IDEAL SEEING CONDITIONS *

THE STUDY OF THE HUMAN VISUAL SYSTEM AS A BASIS FOR PRESCRIBING LIGHTING

BY

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In the Illuminating Engineering Society's pamphlet on the lighting of factories, entitled 'Making Work Lighter,'¹ it is stated: 'Every-day experience is the only proof we need that much better lighting is necessary for seeing very small than very large objects, and scientific investigation has taught us just how much better it needs to be.' The pamphlet goes on to describe the scope of good lighting, pointing out that if the best seeing conditions are to be achieved care must be taken in the choice not only of the lighting installation, but also of the surfaces on which the light falls. Good industrial seeing conditions, in fact, result from a well-designed lighting installation in a tastefully decorated shop and with work suitably arranged. If such good seeing conditions are to be introduced into industry it is essential to have a clear picture of the ideals to be aimed at and how these ideals are deduced from the characteristics of the eyes. The study of the visual system must be carried out with the object of determining its performance in quantitate terms under defined conditions. Moreover, if a complete understanding is ever to be possible, the function of the visual system in terms of the physical concepts, such as visual acuity and brightness difference threshold, must be related to the anatomical details, such as the retinal neurons with their complex cross connections and differing modes of response to stimulation.

To build up a picture of the visual system it is essential firstly to study the simple performance of one eye. The thresholds such as visual and vernier acuity can be studied and related to the anatomical structure of the retina under certain idealized conditions. The responses of single nerve fibres and the electrical stimulation of the optic nerve can be studied for some lower animals and the results correlated with, for example, the intensity-time response of the human eye. Moreover these experiments indicate the importance of time as a factor in the study of visual reactions.

The more complete picture of the visual system with two eyes working interdependently as part of the brain is much more difficult to visualize. This is inevitable as our knowledge of the enormously complex control mechanism is rudimentary, as is our knowledge of the method of analysis of the nervous messages and their subsequent synthesis into a picture of the outside world. This difficulty must not be allowed to divert too much attention from the visual system as a whole to the more easily understood physical picture of monocular vision.

The most complex of all factors to be taken into account in the study of the visual system is the effect of surroundings on the mood and behaviour of the observer. Some places or rooms are gloomy, others pleasing. The conditions leading to a sensation of cheerfulness must be known and defined even if the means by which they achieve their effect cannot be explained.

The simple study of the responses of one eye alone, the more complex behaviour of the two eyes giving a picture of the whole outside world, and finally the psychological effects of this picture must be studied and made a basis of an ideal set of seeing conditions. Realization in practice may or may not be possible, but ideals must not be bound by practicability. On the other hand, of course, recommendations in every real case must always be thoroughly practicable.

Monocular Vision

If an object is to be distinguished from its background it must satisfy four essential requirements:

- (a) *Size*.—It must subtend a sufficient angle at the eye.
- (b) *Contrast*.—The object must contrast sufficiently with its background.
- (c) *Brightness*.—The brightness of the object must be sufficient to excite response.
- (d) *Time*.—The object must be presented to the eye for sufficient time.

These four variables are interdependent and have been studied exhaustively by Luckiesh² for the special case of the visual acuity threshold. As a test object Luckiesh used two parallel black bars on a white background made by eliminating the middle third of a black square. This object corresponds closely to the Snellen type but is, in his opinion, superior.

The results shown in fig. 1 bring out clearly the importance of contrast and brightness in enabling the eyes to discriminate fine details. The importance of time is not shown very clearly though it is evident that the performance of the eye is superior for exposure times of 0.300 seconds to that for exposures of 0.075 seconds, which correspond approximately to the longest and shortest fixation pauses. Important as these results are, they do not give a complete picture of visual resolution. Three additional phenomena must be studied, namely (a) the effect of the surround field brightness on the discrimination for a constant test object brightness; (b) the existence of different types of resolution of which 'Vernier acuity' is the most important; and (c) the effect of

* A paper read to the Birmingham Group of the Association of Industrial Medical Officers on May 11, 1945.

¹ Lighting Reconstruction Pamphlet No. 6 (1945). Illum. Eng. Soc., Lond.

² Luckiesh, M., and Moss, F. K. (1937). *Science of Seeing*. Macmillan, Lond.

FIG. 1.—The threshold conditions. (After Luckiesh.)

supra-threshold conditions as opposed to the thresholds which are easily studied.

Lythgoe³ studied the change in visual acuity with brightness under three sets of conditions:

- with a dark surround;
- with a surround of fixed brightness; and
- with the surround brightness equal to that of the best object.

As shown in fig. 2, these results are clearly of great importance and extend the threshold data given by Luckiesh,

FIG. 2.—Visual acuity and the influence of the surround field. (Lythgoe.)

who has also performed exhaustive experiments on the effect of the surround field. These experiments show conclusively that the performance of retinal element or a small group of elements cannot be studied in complete isolation but only in relation to other retinal elements in its neighbourhood or more strictly as a part of the whole visual system.

The phenomena of contour or Vernier acuity is further evidence of the beneficial operation of these retinal

cross-connexions. It is found that if part of a straight line in the field of view is displaced then a displacement subtending an angle of 10 seconds of arc at the eye can be detected by a normal observer, a much finer degree of resolution than the 1 minute of arc which is taken as normal for the Snellen type test for visual acuity.

Before considering the relation between the two types of visual resolution and the structure of the retina it is worth while considering the scope of Vernier acuity in every-day life. In all probability it is more important than visual acuity and it is somewhat unfortunate that it has not been more extensively studied. Fig. 3 attempts to formalize the types of visual resolution and shows how vernier acuity and spacial perception are related, as has recently been described by Walls.⁴ In addition, we shall later see that Vernier acuity and stereoacuity are related. Since the retina is built up of a very large number of discrete photo-receptors the 'grain-size' of the retina must set a limit to the possible discriminating power of the eye. In terms of visual acuity, if we are to discern the white space between two small rectangles, then the image of the white space must fall on one retinal element while the two black bars fall on the cones each side. More exactly one cone must be stimulated less than its two neighbours by an amount corresponding to the brightness difference threshold for a single cone. In the fovea centralis, that part of the retina devoted to the seeing of fine detail, we find only cone elements, each of which has usually a one to one connexion through the retinal neurons to the optic nerve and the minimum of cross-connexions. This is in contrast to the rods several of which join to one optic nerve fibre, thus helping their greater sensitivity to light, which is essential as they are concerned with night vision. The foveal cones are, moreover, found to be very densely packed. Their average diameter is 2–3 microns (or 0.001 inch), so that if the image of the white space of the visual acuity test object is 6 microns wide there will be one cone completely unstimulated. If the minimum perceptible

³ Lythgoe, R. J. (1932). *Spec. Rep. Ser. Med. Res. Council*, No. 173.

⁴ Walls, G. L. (1943). *J. opt. Soc. Amer.*, 33, 487–505.

retinal image is taken as 0.0002 inch then at a distance of 10 inches from the eye a detail of 0.003 inch can be discerned, and this corresponds to a limiting angle of about 1 minute of arc, which is gratifying agreement with experiment.

A more exhaustive examination of the nature of the retinal image shows that real conditions are far more complex than the simple geometrical image formation pictured above. However it appears that while the image of even the smallest object falls on several cones a very small difference in stimulation is sufficient for discrimination.

A quantitative relation between the retinal structure and Vernier acuity is not so straightforward. With retinal elements subtending about 30 seconds of arc one can attain, at the best, a discrimination of 2 seconds of arc. The mechanism by which this is achieved is somewhat similar to that enabling one to see a clear picture at the cinema, where each individual picture is of very poor quality. The act of discrimination depends upon a large number of retinal elements working together, and since they are arranged in random fashion it is possible to position a line more exactly than the width of a single element.

A further problem in discrimination arises, namely, the finest black line that can be detected on a white back-

ground (fig. 3). This again seems to be a case in which a number of elements work in conjunction, and it is found that a line subtending as small an angle as 0.5 second of arc can be seen under favourable circumstances. The simplest explanation of this phenomenon seems to be to consider it as a case of brightness difference and calculate the percentage area of a cone shielded by the geometrical image of the line. This works out at about 1 per cent., which compares favourably with the best performance for brightness difference threshold, for a large number of cone elements working together.

So far there has been little indication as to why the performance of the eye depends so very largely on the brightness of the visual field. It is probable that the clue lies in the time required for nervous response, and the experiments described so far do not bring out the importance of this factor. Luckiesh has adopted the argument that since the unconscious eye movements limit the eye's rest pauses to between 0.075 second and 0.30 second, we need not consider time intervals beyond this range. This argument may be valid when we are considering practical application of good lighting principles, but there is ample evidence that in the study of nervous responses we must consider a greater range of time intervals.

Two lines of investigation are being followed which

FIG. 3.—Types of visual resolution.

should eventually lead to a better understanding of the nature of the retinal response. Polyak⁵ has made an exhaustive study of the retinal elements and their cross-connexions in the inner layers of the retina. As a result of this work he has listed a number of different types of cone connexion, indicating possible differences in function. This is in general agreement with the findings of Granit⁶ and Hartline,⁷ who have by different techniques analysed the electrical response of a bundle of fibres and of single nerve fibres respectively. The experiments of Hartline illustrated in fig. 4 indicate the effect on the response of changes in both the intensity and duration of the stimulus. It can be seen that over a very wide range not only the strength of response but also the latent period between stimulus and response depends upon the energy of the stimulus. Remembering that the eye movements effectively limit us to those responses which have commenced within 0.3 second, the influence of intensity on the power of discrimination becomes obvious.⁸

These experiments on the nature of the nervous responses have been carried out on the eyes of lower animals. In so far as they show the fundamental nature of these responses the results can be applied to the formulation of a pictorial theory of vision, but if we are to have a quantitative theory it is evident that exact information on the behaviour of the more complex human retinal elements must be available.

Binocular Vision

The study of the fundamental thresholds, visual acuity, contour acuity and the brightness difference threshold, and their relations with the structure of the eye, is necessarily a study of monocular vision. However, under ordinary working conditions we are concerned with binocular vision, and it is essential to relate our studies to the visual system as a whole. The con-

nexions between the two eyes and the brain, of which the retina by its structure must be considered an outpost, are well known. The optic nerves of the two eyes pass to the chiasma, where they are divided so that fibres from the right-hand side of each retina pass to the motor sensory region of the right lobe of the brain, and those from the left-hand side to the left lobe. It is probable that the nervous messages are partially analysed at this stage. For instance, it is thought that anatomical evidence of a triple mechanism to account for colour vision has been found. In particular what might be called the synchronizing messages must be filtered out at this stage and control impulses sent back along the efferent paths to bring about the exact co-ordination of the eyes. From the motor sensory regions the visual radiation transfers the modified nerve messages to the occipital cortex where the final sensation of sight takes place.

Polyak⁵ has traced the course of the principal nervous messages from their stimulation by the image of the outside world through the chiasma to the occipital cortex. His diagram brings out well how the small central field surrounding the fovea is given pride of place and occupies a very large space in the 'picture' received in the cortex. The study of stereoacuity, which may be defined as the smallest angular difference between the two pictures that can be detected, shows that stereoacuity is of the same order as Vernier acuity. Fig. 3 brings out this relation in the idealized case of two vertical rods of different height, one of which is in front of the other. The left eye sees the far rod exactly behind the front one, but the right eye sees the nearer rod to the left-hand side of the far one by about 10 seconds of arc for the limiting condition. The image of the right eye has a difference corresponding to the Vernier acuity limit between its image and that of the left eye. This difference is, however, interpreted as one of position in depth.

There seems to be little quantitative data on the relation between the field brightness and stereoscopic resolution. This is unfortunate as the brightness of the picture is very important, as can be demonstrated by comparing

⁵ Polyak, S. L. (1940). *The Retina*. Chicago University Press.

⁶ Granit, R. (1933). *J. Physiol.*, 77, 207.

⁷ Hartline, H. K. (1934). *J. cell. comp. Physiol.*, 5, 229.

⁸ Wright, W. D. (1938). *The Perception of Light*. Blackie, Lond.

FIG. 4.—Response from single optic nerve of *Limulus* for various intensities and duration of stimulation. (Hartline.)
(With acknowledgments to the *Journal of Cellular and Comparative Physiology*, U.S.A.)

a stereo-print with a stereo-transparency. The latter, having a higher brightness and a great range of contrast, gives a far more realistic appearance.

Psychological Effects of Background and Colour

In studying the threshold conditions for seeing details, it has been evident from the work of Lythgoe and, later, Luckiesh that the power of discrimination depends not only upon the conditions of the details under examination but also upon the surroundings. This is so, not only in the narrow sense that the immediate surround field affects the ability to discriminate detail, but also in the wider sense that the brightness of the surroundings have a profound influence on the behaviour and response of the observer. In a general way the artist has for centuries been aware of the effects which colour harmonies can have, and the great masters have used this knowledge in the composition of their pictures. A few of the ancients have attempted to formalize the effects of colour patterns on the observer, and some have even made attempts to lay down the relations which must exist between the constituent colours of a pattern. Until recently, however, this work has been limited by the fact that the range of coloured pigments available for experiment was very restricted, and also there existed no rational method of specifying colour. In recent years the number of pigments and dyes has been increased so that the range of colours now available is very wide. A matter of greater importance is that the Munsell system of colour specification has been put on a sound basis, though it may not yet fulfil all the requirements that the most exacting might ask.

The early work of Newton and later Young has made the idea of a colour triangle familiar, being based on the experimental fact that all known colours can be specified as mixtures of three suitably chosen primaries. Practical considerations have also led to the specification of a colour as a mixture of a given spectral colour with so much white. The Munsell colour tree (fig. 5) may be thought of as a development of this latter. The greys, from black to white form the trunk, while colours of the same 'hue' are arranged on radial planes so that there is a progressive increase in the 'chroma' or strength of the colours as their distance from the central trunk increases. This colour tree has two great advantages for practical application, (a) it is simple and orderly, and (b) the scales are chosen so that a Munsell step in any direction corresponds to the constant change in sensation.

Colour Harmonies

In the study of the relationship, first described by Moon and Spencer,⁹ between two colours which has been restricted to the special case of the eye being adapted to a Munsell colour N5 the following possibilities are found:

- (a) Identity.
- (b) First ambiguity.
- (c) Similarity.
- (d) Second ambiguity.
- (e) Contrast.
- (f) Glare (limited to 'value').

⁹ Moon, P., and Spencer, D. E. (1944). *J. opt. Soc. Amer.*, 34, 46, 93, 234.

FIG. 5.—The Munsell colour tree.

Of these it was evident that when the relationship was definite the effect was on the whole pleasing, but when the relationship was doubtful, as when two colours were so nearly the same that one was not sure if they were intended to be the same, then the effect was displeasing. In addition, of course, an excessive difference in 'value' was unpleasant as it produced glare.

In fig. 6 the regions corresponding to the five principal relations between the colours are shown for two cases, (a) a plane of constant value and for colours of any chroma, (b) a plane of constant hue for colours varying

but may equally well lie in a plane of constant hue of even an oblique plane through the colour solid.

Area Balance

It is well known that when one selects a sample of wallpaper the small cutting produces a completely different effect from the large expanse on the wall. The effect on a dark colour is apparently to increase in darkness as the area is increased and similarly a very light colour will increase in lightness. These effects have been known and used by artists for centuries, but such an effect can only be described with any degree of exactness in terms of some measurement.

It will be remembered that the colour harmony experiments were carried out with the eye adapted to a neutral tint of value 5, and under these circumstances it was found that if two coloured cards of the same size were to have equal importance the colours must lie at the same distance from the point N.5. in the colour solid. Supposing, however, the two colours were at different distances from the adapting colour then the ratio of their areas must be inversely as their distances from N.5. More exactly it is found that the moment of one colour about the point N.5. must either equal or be some multiple of that of the other colour.

Psychological Effects of a Colour Scheme

The rules of colour harmony state in simple geometrical terms what colours or groups of colours may be used together and in what quantities, but give no indication of the effect the pattern will have on the beholder nor how it will compare with any other pattern obeying the same rules. It is found that the reaction of an observer to a particular colour harmony depends on two factors: (a) the average brightness of value of the whole pattern, and (b) the mean colour, which would be produced by mixing all the colours composing the pattern in proportion to their areas. These two factors are, of course, interdependent in their action, the significance of the mean colour being negligible when the value of the pattern is low, but increasing and becoming dominant for a high value. Table 1, which is taken from Moon and Spencer's original work, indicates the range of psychological effects to be expected.

TABLE 1

PSYCHOLOGICAL EFFECT OF BALANCE POINT

Munsell Hue	Munsell Value	Munsell Chroma	Psychological effect
R	—	>5	Very stimulating, very warm.
YR	—	>5	Stimulating, warm.
Y	—	>5	Slightly stimulating, slightly warm.
GY	—	>5	Slightly restful, neutral temperature effect.
G	—	>5	Restful, slightly cool.
BG	—	>5	Very restful, very cool.
B	—	>5	Non-stimulating, cool.
PB	—	>5	Non-stimulating, cold.
P	—	>5	Slightly stimulating, neutral temperature effect.
RP	—	>5	Stimulating, slightly warm.
Any	>6.5	Any	Cheerful.
Any	<3.5	Any	Gloomy.
Any	Any	<5	Non-stimulating, neutral temperature effect.

(a) REGIONS OF SIMILARITY AND CONTRAST IN A PLANE OF CONSTANT "VALUE."

(b) REGIONS OF SIMILARITY AND CONTRAST IN A PLANE OF CONSTANT "HUE."

FIG. 6.—Regions of similarity and contrast in the Munsell colour tree.

in both value and chroma. One of the two colours is supposed to be at the point 0.0. in the second case and the other may be anywhere in the pattern. Since all Munsell steps correspond to nearly the same sensation interval the relations illustrated can be imagined to be anywhere in the colour solid.

Harmonies of a number of Colours

When more than two colours are to form a harmony, it is found that their points in the Munsell colour solid should form some regular geometrical figure. For example, a pleasing harmony of three colours of the same value would form a triangle, four colours a square, and so on. Such geometrical figures are, of course, not limited to the simple case of colours of constant value

From these results it can be seen that if the mean value of a pattern is below 3.5 (10 per cent. reflectivity) it will always appear gloomy to an observer adapted to a mean value of 5 (20 per cent. reflectivity), but a pattern of mean value above 6.5 (37 per cent. reflectivity) will appear cheerful. Further, it is only for patterns having a value greater than 6.5 that the effects of the mean hue and chroma become significant. Of these the patterns of low chroma (i.e. less than chroma 5) have no specific effect, but the high chroma patterns have definite psychological effects depending on the dominant hue.

FIG. 7.—Illustrating the regions of the Munsell colour tree giving a specific psychological effect.

These results are shown graphically in fig. 7, which represents a plane of constant hue in the Munsell colour solid, and can be considered as typical of all hue planes.

Ideal Seeing Conditions

To specify the best possible seeing conditions experiments should be carried out to determine the nature of

the operation of the eyes under conditions considerably above the threshold. Such experiments are extremely difficult to perform as there is no obvious method of measuring the ease of seeing. Luckiesh¹⁰ has used the involuntary blinking test as a means of indicating the readability of type. Other workers disagree with this method, but do not seriously challenge his conclusions. More recently Weston¹¹ has attempted to formulate a rational basis for prescribing illumination to give at least a 90 per cent. efficiency. The illumination required is based on that used to yield a given visual acuity and a nomograph can be of great practical help when used in conjunction with a thorough job analysis, a problem that often proves very difficult.

Interpreting the lessons from the study of threshold seeing and from the study of the psychological effects of the surroundings the following are suggested as a basis for ideals.

- Details should be as large as practicable—e.g. about 1/100 inch.
- Critical contrasts should be as high as possible without causing glare—say 100 to 1.
- The central field brightness should be of the order of 1000 equivalent foot-candles.
- The immediate surround field should be comparable in brightness with the central field, which with the more remote surroundings should be so coloured to yield variety without distraction.
- The eyes of the operator should either be relaxed or accommodated well within the comfort range for the individual.

¹⁰ Luckiesh, M., and Moss, F. K. (1942). *Reading as a Visual Task*. Chapman and Hall, Lond.

¹¹ Weston, H. C. (1943). *Trans. illum. eng. Soc., Lond.*, 8, 17.

FIG. 8.—Commutator under-cutting machine.

FIG. 9.—Commutator under-cutting machine (view of work).
(By courtesy of Sheet Metal Industries.)

FIG. 10.—Small press with local lighting and finished in a light colour.

FIG. 11.—Cut-away diagram of press showing lighting unit in position.

(By courtesy of Sheet Metal Industries.)

FIG. 12.—'Jig-boring' room with light dado.

FIG. 13.—'Jig-boring' room with dark dado.

(By courtesy of Sheet Metal Industries.)

FIG 14.—General view of tool room.

(By courtesy of Sheet Metal Industries.)

Practical Applications

It is, of course, not always possible to achieve these ideals in practice, both for technical and economic reasons. There are, however, many cases where seeing conditions can, with advantage to both worker and management, be made very good indeed. A typical example of such a case is illustrated in figs. 8 and 9, which show a small special purpose machine designed for under-cutting the mica between the copper segments of a small commutator.¹² An initial brightness of 1500 equivalent foot-candles was obtained by using an illuminated opal panel, a reflection of which was seen in the work. By means of suitably arranged surrounds, having brightnesses in the region of 50–150 equivalent foot-candles, this high work brightness was made comfortable.

The opal panel is a very powerful tool for the lighting of metal surfaces and a further example of its use on a small power press is illustrated in figs. 10 and 11.¹³ The cutaway diagram in fig. 11 shows how the lighting unit is fitted between the side frames in such a way that it gives maximum efficiency with a minimum of interference.

Decoration

Control of the remote surroundings of the visual field cannot be effected with the exactness with which the central visual field can, in many cases, be prescribed. Particularly in an industrial interior, the pattern presented to the eyes is an extremely complex one. The choice of a suitable decoration must depend very largely on the particular circumstances and should have for one of its objects the suppression of distracting elements in the field of view.

In table 2 the details of two industrial decoration schemes are given. That shown in fig. 12 is suitable for a small shop, where the walls form an important proportion of the field of view. The use of a dark dado, so common in many industrial interiors, is not to be recom-

mended for the small space, fig. 13, but is suitable for a larger shop as shown in fig. 14. The two schemes illustrated are applicable to the light engineering industry, and whilst the same principles will apply to all industries their application must be altered to suit the peculiarities of the industry concerned.

TABLE 2

SAMPLE INDUSTRIAL DECORATION SCHEMES

Location	..	Scheme shown in fig. 12.	Scheme shown in figs. 13 and 14.
Ceiling	..	White (reflectivity 75 per cent.)	White.
Walls	..	Broken White (reflectivity 60 per cent.).	Duck Egg Tint (reflectivity 60 per cent.).
Dado	..	Eau de Nil (reflectivity 45 per cent.).	Holly Green.
Machine Tools		Portland Stone (reflectivity 55 per cent.).	Portland Stone.

Summary and Conclusions

The importance of good seeing conditions is becoming recognized in the more progressive sections of industry, and there is a genuine desire to translate this recognition into practice.

If the best results are to be obtained the study of the eyes from the point of view of the physiologist, physicist and psychologist must be directed towards the specification of an ideal set of conditions. The present state of our knowledge of vision is examined in this paper from this point of view.

The relation between the performance of the eye and its structure is shown in the case of visual acuity, and the significance of the time response of the retinal elements in explaining the dependence of the performance on brightness level is pointed out.

The psychological effects of colour and the lightness of the surroundings are described and related to the practical problem of decoration. Examples of this are given by illustrations of machine tools and industrial interiors.

¹² Nelson, J. H. (1944). *Sheet Metal Industries*, Jan. and Feb.

¹³ Nelson, J. H. (1945). *Ibid.*, Apr.