteen male members of the scientific staff of the Photometry Department acting as "subjects". Fourteen of these had previous experience of the tests used. The test tasks required the discrimination and cancellation of all the

Landolt broken rings having a given gap orientation on specially prepared test sheets. The accompanying diagram illustrates the arrangement adopted. The subjects worked along each line of rings from left to right, as in reading or proof-correcting, and the given direction of gap was not the same in any two consecutive tests. Eight positions of the gap are represented in the diagram, but the given positions were always oblique.



Other conditions of the experiment are set out in the following summary and table of contrast data.

B.—Conditions of Experiments

Number of "subjects"	..	15
Number of tests	..	65 per set, comprising 3 sizes in 4 contrasts, plus 1 duplicate, at 5 illuminations.
Work spells	..	One a.m. and one p.m. session per subject
Tests worked	..	Complete set per subject per session
Duration of tests	..	Standard time 1 minute per test, or any fraction of 1 minute as determined by fastest worker per test, plus time required to change illumination, time allowed for adaptation, and mid-session rest-pause. Total time about $1\frac{3}{4}$ hours per session.
Illuminations used	..	0·8 foot-candles and equal ratio steps of x 5 to $0{\cdot}8 \times 5^4 = 500$ foot-candles.

Sizes used .. .. .. 1·0 min., 3·0 mins., 6·0 mins. apparent size of gap in Landolt ring when 13 inches distant from the eyes.

Contrasts used .. .. $\left(\frac{\rho_1-\rho_2}{\rho_1}\right) = 0{\cdot}91_6, 0{\cdot}73_1, 0{\cdot}64_8, 0{\cdot}36_5$

C.—Contrast Data

$\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$	*Reflection factor of paper* ρ_1	*Reflection factor of print* ρ_2	$\left(\frac{\rho_1}{\rho_2}\right)$	$(\rho_1-\rho_2)$	*Relative illumination for equal brightness difference.*
$0{\cdot}91_6$	0·83	0·07	11·90	0·76	1·0
$0{\cdot}73_1$	—	—	—	—	—
$0{\cdot}64_8$	—	—	—	—	—
$0{\cdot}68_2$	*$0{\cdot}46_5$**	*$0{\cdot}147_5$**	*3·15*	*$0{\cdot}317_5$*	*2·4*
$0{\cdot}36_5$	0·63	0·40	1·60	0·23	3·3

* Mean of values involved in contrasts $0{\cdot}73$ and $0{\cdot}64_8$ with which no significant difference of performance was observed.

D.—Arrangement of Tests

The order of exposure to the various illuminations was arranged to avoid extremes in successive tests. Also, the order of individual working with the respective sizes and contrasts, in the two work spells, was so arranged that the average of individual performances in each test could be regarded as being obtained at the same time, i.e., as being unaffected by temporal fluctuations of personal efficiency.

To determine whether fatigue affected the speed and accuracy of work at the end of each series of tests under a given illumination—the time occupied per series being about fifteen minutes—the last test sheet given was identical with the first. There was, however, no significant difference of performance in the first and last test of any series at any given illumination.

There was also no significant difference between the performance obtained with the two intermediate contrasts. On re-investigation of the reflection factors involved—that of the print being difficult to measure with great accuracy—it was found that the difference between these contrasts was so small as to make it unlikely that a significant difference of performance with them could be expected. The observations made with them have accordingly been averaged and regarded as the performance due to a contrast of intermediate numerical value.

E.—Assessment of Performance

The number of rings correctly cancelled was counted, together with the number of rings which should have been cancelled but were overlooked. The sum of these numbers gives the theoretically possible performance per test and subject, i.e. the number of rings of the given gap orientation contained in the test material, or in that portion of it actually examined by the subject. The observed number of correctly cancelled rings expressed as a fraction or percentage of the total number which should have been found is a measure of accuracy. The measure of accuracy should also take account of the number of rings incorrectly cancelled, i.e. having the wrong gap orientation, but it was found that this number was so small that it could be neglected.

The observed number of rings correctly cancelled per minute has been multiplied by the accuracy factor, so that the resulting number is an index of performance which takes into account both speed and accuracy. From this

the time per ring has been found, but the latter obviously includes both "discrimination time" and "action time", i.e. the time required to perform the action of cancelling the ring.

The action time was determined for each subject and each size of ring under a constant illumination (20 ft/cs.) by means of modified test sheets. In these, all the rings to be cancelled were blocked in red; this made the task of visual discrimination so easy, even with the smallest red dots, that the observed time required to cancel them was substantially only action time. The action time has been deducted from the gross cancellation time per ring, found as described above, so as to obtain the net discrimination time. The reciprocal of this represents the speed of discrimination, corrected for accuracy, and is the measure of performance used in this report. It was found that the action time was less than 30 per cent, of the gross time per ring observed in the normal tests, even in the case of the largest size under the highest illumination. With the smallest size under the lowest illumination, it was only about 6 per cent. of the gross time per ring.

F.—Discussion of Results Obtained

The results obtained have been analysed to show how the accuracy and speed of performance vary with illumination and brightness difference between paper and print.

Accuracy, for the purpose of this paper, has already been defined as the ratio of the number of rings correctly marked to the total number which could have been marked in the time available. Similarly, performance has been defined as the reciprocal of the time (in seconds) per ring correctly marked multiplied by the appropriate accuracy factor, so that it includes both accuracy and speed.

The terms relative accuracy and relative performance are also used. Relative accuracy means, for any particular size and contrast, the ratio of the actual accuracy at any illumination or brightness difference to the corresponding maximum accuracy attained with that size and contrast. Similarly, relative performance is the ratio of the actual performance at any illumination or brightness difference to the corresponding maximum performance attained with that size and contrast. Both relative accuracy and relative performance are expressed as percentages.

(*a*) *Accuracy of performance*

The variation of accuracy with illumination and contrast is shown by the figures given in Table I for tasks presenting visual sizes nominally of 1 min., 3 mins, and 6 mins. Inspection of the data relating to the 6-min. size shows that practically the same accuracy is obtained for all the contrasts, and that this is independent of illumination. Relative accuracy, therefore, is also independent of contrast and of illumination, and both accuracy and relative accuracy must thus be independent of any function of the illumination such as brightness difference.

For tasks of the 3-min. size it is also apparent that accuracy is practically independent of contrast and illumination or brightness difference, except for low illuminations or low brightness differences. It therefore appears that tasks requiring only a low degree of visual acuity* do not present sufficient difficulty for accuracy to be determined by variations of brightness contrast and illumination, or brightness difference, within the limits here considered.

* Visual acuity is expressed as the reciprocal of the angle (in minutes) visually separable. Performance of the 6-min, task requires a minimum acuity of 1/6, and of the 3-min. task a minimum acuity of 1/3.

TABLE I

Accuracy and Relative Accuracy

Foot-candles	*Nominal apparent size in minutes*	$\left(\frac{B_1-B_2}{B_1}\right)$					
		0·916	*0·683*	*0·365*	*0·916*	*0·683*	*0·365*
					per cent.	per cent.	per cent.
0·8	1	0·719	0·495	0·455	81·5	61·1	74·1
	3	0·941	0·932	0·871	99·4	86·7	90·5
	6	0·974	0·981	0·954	99·7	100·0	97·9
4·0	1	0·764	0·631	0·521	86·5	77·9	84·9
	3	0·939	0·942	0·939	94·3	97·8	97·7
	6	0·977	0·970	0·951	100·0	98·9	97·5
20·0	1	0·837	0·745	0·525	94·7	92·0	85·5
	3	0·947	0·964	0·955	100·0	100·0	99·3
	6	0·969	0·969	0·975	97·1	98·8	100·0
100·0	1	0·868	0·798	0·573	98·3	98·5	93·3
	3	0·941	0·950	0·957	99·4	98·5	99·5
	6	0·966	0·969	0·971	98·9	98·9	99·5
500·0	1	0·883	0·810	0·614	100·0	100·0	100·0
	3	0·925	0·953	0·962	97·6	98·9	100·0
	6	0·958	0·975	0·973	98·1	99·4	99·8

The difficulty of the task is much increased, however, when the size is 1 min. For this size, accuracy and relative accuracy are plotted against illumination and brightness differences in Figs. 1a, 1b, 1c and 1d. The brightness differences, in equivalent foot-candles, were obtained from the illuminations in Table I by multiplication by the difference of reflection factors of the paper and print used for each contrast. These differences are given in the table of contrast data on p. 7.

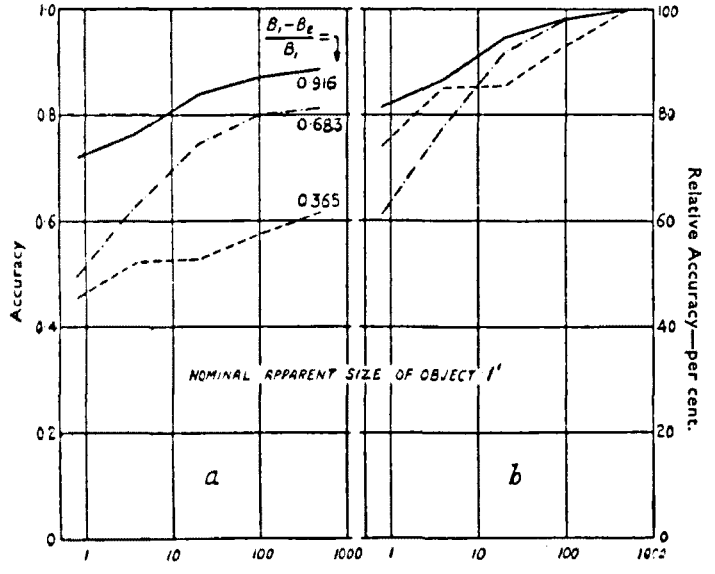


FIG. 1a and b.

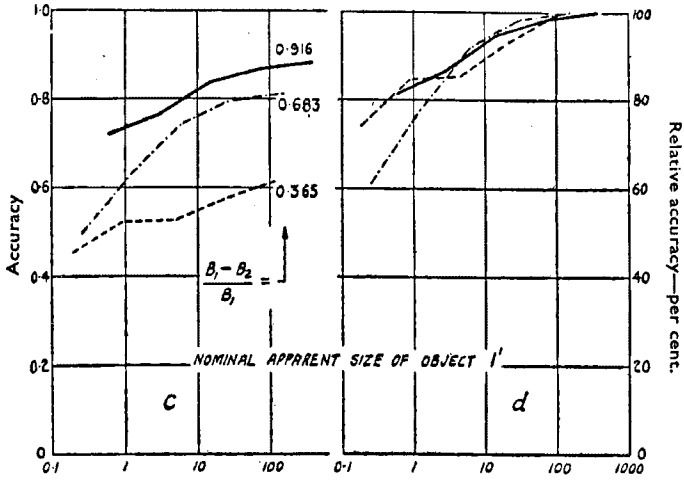


FIG. 1c and d.

The curves of Fig. 1a show that accuracy is a function both of illumination and contrast. It is also a function of brightness difference and contrast, as shown in Fig. 1c. From Fig. 1b, however, it appears that relative accuracy varies little with contrast; in fact, at low illuminations it is higher with the lowest than with the medium contrast. Finally, in Fig. 1d, it is seen that the curves for the different contrasts lie closely together, so that relative accuracy, though a function of brightness difference, is practically independent of contrast. Thus, although the *maximum* accuracy attainable with any contrast depends on that contrast, nearly the same percentage of this maximum is obtained with each contrast if the illumination is adjusted to make the brightness difference the same for all values of contrast. It should be borne in mind, however, that very poor contrasts, such as are sometimes met with in practice, have not been considered.

(*b*) *Overall performance* (*speed and accuracy*)

The variation of performance with illumination and contrast is shown by the data in Table II, from which the curves in Figs. 2, 3 and 4 (a to d) have been drawn. For the 6-min. size it can be seen from the Table, and from Fig. 2a, that over a very wide range of illumination values the performance varies little, and is the same for the highest and the intermediate contrasts. Over nearly as wide a range of illumination, performance with the 3-min. size (Fig. 3a) is also practically constant, and does not differ much for the same two contrasts. But, for the range of illumination over which performance varies appreciably, the relation between both performance and relative performance (Figs. 2a, 2b and 3a, 3b) and illumination depends on the contrast, except in the case of the 6-min. size for values of contrast greater than 0·683. Similarly, for the range of brightness difference over which performance varies appreciably, the relation between both performance and relative performance and brightness difference (Figs. 2c, 2d, and 3c, 3d) depends on the brightness contrast, with the exception made above, which, in this case appears to apply also to the 3-min. size.

For the 1-min. size, Fig. 4a shows that performance is very considerably affected by illumination and contrast. Thus the difficulty of this task is significantly affected by variation of one or both of these factors. Fig. 4a

TABLE II

Performance (speed and accuracy) and Relative Performance

Foot-candles	*Nominal apparent size in minutes*	$\left(\frac{B_1-B_2}{B_1}\right)$					
		0·916	*0·653*	*0·365*	*0·916*	*0·653*	*0·365*
					per cent.	per cent.	per cent.
0·8	1	0·21	0·06	0·035	42·0	19·75	20·6
	3	0·775	0·66	0·40	89·0	76·3	47·3
	6	1·01	1·01	0·745	91·8	91·8	71·6
4·0	1	0·31	0·135	0·07	62·0	44·3	41·2
	3	0·825	0·78	0·65	94·9	90·2	77·0
	6	1·06	1·06	0·88	96·4	96·4	84·6
20·0	1	0·39	0·205	0·105	78·0	67·3	61·8
	3	0·855	0·84	0·77	98·3	97·1	91·2
	6	1·085	1·085	0·975	98·7	98·7	93·75
100·0	1	0·44	0·26	0·133	88·0	85·3	78·25
	3	0·865	0·855	0·83	99·4	98·8	98·25
	6	1·10	1·10	1·02	100·0	100·0	98·15
500·0	1	0·475	0·29	0·156	95·0	95·0	91·75
	3	0·87	0·865	0·845	100·0	100·0	100·0
	6	1·10	1·10	1·04	100·0	100·0	100·0

The above are " smoothed " values.

shows that performance with a poor contrast can never equal the maximum performance with a good one, however high the illumination. Further, from Fig. 4b, it is apparent that relative performance is not determined solely by illumination, though for the two lower contrasts it appears that at the same illumination the relative performances are practically the same and independent of contrast. Fig. 4c shows that performance varies considerably with brightness difference and contrast. Relative performance, however, is seen from Fig. 4d to be independent of contrast, and dependent only on brightness difference.

Thus, for all the contrasts used, approximately the same percentage of the maximum performance with any such contrast is obtained for the same brightness difference, and the brightness difference determines what this percentage is. In other words, equal relative performance will be possible with similar tasks, varying only in contrast, if the illumination provided is such as to give the same brightness difference for each contrast.

The foregoing conclusion has been arrived at from a consideration of the most difficult task investigated, i.e., that involving a size of 1 min., but it does not seem possible to draw this conclusion from the less difficult tasks.

In any investigation of the kind described, uncontrollable variables are always present, chiefly, perhaps, of a psychological nature. It is probable that these variables play a larger part in determining variations of performance when the task " looks easy " than when it is obviously difficult. Evidence of this was not lacking in the present investigation, and it was more difficult to draw " smooth " curves to fit the observations for the larger sizes than for the smallest size used. In fact, all the observations for the 1-min. size lie on or very close to the curves shown.

Thus, though the conclusion drawn from the results for the 1-min. size seems valid for the range of contrasts considered, it cannot from this investigation be extended to the larger sizes, nor is it possible to say whether it will be valid for a wider range of contrasts.

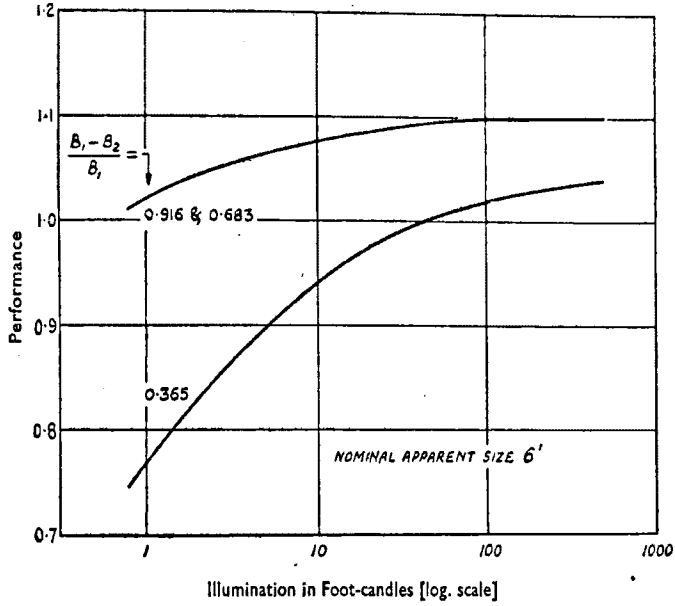

1·2
1·1
1·0
0·9
0·8
0·7
Performance
$\frac{B_1 - B_2}{B_1}$ =
0·916 & 0·683
0·365
NOMINAL APPARENT SIZE 6'
1
10
100
1000
Illumination in Foot-candles [log. scale]

FIG. 2a.

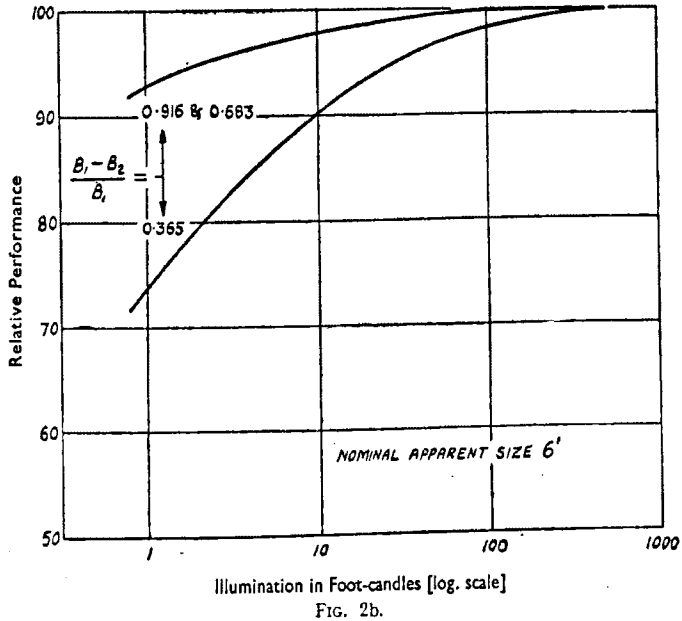
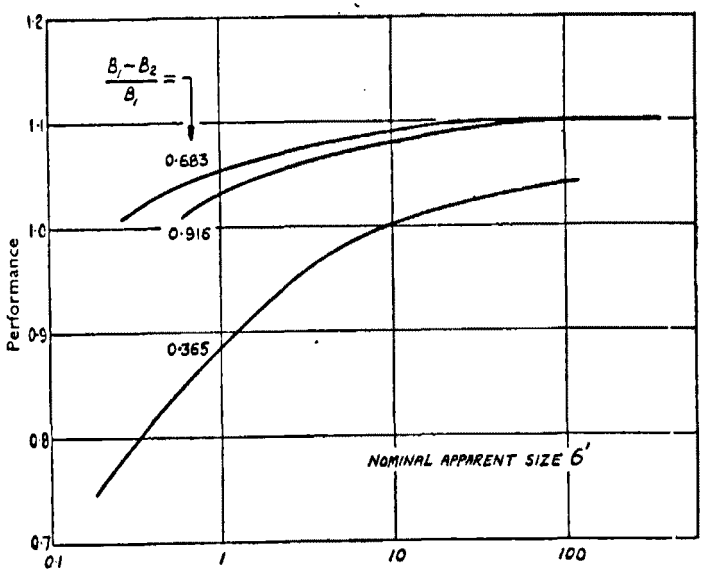
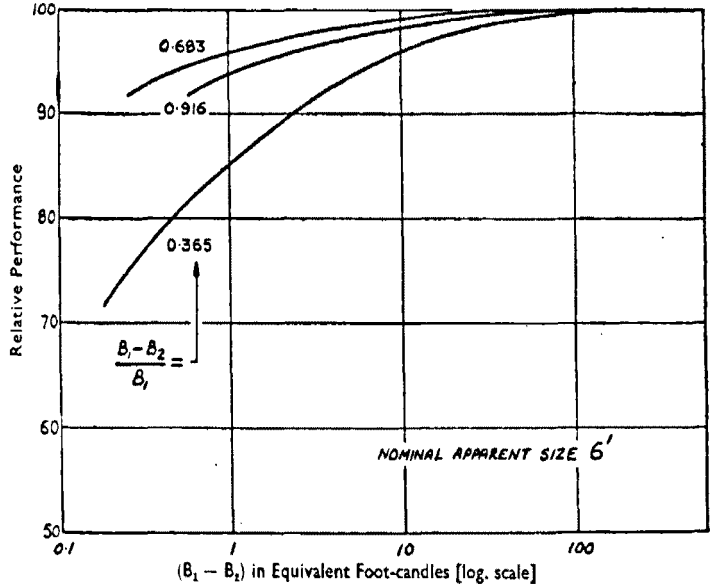

100
90
80
70
60
50
Relative Performance
0·916 & 0·683
$\frac{B_1 - B_2}{B_1}$ =
0·365
NOMINAL APPARENT SIZE 6'
1
10
100
1000
Illumination in Foot-candles [log. scale]

FIG. 2b.



$(B_1 - B_2)$ in Equivalent Foot-candles [log. scale]

FIG. 2c.



$(B_1 - B_2)$ in Equivalent Foot-candles [log. scale]

FIG. 2d.

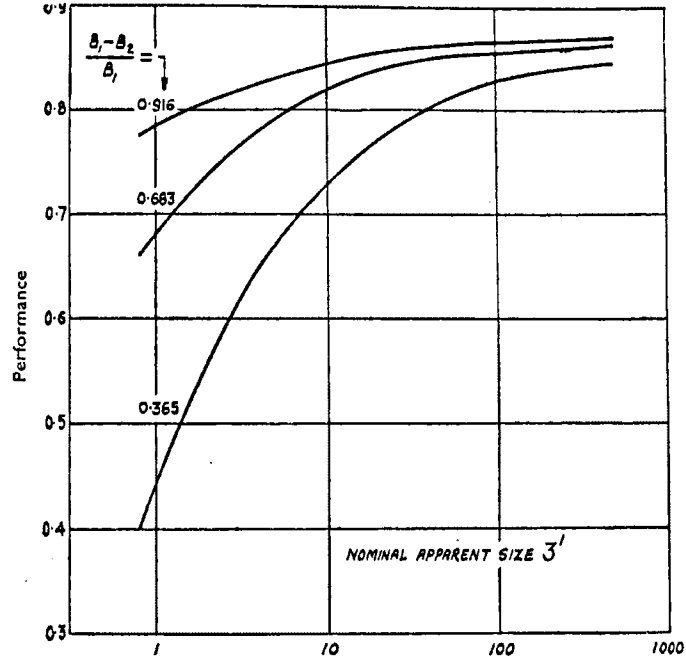

$\frac{B_1 - B_2}{B_1}$ =
0·916
0·683
0·365
Performance
0·8
0·7
0·6
0·5
0·4
0·3
NOMINAL APPARENT SIZE 3'
1
10
100
1000
Illumination in Foot-candles [log. scale]

FIG. 3a.

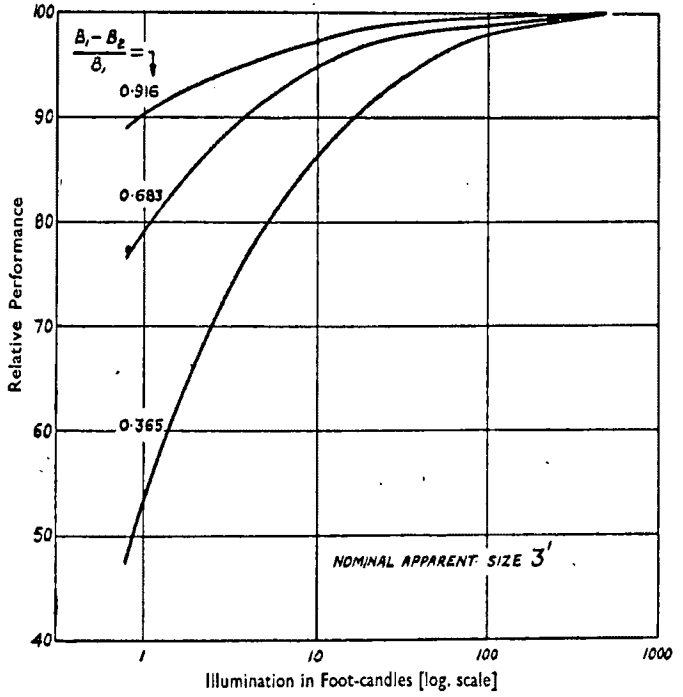

$\frac{B_1 - B_2}{B_1}$ =
0·916
0·683
0·365
Relative Performance
100
90
80
70
60
50
40
NOMINAL APPARENT SIZE 3'
1
10
100
1000
Illumination in Foot-candles [log. scale]

FIG. 3b.

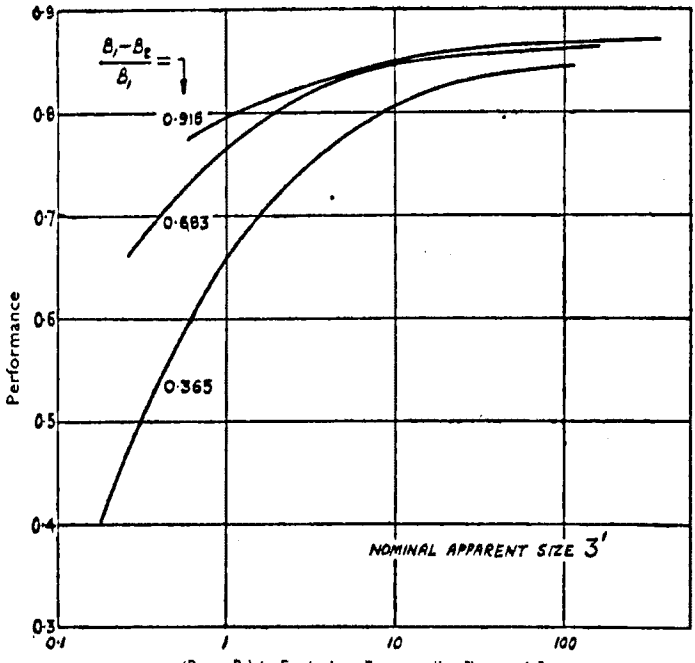

$\frac{B_1-B_2}{B_1}$ =
0·916
0·683
0·365
Performance
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·1
1
10
100
NOMINAL APPARENT SIZE 3'
(B₁ − B₂) in Equivalent Foot-candles [log. scale]

FIG. 3c.

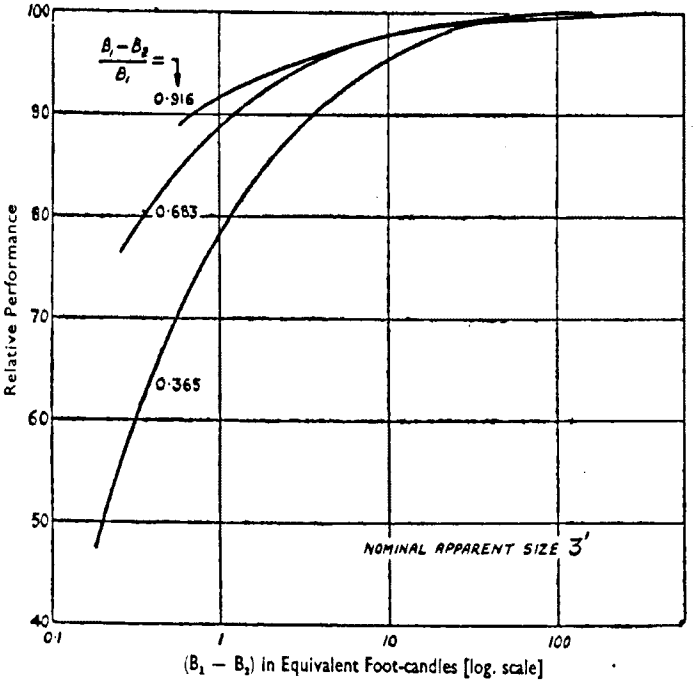

$\frac{B_1-B_2}{B_1}$ =
0·916
0·683
0·365
Relative Performance
100
90
80
70
60
50
40
0·1
1
10
100
NOMINAL APPARENT SIZE 3'
(B₁ − B₂) in Equivalent Foot-candles [log. scale]

FIG. 3d.

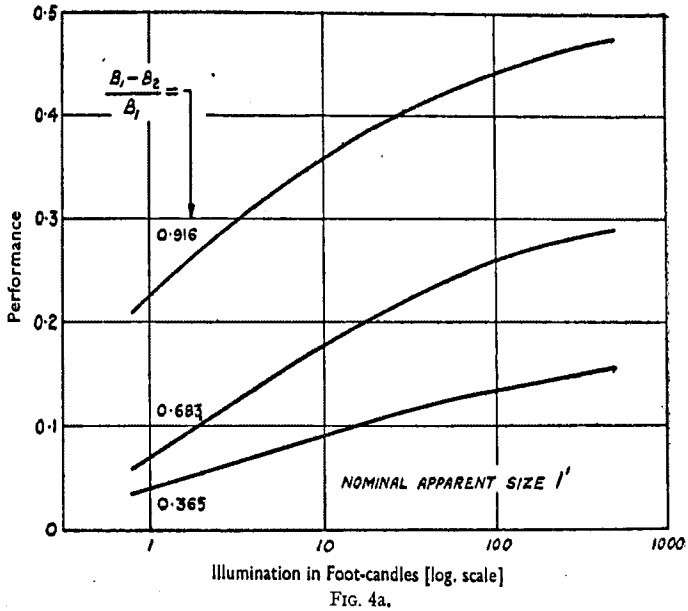

0·5
0·4
0·3
0·2
0·1
0
Performance
$\frac{B_1-B_2}{B_1}$ =
0·916
0·683
0·365
NOMINAL APPARENT SIZE 1'
1
10
100
1000
Illumination in Foot-candles [log. scale]

FIG. 4a.

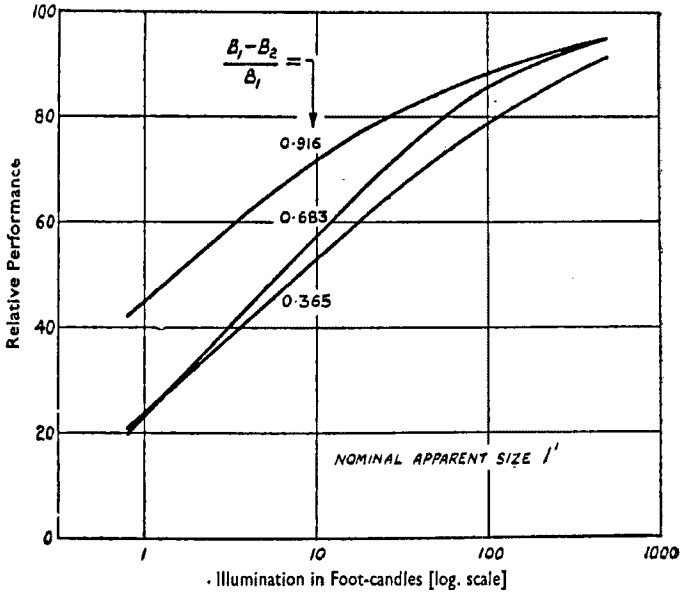
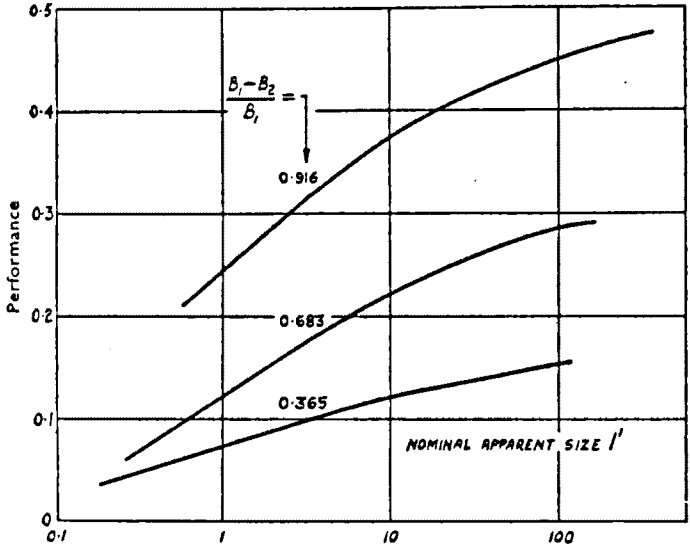
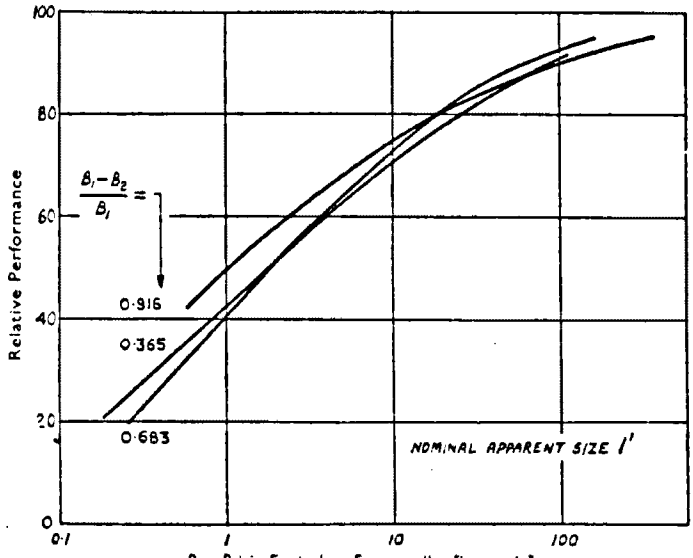

100
80
60
40
20
0
Relative Performance
$\frac{B_1-B_2}{B_1}$ =
0·916
0·683
0·365
NOMINAL APPARENT SIZE 1'
1
10
100
1000
Illumination in Foot-candles [log. scale]

FIG. 4b.



$(B_1 - B_2)$ in Equivalent Foot-candles [log. scale]

FIG. 4c.



$(B_1 - B_2)$ in Equivalent Foot-candles [log. scale]

FIG. 4d.

III. SECOND INVESTIGATION

A.—The Test Work

In this investigation, the range of contrasts used was extended to include a lower value. Tests were also made with a "reverse" contrast, i.e. one in which the Landolt rings were made brighter than their background, by printing them in pale grey on a darker grey paper. All the "normal" contrasts used were obtained by printing the rings in black or different shades of grey on white paper. The size range was narrowed, the largest size used being 4·5 minutes and the smallest 1·5 minutes.

B.—Procedure and Assessment of Performance

The experiments were carried out at the National Physical Laboratory, the general procedure followed being similar to that described for the first investigation.

The conditions of the experiments are given in detail below, together with a table of contrast data.

The "action time" was determined in the manner previously described, but the determination was made at each illumination used, instead of at only one illumination. It was found that the action time of the average subject varied with illumination and size. Smoothed values for the 3-min, size are as follows:—

Illumination, foot-candles

0·5	2·0	8·0	32	128	512
"Action time", seconds per ring					
0·7	0·685	0·67	0·655	0·64	0·625

These times are increased by 4 per cent. for the 4·5-min. and the 1·5-min. sizes. The appropriate average action time has been deducted from the average gross time per ring found for each test, in order to obtain the net discrimination time and speed.

C.—Conditions of Experiments

Number of "subjects" ..	12
Number of tests	78 per set, comprising 3 sizes, in 4 contrasts, plus 1 "reverse" contrast in 1 size, at 6 illuminations.
Work spells	One a.m. and one p.m. session per subject.
Tests worked	Complete set per subject per session
Duration of tests	Standard time 1 minute per test, or any fraction of 1 minute as determined by fastest worker per test, plus time required to change illumination, time allowed for adaptation, and mid-session rest-pause. Total time approximately 2 hours per session.
Illuminations used	0·5 foot-candles and equal ratio steps of $\times 4$ to $0{\cdot}5 \times 4^5 = 512$ foot-candles.
Sizes used	1·5 mins., 3·0 mins., 4·5 mins. apparent size of gap in Landolt ring when 10 inches distant from the eyes.
Contrasts used	$\left(\frac{\rho_1-\rho_2}{\rho_1}\right) = 0{\cdot}97,\ 0{\cdot}56,\ 0{\cdot}39,\ 0{\cdot}28,$ and with size 3 min. only, $\left(\frac{\rho_2-\rho_1}{\rho_2}\right) = 0{\cdot}25.$

D.—Contrast Data

$\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$	*Reflection factor of paper* ρ_1	*Reflection factor of print* ρ_2	$\left(\frac{\rho_1}{\rho_2}\right)$	$(\rho_1-\rho_2)$	*Relative illumination for equal brightness difference*
0·97	0·9	0·03	30·0	0·87	1·00
0·56	0·9	0·40	2·25	0·50	1·74
0·39	0·9	0·55	1·64	0·35	2·49
0·28	0·9	0·65	1·385	0·25	3·48
$\left(\frac{\rho_2-\rho_1}{\rho_2}\right)$			$\left(\frac{\rho_2}{\rho_1}\right)$	$(\rho_2-\rho_1)$	
0·25	0·385	0·515	1·34	0·13	6·69

E.—Discussion of Results Obtained

The variation of performance with illumination and contrast is shown by the data in Table III, from which the curves in Figs. 5a, 5b and 5c have been drawn. The performances given are "smoothed" values which do not, in any case, differ from the observed average values by an amount greater than the probable error of the latter.

Table III

Variation of Performance with Illumination and Contrast

Foot-candles	*Nominal apparent size in minutes*	$\left(\frac{B_1-B_2}{B_1}\right)$				$\left(\frac{B_2-B_1}{B_2}\right)$
		0·97	*0·56*	*0·39*	*0·28*	*0·25*
0·5	1·5	0·18	0·05	0·03	0·005	
	3·0	0·45	0·30	0·16	0·08	0·11
	4·5	0·50	0·36	0·28	0·21	
2·0	1·5	0·24	0·105	0·06	0·023	
	3·0	0·48	0·36	0·26	0·16	0·20
	4·5	0·54	0·45	0·36	0·275	
8·0	1·5	0·29	0·16	0·11	0·05	
	3·0	0·505	0·425	0·345	0·23	0·27
	4·5	0·56	0·51	0·43	0·335	
32·0	1·5	0·33	0·21	0·165	0·07	
	3·0	0·525	0·47	0·39	0·28	0·32
	4·5	0·57	0·545	0·48	0·38	
128·0	1·5	0·345	0·26	0·215	0·09	
	3·0	0·53	0·485	0·415	0·32	0·335
	4·5	0·575	0·555	0·495	0·40	
512·0	1·5	0·35	0·28	0·245	0·11	
	3·0	0·53	0·49	0·43	0·34	0·34
	4·5	0·575	0·56	0·50	0·41	

For the 4·5-min. size, it can be seen that the range of illumination over which performance varies appreciably is different for each contrast, and becomes wider as the contrast becomes poorer. This is true also for the two smaller sizes, the effect of reduction of size being also to widen the range of illumination

over which performance varies considerably. For each size it is apparent that the relation between performance and illumination depends on the contrast, though, for the largest size, it appears that the maximum performance attainable is only slightly reduced by lowering the value of $\left(\frac{B_1-B_2}{B_1}\right)$ from 0·97 to 0·56. It is evident from all the curves that, however high the illumination is made, performance with a poor contrast can never equal the maximum performance with a good one. Further, from Fig. 5b, it will be seen that performance with the "reverse" contrast is appreciably better than with its "normal" counterpart at any illumination up to about 100 foot-candles, although with equal illumination the "reverse" contrast involves lower brightnesses.

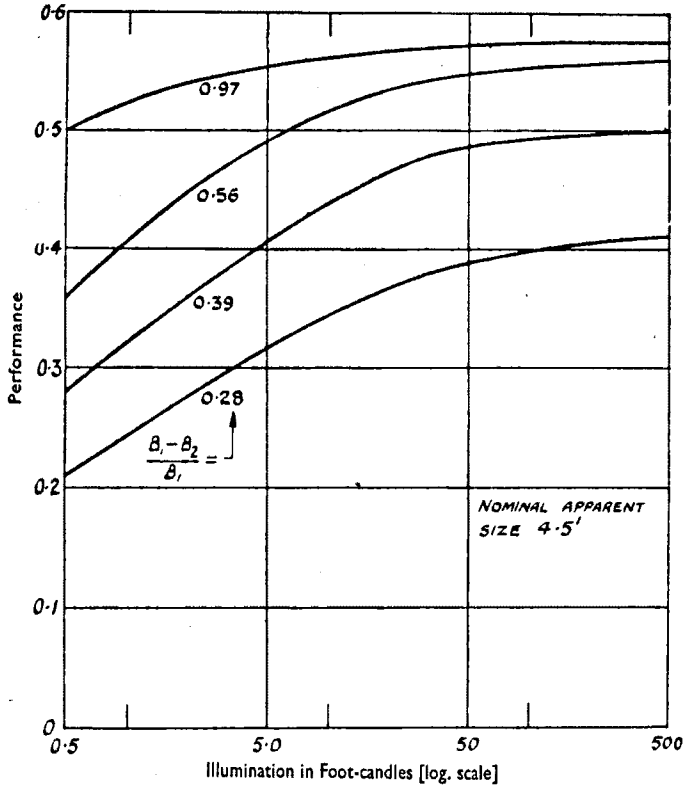


FIG. 5a.

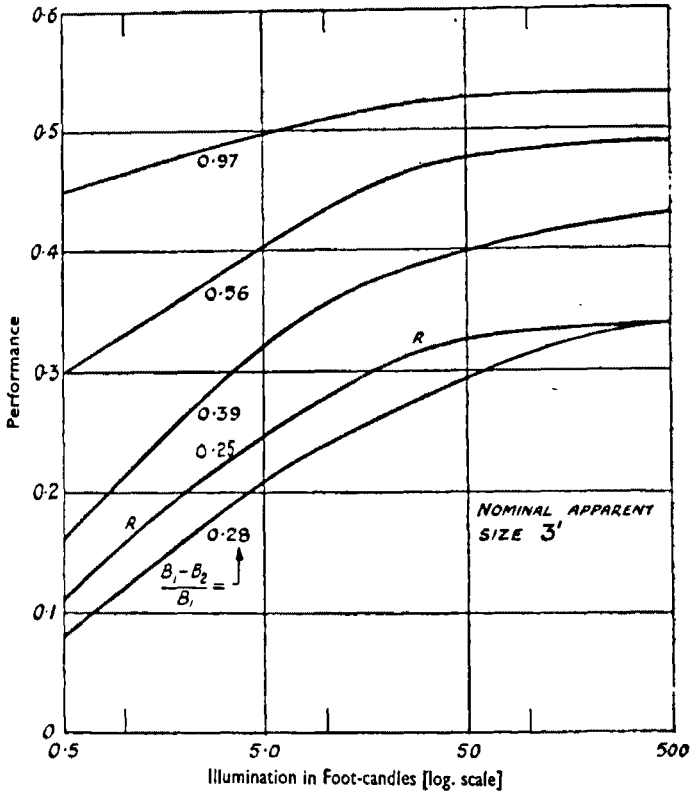

0·6
0·5
0·4
0·3
0·2
0·1
0
Performance
0·97
0·56
0·39
0·25
0·28
R
R
$\frac{B_1-B_2}{B_1}$ =
NOMINAL APPARENT SIZE 3'
0·5
5·0
50
500
Illumination in Foot-candles [log. scale]

FIG. 5b.

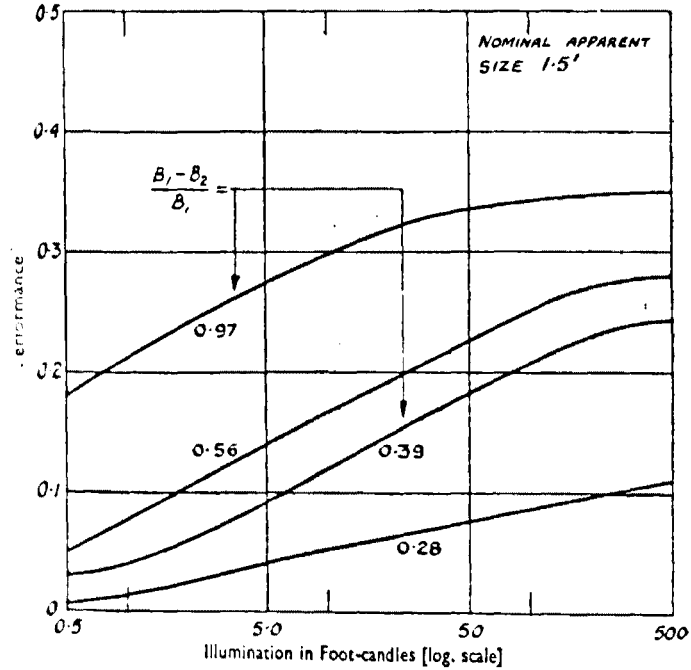

0·5
0·4
0·3
0·2
0·1
0
erformance
NOMINAL APPARENT SIZE 1·5'
$\frac{B_1-B_2}{B_1}$ =
0·97
0·56
0·39
0·28
0·5
5·0
50
500
Illumination in Foot-candles [log. scale]

FIG. 5c.

The data in Table IV show the variation of relative performance with illumination and contrast. From them the curves in Figs. 6a, 6b and 6c have been drawn. It is apparent that, for each size, the relation between relative performance and illumination depends on the contrast, except where relative performance is given a constant value at the highest illumination. In the case of the 3-min. size, relative performance is only slightly different with the task for which the $\left(\frac{B_1-B_2}{B_1}\right)$ value is 0·39 and that in which the brightnesses are reversed and for which the value of $\left(\frac{B_2-B_1}{B_2}\right)$ is 0·25, although, for any given illumination, the former contrast presents nearly three times the brightness difference presented by the latter.

With the 1·5-min. size, over a wide range of illuminations, relative performance is not appreciably different with the two poorest contrasts. It differs widely as between the two better contrasts, whose $\left(\frac{B_1-B_2}{B_1}\right)$ values are respectively 0·97 and 0·56.

TABLE IV

Variation of Relative Performance with Illumination and Contrast

Foot-candles.	*Nominal apparent size in minutes.*	$\left(\frac{B_1-B_2}{B_1}\right)$				$\left(\frac{B_2-B_1}{B_2}\right)$
		0·97	*0·56*	*0·39*	*0·28*	*0·25*
0·5	1·5	51·5	17·9	12·25	4·54	32·4
	3·0	85·0	61·2	37·2	23·5	
	4·5	87·0	64·3	56·0	51·2	
2·0	1·5	68·6	37·5	24·5	20·9	58·8
	3·0	90·5	73·5	60·5	47·0	
	4·5	95·0	80·4	72·0	67·0	
8·0	1·5	82·8	57·2	44·8	45·4	79·4
	3·0	95·3	86·8	80·3	67·6	
	4·5	97·3	91·1	86·0	81·7	
32·0	1·5	94·3	75·0	67·4	63·6	94·1
	3·0	99·0	96·0	90·7	82·4	
	4·5	99·1	97·4	96·0	92·7	
128·0	1·5	98·6	93·0	87·8	85·7	98·5
	3·0	100·0	99·0	96·5	94·1	
	4·5	100·0	99·0	99·0	97·5	
512·0	1·5	100·0	100·0	100·0	100·0	100·0
	3·0	100·0	100·0	100·0	100·0	
	4·5	100·0	100·0	100·0	100·0	

In general, it appears that, for a wide range of illuminations, the effect of change of contrast on performance is proportionately greater the smaller the size involved, except in the case of the change of contrast from 0·39 to 0·28 with the smallest size.

Figs. 7a, 7b and 7c show the relation between performance and brightness difference. The curves are, of course, those of Figs, 5a, 5b and 5c, but are displaced laterally so as to correspond with values of brightness difference obtained from the illuminations in Table III by multiplication by the difference of reflection factors of paper and print used for each contrast.

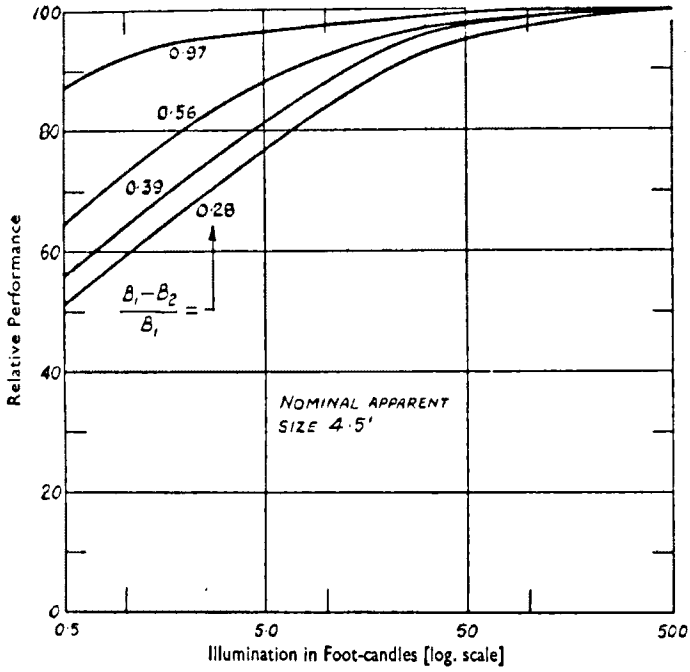

100
80
60
40
20
0
0·97
0·56
0·39
0·28
$\frac{B_1-B_2}{B_1}$ =
NOMINAL APPARENT SIZE 4·5'
Relative Performance
0·5
5·0
50
500
Illumination in Foot-candles [log. scale]

FIG. 6a.

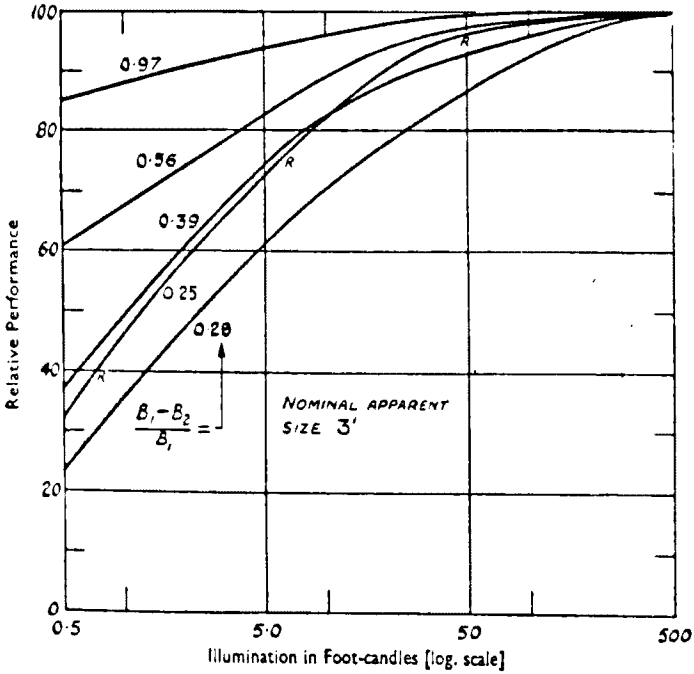

100
80
60
40
20
0
0·97
0·56
0·39
0·25
0·28
R
R
R
$\frac{B_1-B_2}{B_1}$ =
NOMINAL APPARENT SIZE 3'
Relative Performance
0·5
5·0
50
500
Illumination in Foot-candles [log. scale]

FIG. 6b.

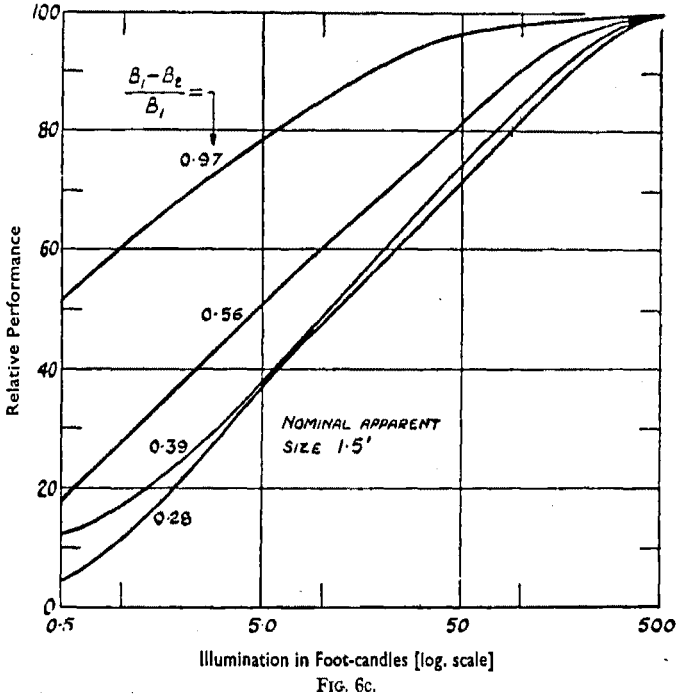


FIG. 6c.

For all sizes, performance varies considerably with brightness difference and also with contrast. It has already been noted that an increase of illumination, however great, does not enable performance of a task presenting a low relative brightness difference to reach the maximum possible when the relative brightness difference or contrast is high. Hence it follows, and is also apparent from Figs. 7a, 7b, and 7c, that with the illuminations necessary to give different contrasts the same absolute brightness difference, performance does not become independent of contrast, however high the brightness difference is made. Performance does, however, vary less when the brightness difference is constant than when the same illumination is used for each contrast, and Beuttell's theory is borne out to this extent. But, it must be noted that different contrasts may present the same brightness difference with the same illumination, since the brightness difference depends on $(\rho_1-\rho_2)$ and not on $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$. For example, the poor contrast between $\rho_1 = 0{\cdot}9$ and $\rho_2 = 0{\cdot}65$, and the good contrast between $\rho_1 = 0{\cdot}3$ and $\rho_2 = 0{\cdot}05$, both present the same brightness difference at the same illumination. In such cases, the relations between performance and illumination or brightness difference are obviously similar.

Fig. 7b shows that the superiority of the "reverse" contrast over its "normal" counterpart is greater as regards the relation between performance and brightness difference than the relation between performance and illumination which is shown in Fig. 5b. With the same brightness difference, the brightness of the paper used for the "reverse" contrast is 82 per cent. of that used for the "normal" counterpart, while the brightness of the "reverse" print is 52 per cent. higher than the "normal" print.

Figs. 8a, 8b and 8c show the relation between relative performance and brightness difference for each size and contrast. For the 4·5-min. size, it appears

that for values of contrast below 0·39 relative performance depends only on brightness difference. Further, above a brightness difference of 5 equivalent foot-candles relative performance is practically independent of contrast when this has values between 0·28 and 0·56, and above a brightness difference of 20 e.f.c. it does not vary appreciably either with contrast or with brightness difference. With the 3-min. size relative performance varies considerably

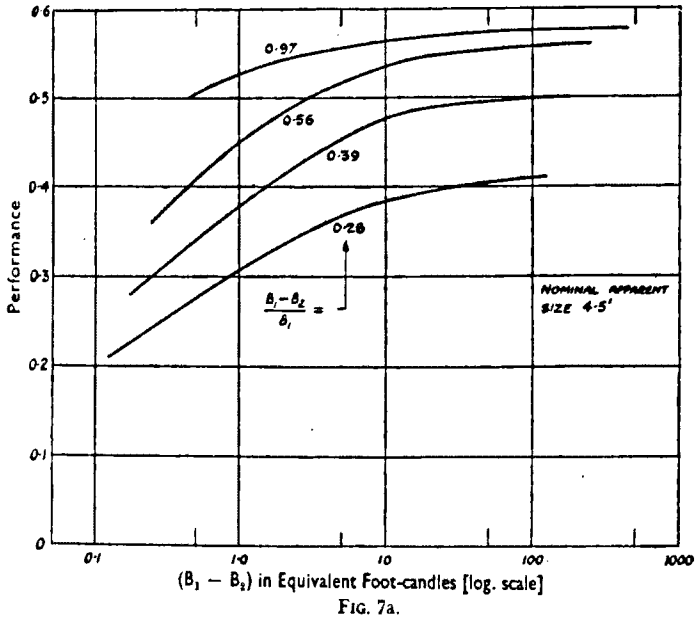


FIG. 7a.

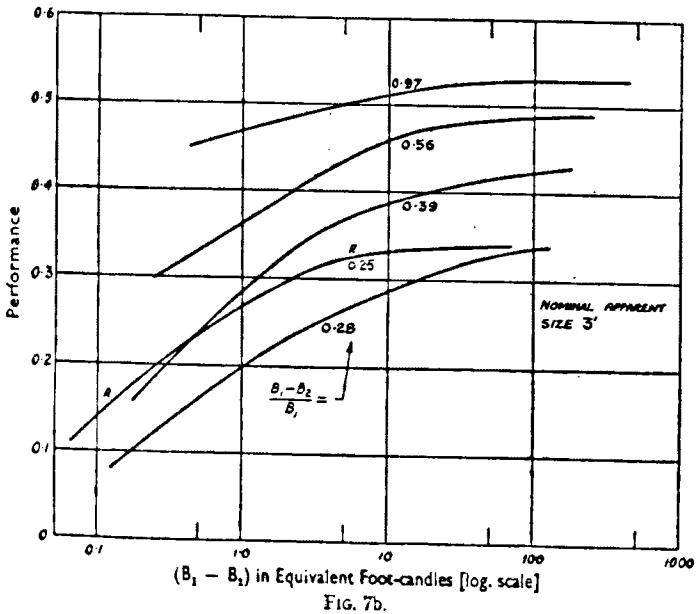


FIG. 7b.

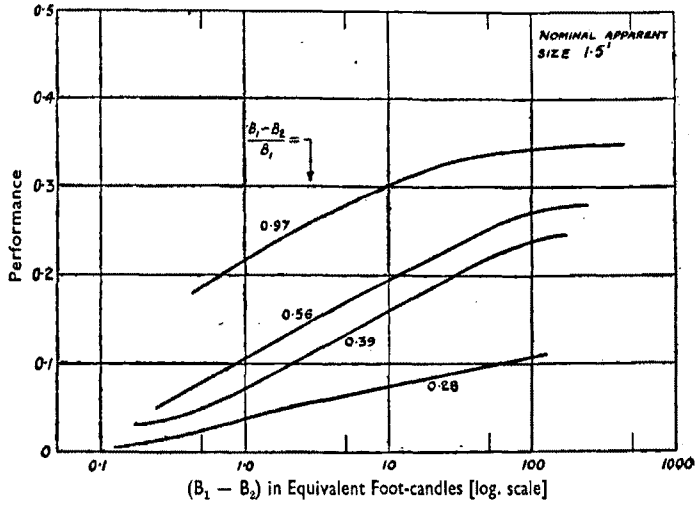


FIG. 7c.

with both contrast and brightness difference, except that, above a brightness difference of 3 e.f.c. it is nearly the same for the best and the "reverse" contrasts. In the case of the 1·5-min. size it appears that, as with the 4·5-min. size, relative performance depends only on brightness difference above 5 e.f.c., except when $\left(\frac{B_1-B_2}{B_1}\right)$ exceeds 0·56.

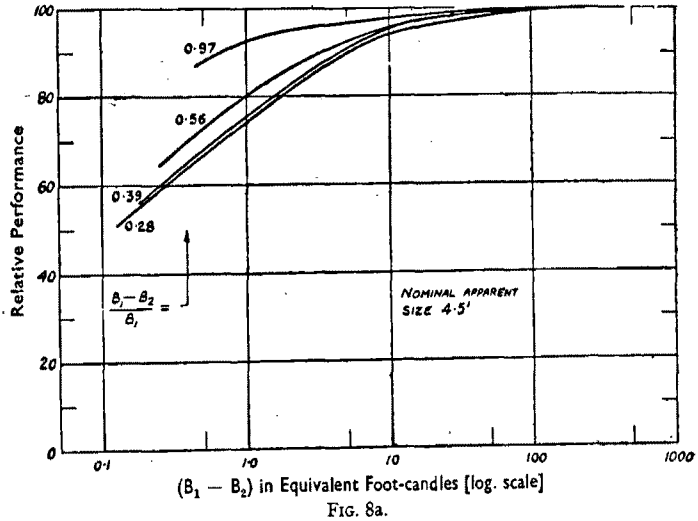


FIG. 8a.

Thus, for the limiting sizes used, and for contrasts having values between 0·28 and 0·56, approximately the same percentage of the maximum performance with any of these contrasts is obtained when their brightness difference is the same (and not less than 5 e.f.c.), and the brightness difference determines this percentage. Otherwise expressed, and subject to the foregoing qualifications, equal relative (but not absolute) performance will be possible

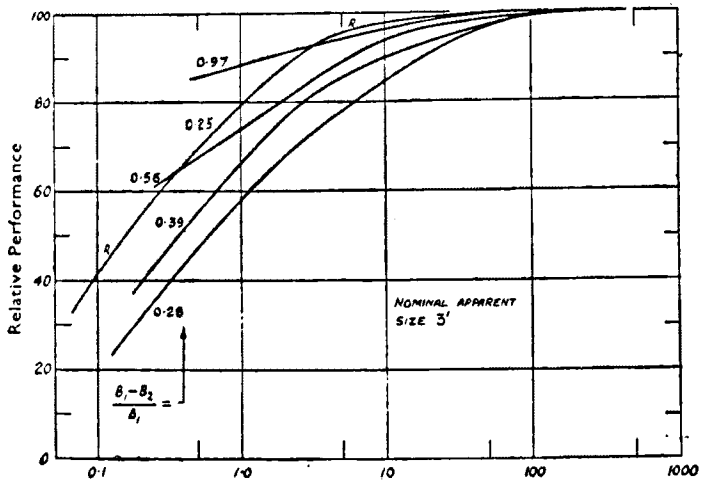


FIG. 8b.

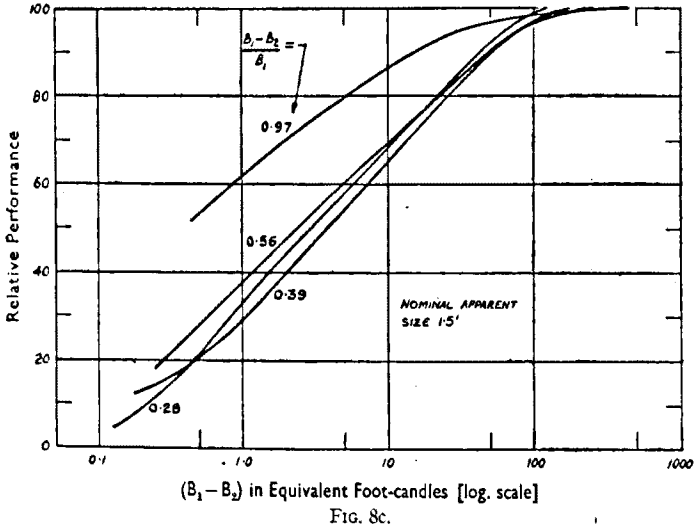


FIG. 8c.

with similar tasks, differing only in contrast, if the illumination provided is such as to give each contrast the same brightness difference. A similar conclusion cannot be drawn for the 3-min. size which, in this respect, is typical of many practical tasks. Moreover, the results of the experiment in which the poorest contrast was reversed, show that neither the same absolute nor the same relative performance was obtained when each contrast presented the same brightness difference. These results suggest that the conclusion reached above for the 4·5-min. and 1·5-min. sizes may be valid only as a conclusion from the limited data obtained, and may not be confirmed by further experiment. However, the experiments of the first investigation did, in fact, lead to a similar conclusion for the smallest size.

F.—Results with "Reverse" Contrast

Further analysis of the results obtained with the "reverse" contrast reveal the complexity of the problem of contrast appreciation (even in the absence of colour difference), and the difficulty of relating the response aroused to mathematical functions of the physical brightnesses involved.

The curves relating performance and relative performance with illumination for the "reverse" contrast $\left(\frac{B_2-B_1}{B_2}\right) = 0{\cdot}25$ and the "normal" contrast $\left(\frac{B_1-B_2}{B_1}\right) = 0{\cdot}28$ are reproduced in Fig. 9 from Figs. 5b and 6b. It will

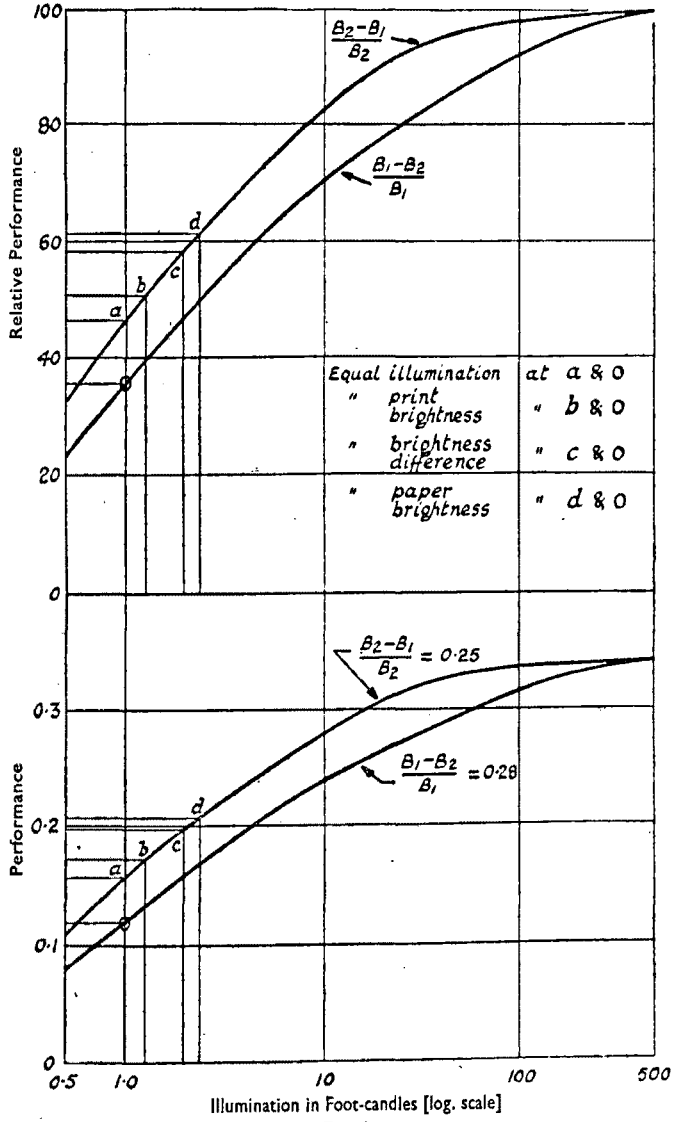


Fig. 9.

be seen that the curves are nearly parallel over the illumination range 0·5 to 50 ft/cs. and thereafter converge to the same maximum. At all values of illumination, except the maximum, performance is consistently better with the "reverse" contrast. Over the range for which the curves are parallel this superiority is about 11 per cent. A difference of this magnitude is very unlikely to be observed in successive trials if no real difference exists between the "visibilities" of these two numerically similar contrasts. The superiority of the "reverse" contrast is increased if performance is compared at illuminations b and o, giving the same print brightness. It is further increased at illuminations c and o, giving the same brightness difference, and is still further increased at illuminations d and o, giving the same paper brightness. This, of course, necessarily follows, within the illumination range considered, from the fact that these several conditions of equality of brightness involve successively higher illuminations for the "reverse" contrast.

If the "reverse" and "normal" contrasts involved the same reflection factors, these being merely interchanged between object and ground, obviously the physical brightness contrasts would be numerically identical, both relatively and absolutely, with the same illumination. But the reversal of object and ground reflection factors involves a change in the average brightness of the contrast field as a whole, except when its area is equally apportioned between object and ground. In the case under consideration, the reversal did involve such a change in average field brightness, but it is not likely that this accounts for the results observed. It might, in fact, be expected to have the opposite effect and to depress the performance with the "reverse" contrast.

At the same illumination, the "reverse" contrast presented lower brightnesses and a lower brightness difference than its "normal" counterpart, yet yielded a better performance. The explanation of its superiority seems to lie in its appearance, or in the physiological effect of the *arrangement* of its two brightnesses. The former is merely the psychological aspect of the latter.

The "reverse" contrast consisted of a very pale grey, or grey-white, broken ring on a darker grey background, and the "normal" contrast of a very pale grey broken ring on a white background. In the former case, a sensation of uniform brightness is prevented by the greater stimulation of a few retinal elements and, in the latter, by their relatively weak stimulation. Suppose the illumination of the two pairs of reflecting surfaces described to be reduced until the lower of their brightness components is just below the absolute brightness threshold: the "reverse" contrast will then result in the stimulation of a few cones only among the large majority from which no sensation of brightness will arise. Accordingly, attention can only be focused on the stimulus source, or object, which alone is visible. On the other hand, the "normal" contrast will then result in the stimulation of a large majority of receptors and the non-stimulation of very few. It seems plausible to suggest that the absence of sensation from a small number of unstimulated receptors, while all the others are stimulated, may be perceived less readily than the presence of sensation derived solely from a few stimulated receptors. In the one case, the object to be seen is negative—a non-sensation in a field of sensation—while in the other, it is the *only* sensation.

If this argument has any validity, it may be applicable when both brightnesses in the contrasts have supra-threshold values, i.e. when both contrasting components are positive, since one may still be regarded as negative relative to the other, and the object will be the positive element in the "reverse" contrast and the negative element in the "normal" contrast. In this connection, it is well known that "reverse" contrasts are frequently used

when it is particularly desired to attract attention and ensure rapid perception.*

It is possible, however, that closer attention was given to the reverse contrast merely on account of its novelty, and that for this reason better results were obtained with it. But the persistent occurrence of better results at every trial, except at the highest illumination, is against this explanation. In the reverse contrast the object is made the brightest thing in the field and tends to "stand out". This, rather than any novelty in the arrangement, seems most likely to be significant.

The phenomenon of irradiation is often considered to have an adverse effect on the visibility of "reverse" brightness contrasts. In the case under consideration, it might be expected to produce an apparent thickening of the ring and narrowing of the gap, i.e. to blur the image of the gap. And, since irradiation increases with brightness, its effect should be more marked as illumination is increased. With a "normal" brightness contrast, irradiation must also occur, but from the background instead of from the ring. It should, therefore, tend to reduce the apparent thickness of the ring and, possibly, to increase the apparent width of the gap.

While irradiation varies with brightness, it depends also on brightness contrast. Thus, with the same illumination, irradiation has a greater effect on the apparent size of a white object on a black ground than of a similar object on a grey ground. Hence, when the difference of brightness between object and background is small, irradiation may be unnoticeable. In the particular case under discussion, it appears to have had no adverse effect whatever on the performance obtained with the "reverse" contrast.

Subjectively, the "reverse" contrast was judged better than its counterpart. For both contrasts, the paper and print used were to some extent specular. While this factor introduces a degree of uncertainty into the evaluation of the contrasts in terms of ρ_1 and ρ_2, there is no reason to believe that its effect was not similar in both cases.

The maximum performance obtained with the "reverse" and equivalent "normal" contrasts is the same. But, for the same high relative performance (97 per cent.), the "reverse" contrast requires only one fourth of the illumination required for the "normal" contrast, and little more than one eighth of the brightness difference. The present data, therefore, suggest the conclusion that when the contrast is poor, better results are obtained if the object, rather than the background, is the brighter component. This, however, is a question of considerable practical interest, which should be the subject of further investigation.

G.—Conclusions

When visual tasks differing only in the contrast $\left(\frac{B_1-B_2}{B_1}\right)$ they present are illuminated so as to present a constant brightness difference (of any magnitude within the limits considered), performance is not made independent of the contrast. This conclusion applies to contrasts whose values range from 0·25 to 0·97, and is true for each size of object studied.

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* Luminous advertising signs and signals may be cited, while there is a growing tendency in certain popular magazines to use white print on a darker or black background for picture captions and other matter intended to be outstanding. This practice is not new, however. More than 100 illustrations in the 16th edition of Ganot's Physics (1902) are in white on black. Blue prints and black-boards may also be mentioned. Whether the common practice of printing in black on white is best or not, it owes its origin and persistence to practical convenience. Very much of the detail seen in natural objects is, of course, brighter than its background and, printed matter excepted, there is no justification for qualifying such contrasts as "reverse".

In the case of relative performance (per cent. of maximum performance attained with each contrast), a brightness difference, which depends on the size of object involved in the task, can be found such that relative performance does not vary considerably with contrast. The minimum brightness difference for which this statement is true is that which gives an average relative performance of the order of 85 per cent. for all contrasts.

IV. SUMMARY

The report describes investigations intended to test the value of a method suggested by A. W. Beuttell for determining the illumination required for the efficient performance of any kind of work involving visual discrimination.

Facility in seeing the object, or objects, concerned in any visual task depends upon certain characteristics of the object and upon the degree of illumination it receives. The characteristics of the object vary with different types of task, and so the illumination required is different for different tasks. Beuttell's method involves, in effect, taking the task to pieces, assessing its principal characteristics, and putting it together again in terms of the illumination required for its satisfactory performance; but the application of the method is dependent upon a previous determination of the relationship between each of the task characteristics and the illumination necessary to "compensate" for it.

Among the most important of these characteristics are size and contrast. The results of an investigation of the effect of size on the illumination required have previously been published, and the present report deals with the effect of brightness contrast.

Brightness contrast is presented whenever juxtoposed surfaces, or objects, differ in brightness; and contrast of brightness or colour is essential for the differentiation of objects by sight. Brightness contrast may be numerically expressed in various ways, in terms of the physical brightness (stimulus intensities) involved. However, since visual appreciation of contrast depends chiefly on *relative* rather than absolute differences of brightness, it is better to use a ratio than a difference for expressing contrasts numerically, and it is convenient to use the ratio of the difference to the greater brightness, $\left(\frac{B_1-B_2}{B_1}\right)$, even though values obtained from this expression cannot be assumed to be proportional to the corresponding sensations of contrast.

The object of the investigations described has been to determine how the performance of simple visual tasks, differing only in the contrast involved, varies with (*a*) illumination, and (*b*) absolute brightness difference between the components of the contrast.

The results obtained are summarised in the following conclusions:

(1) With the same illumination, whatever its value within the range considered, the performance of tasks differing in contrast, i.e. in the value of $\left(\frac{B_1-B_2}{B_1}\right)$, appears to be unaffected by this difference, providing the size involved is large (6 mins.) and the contrast does not fall below a certain value (Fig. 2a).

(2) When size is smaller, performance increases with increase of illumination in a different way, and reaches a different maximum, for different contrasts, i.e. the relation between performance and illumination depends on the contrast presented by the task. The illumination for maximum performance varies inversely and the maximum performance varies directly with the contrast. Thus, with equal illumination, however high its value, equal performance of tasks presenting different contrasts cannot be obtained.

(3) Performance also depends on the contrast presented by the task, even if different contrast tasks are given different illuminations such that each task presents the same absolute brightness difference. But, at a certain brightness difference, depending on size, performance reaches, or very closely approximates to, its maximum for each contrast within the range studied. Further, it is shown that when size is small (about 1 min.) the relation between relative performance (i.e. actual performance with any contrast expressed as a percentage of the maximum performance attainable with that contrast) and brightness difference is the same whatever the contrast of the task. It is also shown that, above a certain relative performance, the relation between this variable and brightness difference, for sizes up to 4·5 mins., is not much affected by the contrast of the task. Hence, it is possible to predict the illumination necessary to give approximately a certain percentage of the maximum performance possible with a task presenting any given size and contrast, within the limits considered, from the relation

$$E_1 = \frac{E\ (\rho_1 - \rho_2)}{(\rho_3 - \rho_4)},$$ where E is the known illumination required to give the same percentage of the maximum performance possible with a task of that size presenting contrast depending on reflection factors ρ_1 and ρ_2.

(4) Experiments with a "reverse" contrast of low order, having the reflection factor of the object greater than of the background, show that performance and relative performance are better at both the same illumination and the same brightness difference than for a similar "normal" contrast.

APPENDIX A

Value of the Constant Brightness Difference Rule

Though the maintenance of a constant brightness difference, whatever the numeric value of the contrast, does not give the best results, in the sense of minimizing the differen of performance obtained with different contrasts, it is clear that it has certain merits. I the first place, it ensures that tasks presenting the same contrast but involving differe pairs of reflection factors will always present the same physical brightnesses. Thus sewi on white cloth with white thread, or on black cloth with black thread, are tasks which m involve the same order of contrast but, with the same illumination, will present ve different brightnesses, and are known by experience to differ in difficulty. The objecti difference between these tasks will evidently be removed by providing, for each, illum nations which differ in the ratio $\left(\frac{\rho_1-\rho_2}{\rho_3-\rho_4}\right)$, where ρ_1, ρ_2, are the reflection factors of t white, and ρ_3, ρ_4, those of the black materials. In other cases, where tasks differ also relative difference of reflection factors, the mean of their brightnesses will vary inverse with their reflection factor difference at illuminations which give them equal brightne difference. This lessens the difference of performance with different contrasts that occu when equal brightness difference is not secured. Referring to Figs. 8a, 8b and 8c, showi the relation between relative performance and (B_1-B_2), it is evident that, for the lowe value of $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ considered, values of (B_1-B_2), different for each size, can be fou at which relative performance has any desired value and is the same for each size.

At these values of (B_1-B_2) relative performance may differ with higher values of $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ but only in excess of the chosen value. If a high value of relative performance is chose

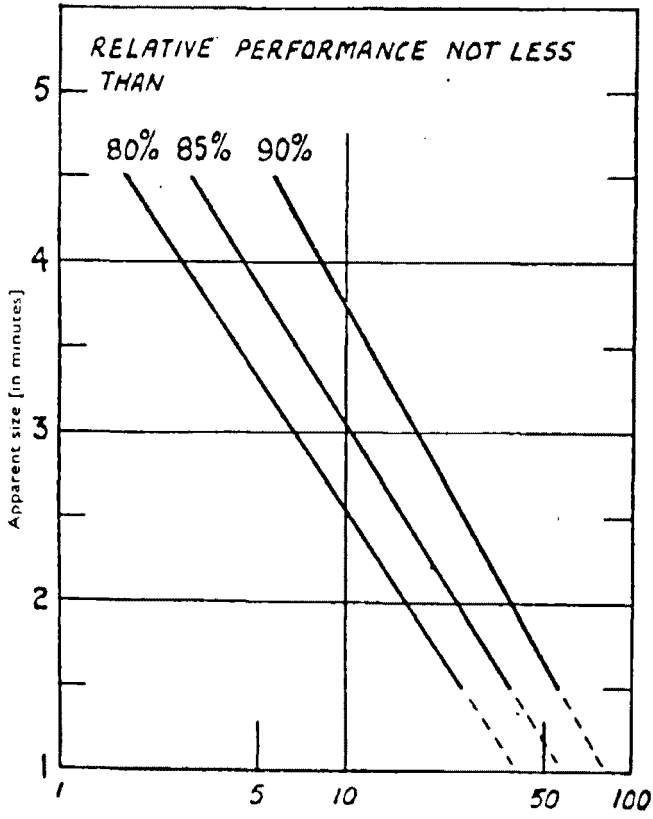

FIG. 10.

the necessary values of (B_1-B_2) lie on, or very close to, a straight line relating size with the logarithm of (B_1-B_2). Thus, an empirical formula can be derived for calculating the brightness difference necessary to give *not less* than a specified relative performance with visual tasks involving any size and $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ value within the range of these variables considered.

The relation between size and (B_1-B_2) for three minimum standards of relative performance is shown in Fig. 10. The equations are as follows :—

Relative performance—with any $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ value—not less than—

(1) 80 per cent. .. .. $\log_{10}(B_1-B_2)=1\cdot99-0\cdot39\ S$
or $(B_1-B_2)=10^{1\cdot99-0\cdot39\ S}$ e.f.c.

(2) 85 per cent. .. .. $\log_{10}(B_1-B_2)=2\cdot12-0\cdot37\ S$
or $(B_1-B_2)=10^{2\cdot12-0\cdot37\ S}$ e.f.c.

(3) 90 per cent. .. .. $\log_{10}(B_1-B_2)=2\cdot23-0\cdot33\ S$
or $(B_1-B_2)=10^{2\cdot23-0\cdot33\ S}$ e.f.c.

where S = visual size in minutes of arc.

The corresponding values of relative performance for all values of $\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ used in the second investigation are given in Table V.

The illumination E required to provide the necessary brightness difference is a function only of $(\rho_1-\rho_2)$, hence

$$E=\frac{(B_1-B_2)\text{ e.f.c.}}{(\rho_1-}\text{ foot-candles.}$$

and

$$\frac{E=10^{K-k\theta}\text{ e.f.c.}}{(\rho_1-\rho_2)}\text{ foot-candles.}$$

Between the limiting values of size and $(\rho_1-\rho_2)$ here considered the brightness difference values found from equation (1) correspond with illuminations which range from $\frac{1\cdot718}{0\cdot87}=1\cdot975$ ft./cs. to $\frac{25\cdot41}{0\cdot25}=101\cdot6$ ft./cs.

But the lowest order of contrast used, viz. :— $\frac{\rho_1-\rho_2}{\rho_1}=0\cdot28$, might be obtained with a value of $(\rho_1-\rho_2)$ only one-tenth of 0·25, i.e. by means of reflection factors $\rho_1=0\cdot09$, $\rho_2=0\cdot065$. In this case, for a size of 1·5 mins., $E=\left(\frac{25\cdot41}{0\cdot025}\right)=1{,}016$ ft./cs. This value may exceed that required for a relative performance of 100 per cent. with many practical tasks involving this size if they are not purely visual tasks. It is only a practicable value for local artificial lighting.

TABLE V

R.P. not less than	*Size in minutes*	(B_1-B_2) *e.f.c.*	$\left(\frac{\rho_1-\rho_2}{\rho_1}\right)$ *0·97*	*0·56*	*0·39*	*0·28*	$\left(\frac{\rho_2-\rho_1}{\rho_2}\right)$ *0·25*
Per cent.							
	4·5	1·718	94·5	85·0	81·0	80·0	
80	3·0	6·607	95·0	91·0	87·5	80·5	96·5
	1·5	25·41	93·5	81·0	80·0	82·0	
	4·5	2·851	95·5	89·0	86·0	85·0	
85	3·0	10·23	96·0	93·5	90·0	85·0	97·7
	1·5	36·73	95·5	86·0	85·0	87·0	
	4·5	6·095	97·0	93·0	92·0	91·0	
90	3·0	19·05	98·0	96·0	93·0	90·0	98·7
	1·5	59·57	97·0	91·0	90·0	93·0	

It is evident, of course, and will be seen on inspection of Table V, that the higher the standard of relative performance, the closer will be the approximation to this standard with any contrast when it presents the given brightness difference.

Other forms of the relation between size and brightness difference can be derived from the data obtained, which will be valid for other criteria of relative performance. For example, taking the values of brightness difference at which exactly, instead of not less than, 90 per cent. R.P. is obtained with each contrast, it is found that, for each size, the

mean of these values lies close to a straight line relating the logarithm of size with the logarithm of brightness difference. The equation to this line is, log. BD=2−(2·33 log.S) or $BD = \frac{10^2}{S^{2\cdot33}}$, where S = visual size in minutes of arc.

The calculated value of brightness difference appropriate to each size is as follows :—

Size	*Constant brightness difference*
4·5 mins.	3·0 e.f.c.
3·0 mins.	7·7 e.f.c.
1·5 mins.	38·9 e.f.c.

and the mean deviation of these values from the corresponding means of the observed values is ± 7·5 per cent.

APPENDIX B

Variation of Mean Brightness with $\left(\frac{B_1 - B_2}{B_1}\right)$ *for Unit Brightness Difference*

In Fig. 11 the relation is shown between $\left(\frac{B_1 - B_2}{B_1}\right)$ and the mean of the brightnesses involved when their difference is constant. As stated in the report, the illumination required to give constant brightness difference may be the same for different contrasts, or, alternatively, different illuminations may be required either for different contrasts or for the same contrast, according to the reflection factors involved. But whether the same or different illuminations are required, the mean of the brightnesses involved will differ as shown, being always greater for the poorer contrast but constant for the same contrast whatever the values of its reflection factors.

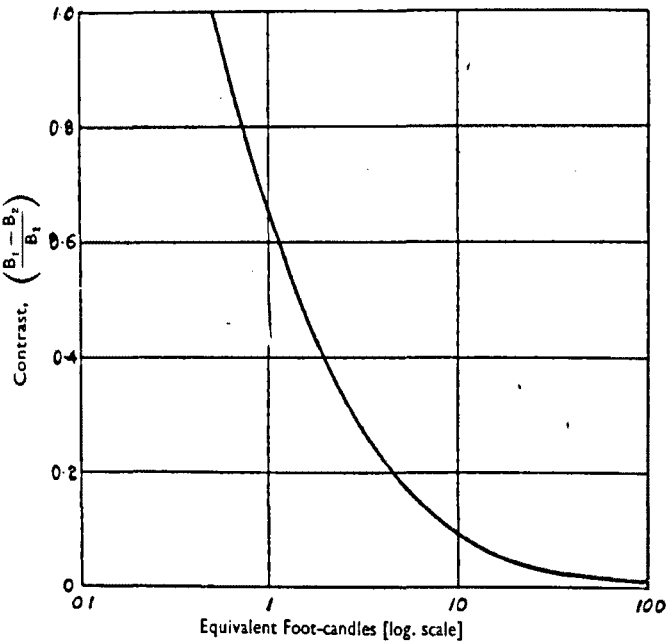

FIG. 11.—Relation between contrast, $\left(\frac{B_1 - B_2}{B_1}\right)$, and the mean of the brightnesses required to present a constant brightness difference of 1 e.f.c.

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