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LIGHT AND WORK

A DISCUSSION OF QUALITY AND QUANTITY OF LIGHT IN RELATION TO EFFECTIVE VISION AND EFFICIENT WORK

BY

M. LUCKIESH

DIRECTOR, LIGHTING RESEARCH LABORATORY
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PREFACE

DEVELOPMENTS in the production and the utilization of artificial light have been so great in recent years that for the first time in the history of mankind we are encouraged to hope for lighting conditions in the near future which approach the ideal. During the countless centuries preceding the present one, mankind had to be satisfied with mere light of very limited possibilities when daylight failed. It was less than a score of years ago that artificial light first showed promise of being a formidable competitor of natural light indoors. Now this promise may be realized because artificial light is not only a serious competitor of daylight on a cost basis but is far superior from the viewpoint of control. With the decreasing cost of artificial light it becomes increasingly practicable to simulate daylight in quality and to provide more desirable illumination intensities.

A score of years ago the discussions presented in these chapters would have been only of scientific interest. Now they are of very practical interest. The advent of promising artificial light has stimulated investigation in the complex field of light, color, and vision. Researches in the laboratory and in actual practice have yielded valuable data which can be rendered of most practical value only by correlation and interpretation. Many questions still remain unanswered but it is ever so, for with more knowledge, more questions arise. Quality is the fundamental of light; quantity is the fundamental of lighting. These two factors are constantly in mind throughout the discussions presented herewith. Design of lighting is not treated as such for the aim has been to present foundational material for the designer and user of lighting.

Natural lighting outdoors is discussed as a powerful factor in the environment of man during the period of evolution and adaptation. Daylight is then discussed indoors. Artificial light is treated from the viewpoints of quality, quantity, and cost. Many fundamentals of vision and visual functions are treated from the viewpoint of efficient vision. The time element of vision is then introduced and this is followed by a discussion of the influence of intensity of illumination on production. An attempt is made to establish the best range of illumination intensity and also the best quality of light for effective work as influenced by efficient vision. Some rather surprising conclusions are reached pertaining to the economic value of adequate and proper lighting and to the amount of artificial light that we can afford to use at the present time. It is hoped that the book will be helpful to lighting specialists, employers, workers, and all others interested in lighting in relation to the safety, the efficiency, the production, and the happiness of mankind in the field of work.

M. Luckiesh

February 12, 1924

CONTENTS

TABLES

LIST OF ILLUSTRATIONS

LIGHT AND WORK

Chapter I

LIGHT AND LIFE

EVER since primitive man began to think of his own potentiality and began to resist the whims of his environment, he has been building for himself and his posterity an artificial world. He is incessantly engaged in unravelling the mysteries of Nature and he weaves the knowledge gained into a fabric for his own specific use. The natural environment can be no more than a compromise, for into it is woven a very complex life which, doubtless, is as well adapted to survive as is possible in such a complexity. Man cannot escape the fact that he is still Nature's being, subject to Nature's laws. However, with knowledge of these laws and of the imprints which natural environment have left upon him, he should be able to make a better environment for himself alone than Nature provided for him as merely a detail of a complex whole.

It is not the intention to attempt to discuss whether or not mankind is progressing toward salvation or downfall in building to some extent an independent artificial world. Any one of the great fundamental elements of the natural world provides a problem complex enough. *Light* and its associates — color, lighting, and vision — and their influence upon the economic activities of civilized peoples are of primary importance in this artificial world now under construction. Man evolved under an environment in which very adequate lighting by means of light of certain characteristics was, and still is, a factor of equal importance with "air, earth, and water." By coming indoors he created certain restrictions on daylighting. Furthermore, we find man, product of an environment of adequate light of certain qualities, forced to begin at the other end of the scale in the development of artificial lighting. Whether or not man is tempting fate in building this elaborate artificial world is a question that can not be answered until this structure is more nearly complete and has a record of operation. The pertinent fact is that he *is* building it and desires artificial light for use where Nature's light cannot penetrate and where Nature's light daily fails — a failing to which life adapted itself as a period of rest.

However, leaving all that aside, we find man in darkness "making light." We find him developing an art of artificial lighting, beginning with darkness which is so far from the tremendous intensities of lighting in which he and his physiological and mental processes evolved. We may picture man in ecstacy over his successes in making light. In comparison with natural lighting, he has done little more up to the present time than dissipate darkness in the vicinity of his light-sources. It is as if he had lighted a match in a huge dark room. But being able to see here and there, he goes on with his daily work serene in the conviction that he has adequate lighting of the proper qualities. He little realizes that, so far, he has merely dispelled darkness here and there by means of light of more or less accidental qualities. In general, he does not know that the advantages of lighting increase in proportion to the progress of artificial lighting up the scale from darkness toward the conditions of natural lighting. He is not generally conscious of the fact that, if artificial lighting is founded upon the fundamental principles of natural lighting and includes improvements upon natural lighting where such are obviously safe and desirable, his activities will be the most efficient, productive and enjoyable.

The economic value of the results in which visual processes play an essential and important part is almost identical to man's entire achievements because he is so dependent upon vision. It follows, not only logically but from experiments and general experience, that the economic advantages which would result from raising the standard of artificial lighting to a level even now practicable, would be very great. It is necessary to realize that mere light and haphazard lighting eliminate darkness but do not provide the best economic lighting conditions which are now possible even in this early stage of mankind's progress toward independence or improvement upon natural conditions. It is the aim of this book to analyze natural lighting, to point out its important fundamentals, to suggest improvements, to reveal the relations between lighting and vision, and to show the economic results of adequate and proper lighting in increasing the safety, efficiency and happiness of mankind. To those who must appraise progress in terms of gold, the promise is given that improved lighting in this country would be worth billions of dollars annually for it can create this value in excess of its cost.

Environment

No adequate conception of the powers of light and of the possibilities of modern light can be achieved without a study of the environment under which the human race evolved. One of the most important environmental factors throughout the eons of evolution of life was light, or more broadly, solar radiation. The quantity and the quality of sunlight are fundamental characteristics to which the visual sense-organ became adjusted throughout these ages of development. The direction of the dominant light was so powerfully influential during the development of the human body that the physiognomy was moulded to best suit it. The eyebrows were projected forward to screen the eyes somewhat from the dominant light-sources — the sun and the sky.

The distribution of brightnesses outdoors where the human race developed, has left its imprint. A " natural " distribution of brightness to us in general has relatively lower brightnesses below the horizontal as compared with the brightnesses in the upper portions of the visual field. In other words, the sky is the brightest of the large areas and this is usually the most pleasing to us. On the other hand, the sun is a source of direct light which has also played its important rôle with lasting effect upon the human being. All these factors and many others discussed in later chapters, have moulded us physically, physiologically and psychologically. And these influences of the continued adaptation of ages cannot be wiped out in a short time. Perhaps the psychological imprints of these environmental factors of natural lighting are most susceptible to alteration. Certainly the physiological factors of vision cannot be generally altered in a short time. It seems reasonable to believe that they would require nearly as many centuries of adaptation to another environment to alter them as it would to relocate protective eyebrows by adaptation to a radically different location of the dominant light-sources. The receptors in the human eye have been adapted to certain wave-lengths of radiation, to certain intensities of illumination, and to various other factors which are discussed in these chapters.

These great facts of environment which have made us what we are and our sense-organs what they are, and which have established our psychological attitude, cannot be ignored if we are to get the best out of lighting and of the human being. Still they are almost universally ignored. What thought does the factory manager, and others who employ labor for its output, give to these matters? How oblivious most persons are to the importance of light and particularly of proper and adequate lighting. Even many of those dealing with lighting directly, lose sight of the importance of lighting conditions similar to those Nature provided. It is easy to forget that what is, was not always. It is easy to be so intent upon today that sight is lost of the fact that artificial light made its advent only yestercentury.

In this highly artificial age when conditions are changing rapidly we should be certain that change means progress. One of the details of this high-speed age is our dependence upon artificial light. Therefore, every practicable advantage should be grasped and this cannot be done without a breadth of view obtained by a study of natural lighting. Certainly by lighting a match or a glaring lamp we have not overcome all the handicaps of darkness. Certainly this act does not span the gap between darkness and outdoor daylighting conditions. For this reason these early chapters are designed to give the reader a view of lighting conditions to which our eyes, bodies, and minds were adjusted throughout the ages. But first let us consider further, though briefly, some important fundamentals.

Living Things

Light is as essential to most kinds of life as it is to vision. It is as indispensable to nearly all plants and animals as it is to practically all human activities. It is one of the foundational stones of the universe. Mere accident has not made it essential to life and to civilized progress. Its overwhelming and universal importance indicates that light is one of the few materials from which the mechanism of the universe is composed and energized. Certainly it plays a fundamental rôle in the evolution of life. If we look backward to that distant period which exists in our imagination when we see its history written in geology, it may occur to us to ask why the evolution of life was such as to make light essential to it. In that early period when the earth was still steaming, darkness had just the same opportunity as light. But darkness succumbed to light as a potent power.

At best we may state that darkness is the period of general rest.

In the dark cellar or cave what life is found, is so different from that found in the light. In those unillumined places plant-life is ghostly — at best, delicate and unreal. The animal life is usually repulsive — at best, unattractive to us. At night most birds are asleep. Some of the more exuberant or optimistic ones, such as the song-sparrow and the mocking bird, occasionally burst into song after dark but usually the night is given over to bats and owls. Predatory animals are abroad after dark, but this is a matter of necessity for their preying habits require the shelter of darkness. Only those who are weak or bent upon mischief operate behind the screen of darkness. Of course, we can learn to be useful within a limited sphere of activities without light. In proof of this behold the blind person; but his uncertain step as he feels his way is pitiful evidence of the absence of the security and certainty which light provides.

The life-giving value of light is seen on every hand. Plants require light for normal growth and, in general, they require much more light for healthy growth than animals. Most of them require the intensities of daylight hundreds of times greater than those commonly encountered in artificial light. Man and many animals seem to live in comfort and health under intensities of illumination which are inadequate for most plants. Even in a well-lighted room plants grow toward the window for they want even more light. They are used to the outdoor intensities and most of them are sickly if their lighting is restricted to the extent that man has restricted his lighting.

Primitive Man

What effect has the donning of clothing and the coming indoors had upon mankind? Has it been good or bad? Certainly the ancestors of civilized man were at one time adapted to the great intensities of illumination outdoors in the daytime. Primitive races are now living under these conditions outdoors. Would they survive a sudden transplanting to the indoor environment of civilized man? The human race came indoors gradually and this gradual change was accompanied by knowledge which substituted somewhat for the blessings of the sun. For example, civilized man gives some consideration to sanitation and personal hygiene. It is true that he has not at any time in his history been too exercised in these directions, but at least he has given them much more consideration owing to his intelligence than the savage would give them if he suddenly came indoors. With the sun no longer acting directly upon his body or wound or scanty apparel, the savage would be in grave danger from germs. Lacking in knowledge and inclination this savage race would likely decay and even perish if it withdrew from the sun to the extent that most civilized persons have.

But knowledge cannot overcome in a short time the results of ages of environment. It cannot alter physiological and psychological laws and processes that are the products of long adaptation. The eye cannot function best under a low intensity of illumination when it has been developed for serious activity under the great intensities outdoors. Continued vision is not likely to be as satisfactory or free from fatigue and harmful results under conditions radically different from the general conditions outdoors. Illuminants differing radically from daylight, and particularly from sunlight, may be logically subjected to close inquiry if they are to be used for long periods for serious visual work. Psychological effects of radically different lighting conditions are also proper subjects of investigation. Man, in building his artificial world, wrests secrets from Nature and uses this knowledge in his struggle for independence. He has a right to improve upon Nature and he often does so. However, Nature's way is the safe way until man is sure that he has equalled or improved upon it.

Throughout the ages during which man knew nothing of the laws of the physical world, he was purely a product of environment — not only of his own environment but of that of his ancestors. In this condition he was also evolving helplessly and unconsciously into a future over which he could exercise no influence without knowledge. In the earlier ages, of course, he noticed that a rock was heavy and a feather was not but he more generally learned facts pertaining to his own immediate material needs. His crude learning was a matter of experience. His instincts were the result of the experience of ancestors. But his knowledge of natural phenomena and their laws and relations remained meagre indeed until recent centuries when serious inquiry by experimentation began. As far as the human race is concerned, experimental research has just begun and the job to be done is of great magnitude. Therefore, it is not surprising that we often meet questions that we cannot answer as yet. Naturally we know more of physical phenomena than of the physiological and psychological phase of life. This is particularly true of light and of radiation in general. However, it is true now, and always will be, that practice lags behind knowledge.

Light

In respect to light we have the physical energy which we speak of as radiation or radiant energy. For example, such energy, emitted by the sun, may be termed solar radiation. It is emitted in all directions in space and some of it is intercepted by the relatively small body which we call the Earth. Here this radiation performs many functions. Some of it is absorbed and changed into heat energy, thereby warming the absorbing objects. Some of this radiation kills germs. Some of it produces chemical changes resulting in the growth of plants. Some of it is received by the eye resulting in a sensation of light. There are many interesting effects of solar radiation but here we are particularly concerned with the human being and the effect of light and accompanying radiations. (See Fig. 1)

Solar radiation consists of radiant energy of many wavelengths. It can be separated according to wavelength by means of prisms and other devices. On doing so we find that the eye is sensitive to only a certain range of these wavelengths. It is a receiving station and the sun is a sending station. This radiant energy is really electromagnetic radiation differing only in wavelength from that used in wireless telegraphy or "radio." The eye responds to only a certain narrow range of wavelengths just as the "radio" receiving station. These radiations of various wavelengths to which our visual sense-organ is sensitive produce sensations of color.[1] Beginning with the shortest wavelength of radiation to which the eye is "tuned," the result is a sensation of violet. With increasing wavelength there is a progressive change in the color-sensation which passes through blue, green, yellow, orange, and red. These are merely the most distinctive colors. There is no dividing line between them. Theoretically there are as many different hues as there are different wavelengths within the range of sensibility of the eye. Practically, we can distinguish only about 125 distinctly different hues. If a normal eye receives all these radiations at the same time and in the same relative amounts emitted by the sun (as seen at noon on a clear day) the resulting sensation is a combination of all the possible individual ones. This resultant sensation is approximately *white*. This is an extremely important matter as later chapters will show.

Evolution of the Eye

Let us pause a moment to consider a very interesting fact. We have just discussed the visible spectrum or the range of wavelengths of radiation which our visual sense-organ converts into sensations of light or color. If we measure the relative amounts of energy of these various wavelengths reaching the earth from the sun at midday, we find that the maximum amount is that of wavelengths which produce the sensation of yellow-green. If we measure the relative sensibilities of the eye for radiations of different wavelengths we find that it is most sensitive to that which produces the sensation of yellow-green. In other words, if we produce a normal visible spectrum in which equal amounts of energy of all visible wavelengths are present, we find that it is brightest in the yellow-green portion. This is not strange for the human eye is the result of countless ages of evolution under an environment in which sunlight is a prominent factor. Animal life that followed other courses of evolution which resulted in different environments shows approximately different characteristics. Water of considerable depth is bluish green in color. Therefore, only light of this color is transmitted to this depth. Fish living at these depths need not have eyes sensitive to all the radiations that the human eye can see and it is interesting to note that their color-vision is correspondingly restricted. None, or at best only the crudest eye, is found in life beyond the reach of solar radiation, such as in caves and at the bottom of the sea. It is against a fortress of such evidence that certain puny men with strange minds which do not seek or recognize truth, are training their antiquated guns loaded with bullets of blind prejudice and powder of ignorance.

Radiant Energy or Radiation

The radiations to which the eye responds and converts into sensations of brightnesses and hues (or colors), may be grouped in the term *visible radiation* and their visual effects, in the term *light*. These radiations, when separated, are seen as a series of colors as in the rainbow and this series of colors is termed the *visible spectrum.* Accompanying the visible radiation from the sun and other sources of radiant energy, are invisible radiations of various wavelengths. The region of longer wavelengths than that which produces in our visual sense-organ the sensation of red, is termed *infra-red radiation.* The region of shorter wavelengths than that causing the sensation of violet is termed *ultraviolet radiation.*[2]

It broadens and, at the same time, simplifies our view of radiant energy from the sun and other sources, to consider that the eye is just one of many " receiving stations " which, in general, differ in range of wavelengths to which they are sensitive. For example, the ordinary photographic emulsion is sensitive to wavelengths which we see as blue and violet light and also to a great range of wavelengths in the ultraviolet region. Plants absorb radiations of various wavelengths. There are many photochemical reactions each of which is caused by radiations of certain wavelengths peculiar to it. In all cases where radiant energy is absorbed some result is achieved such as chemical reaction or a rise in temperature. Perhaps it should be conversely stated that any effect of radiation is due to an absorption of it and some kind of transformation.

These invisible radiations are not of primary importance from the viewpoint of light, but they must be considered in connection with Nature's lighting. They are a part of the environment under which life evolved and inasmuch as this environment is foundational with respect to this book they cannot be ignored. Furthermore, these radiations accompany the visible radiation from artificial sources; from the viewpoint of light-production, they represent waste and, therefore, inefficiency. On the other hand, they are being turned to good use in many chemical reactions, in therapy, in sterilization, etc.[2] Our chief interest in them is in the safe assumption that the human being is (or was before he came indoors) adapted to those found in solar radiation. We know less about their applications than we do about visible radiation or light, but we are learning rapidly. Here, as in other fields, we are improving upon Nature by producing specific radiations for specific purposes.

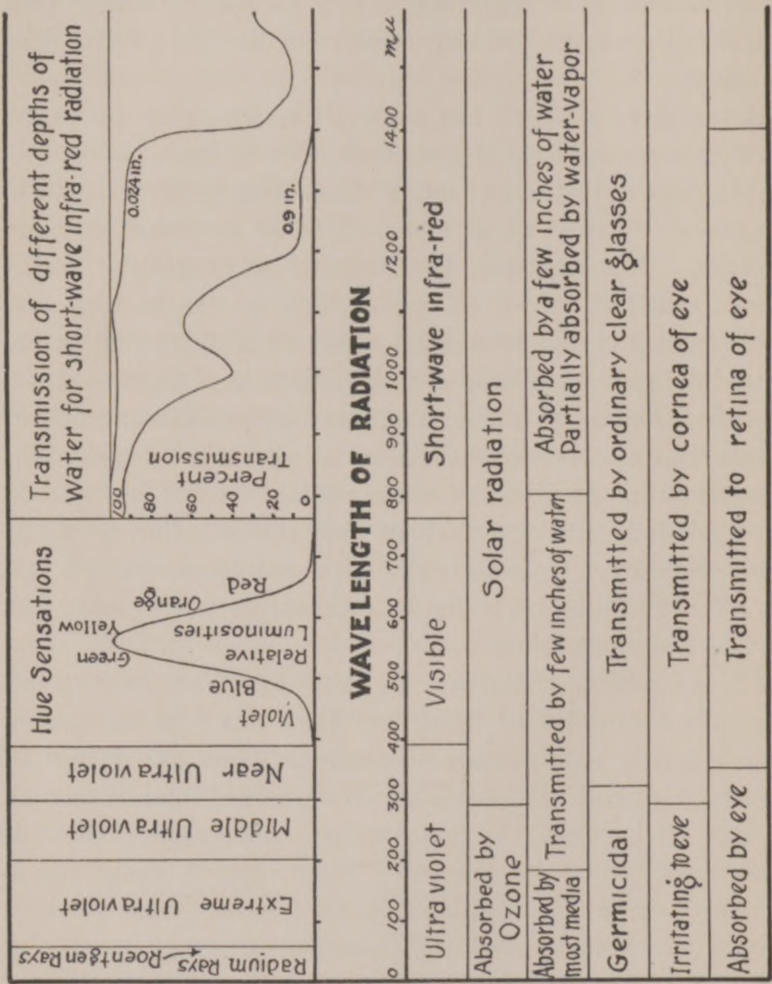


Fig. 1. Various spectral regions and properties of radiation of different wavelengths.

In Fig. 1, are shown graphically, on a true scale of wavelengths, the ultraviolet, visible, and near infra-red regions; the short-wave limit of transmission of quartz, water, and ordinary glasses; the short-wave limit of solar radiation reaching the earth; the long-wave limit of germicidal action; the relative visibility of visible radiations of various wavelengths and the sensations of hue which they give rise to. These limits are only approximate because, in general, they cannot be exactly defined excepting for a specific case. The infra-red region extends much further than shown and this is indicated by leaving the diagram unclosed at the right. However, the details of infra-red radiations of larger wavelengths are of less interest than the radiations of the wavelengths shown. It will also be noted that no such terms as "actinic" or "chemical" rays are used. These are vague terms because most, if not all, radiations have some direct or indirect chemical effect. This diagram is supplemented by a verbal summary in Table I. Although the magnitude of the unit of wavelength, mμ, which is used here is of little interest, some readers may wish to attempt to visualize its very small value or to refresh their memory. It is one millionth of a millimeter.

TABLE I

Some Facts Pertaining to Radiation

(See also Fig. 1)

Wavelength in mμ	
... to 200	Extreme ultraviolet region Absorbed by most media
200 to 300	Middle ultraviolet region Transmitted by quartz and water Absorbed by ordinary glasses and ozone Destroys animal tissue Destroys germs
290	Approximate short-wave limit of solar radiation at the earth, the radiation of shorter wavelength probably being absorbed by ozone in upper atmosphere.
310	Approximate long-wave limit of germicidal action
300 to 400	Near ultraviolet region Transmitted by quartz, water and ordinary glasses
390 to 760	Visible radiation or radiations causing sensation of light and color
390 to 430	Violet region
430 to 470	Blue region
470 to 500	Blue-green region
500 to 530	Green region
530 to 560	Yellow-green region

Wavelength in $m\mu$	
560 to 590	Yellow region
590 to 620	Orange region
620 to 760	Red region
460	Maximum energy in blue-sky radiation
555	Maximum sensibility of the eye
555 (approx)	Maximum energy in solar radiation
760 to ...	Infra-red radiation
	Absorbed by thick layers of water
	Partially absorbed by water-vapor in atmosphere

Biological Effects of Radiation

Let us return for the moment to daylight in order not to lose sight of the conditions under which civilized man evolved. Complete ignorance could not exist where experience was remembered. This was the situation with early primitive beings. Gradually observation developed and then finally experimentation which has done so much in harnessing natural phenomena for our specific uses.[2] The present-day savage is not without some knowledge of the properties of solar radiation. In a vague way he knows that it helps to heal wounds and to make water safer to drink. He knows nothing of germs or of therapeutics. Perhaps instinct and vague knowledge cause him to utilize to some extent the beneficial effects of solar radiation, but does he suspect the consequence of the absence of sunlight particularly for one who is unfortified by an inclination to substitute cleanliness for the protection of solar radiation? Modern man has learned many facts of radiation, but much remains to be unravelled in the realm of radiation and light therapeutics.

Sunbaths are known to be efficacious in certain cases. As a consequence mankind has developed baths of artificial radiation. Sometimes only the light is considered and this can be of various colors but there is always the invisible radiation which may be playing a part. The germicidal activity of solar radiation is known to be due to the ultraviolet radiation. Rain falls over the earth and it runs off to streams, rivers and lakes, carrying with it vegetable matter and the germs of animal disease and waste. In sunlight these germs are killed so that we have outdoors an extensive sterilizing process operating on land and in the water. Hence, we have our open reservoirs where the sun's aid is invited in sterilizing the water for our towns and cities.

Too much solar radiation is harmful but on the other hand many diseases show a seasonal variation with maximum prevalence in months of diminished sunlight. For example, rickets are more prevalent in the winter months than in the summer and it is now fairly well proved that the low intensity of sunlight and the consequent small amount of ultraviolet radiation is responsible for the increase in rickets in winter. In many other ways solar radiation is a protector and a servant. In this age of artificial light we must consider the composition and intensity of daylight. Without other knowledge we may safely assume that artificial light which approximates the characteristics of daylight is best. The radiations found in daylight should be harmless when they accompany artificial light. Natural lighting conditions should be best suited to life and therefore should be approached if possible by artificial lighting. Of course, adequate knowledge may lead to improvement over Nature in specific requirements arising from the artificial conditions which mankind has produced.

Fundamental Lighting Conditions

If artificial lighting conditions differ radically from natural lighting conditions in such matters as intensity, spectral character, distribution, and accompanying invisible radiations, they must be questioned until adequate knowledge of the psycho-physiological is available. Human beings are still Nature's animals in respect to the great environmental factors. From the viewpoint of evolution we have just come indoors. We must still view our welfare in terms of that environment in which we evolved. Of course, natural conditions are a resultant or a compromise well suited to the complexity of requirements of outdoor life. It seems reasonable to suppose that man can improve upon these conditions in specific cases. Perhaps he may finally acquire the knowledge necessary to improve upon natural conditions in every specific respect. However, many environmental factors which require countless generations to show their effects, must be reckoned with. We cannot expect our visual organs and physiological processes to reconcile themselves in a day or a year or a century to radical changes in a foundational factor such as lighting.

Fortunately, the human being is fortified with a certain resistance to harmful conditions. The human body is constantly repairing damages. The mental process of man is adaptive and can ignore unnatural conditions to some extent. But is not the best environment that which would permit most of the energy required for repairs to be utilized in material and mental *output?* A factory, for example, in which friction and other forms of waste are reduced, will produce more at the same expenditure of horse-power and man-power than the wasteful factory. Lighting which is inadequate or improper, or both, produces friction in many ways. It decreases the output whether the factory or office manager knows it or not. Furthermore, a light-source just here and there does not produce a condition conducive to the best production. It is too commonly believed that if darkness is dispelled the lighting problem is solved. Let us view the span from darkness to the natural lighting conditions outdoors on a reasonably clear day. The one extreme represents a condition of little or no activity possible. The other extreme is that under which we as active beings evolved. Sometimes the intensity is too great for serious visual work, such as reading, but this intensity is not likely to be approached in general artificial lighting. However, viewed in this manner we find ordinary intensities of artificial illumination hovering near the darkness extreme. From every viewpoint, available data show that great advantages would accrue if artificial lighting conditions were further away from the darkness extreme and closer to natural lighting conditions outdoors.

What Good Lighting Accomplishes

Further discussions of these factors will be found in chapters devoted to the specific phases. In closing this introduction let us consider what adequate and proper lighting may accomplish in human activities.

a. Certainly the production of a factory in darkness would be small and uncertain. It increases with increasing light. Why should we expect it to reach a maximum under conditions now prevalent when these can be improved in so many ways. Experiments point conclusively to greater production with better lighting and the value of this production is many times greater than the additional cost of lighting.

b. We cannot expect good workmanship in the dark. The best workmanship certainly is not achieved even under poor lighting. Evidence points to increasing quality of work as we improve the lighting. Particularly for fine work, very much higher intensities than are now prevalent will pay dividends. The lighting must be proper as well as adequate.

c. We would expect workmen to spoil much material in the dark. This spoilage is reduced even with poor lighting but it is not a minimum until the lighting is adequate and proper.

d. Safety is certainly not a product of darkness. Adequate and proper lighting increase the safety of the workmen.

e. The eyes are rested in the dark and therefore eye-strain and eye-fatigue are not produced in darkness. They are the consequence of inadequate and improper lighting. Certainly our eyes which have evolved under natural lighting conditions, would be less strained and fatigued under artificial lighting conditions approximating these in quality, quantity, and distribution of light and brightness.

f. Darkness is the period of rest. Light is stimulating. Adequate and proper lighting stimulate greater activity which, properly directed, results in greater production.

g. Well-lighted surroundings promote cheerfulness and workmen are not likely to become too cheerful from light alone. Therefore, there is no danger of overlighting in this respect. Certainly workmen are depressed by improper and inadequate lighting.

h. We would not expect orderliness and good discipline to be best in darkness and we have no reason to expect them to reach their highest development excepting under adequate and proper lighting.

Doubtless there are many minor factors which could be mentioned, but these chief ones are sufficient to indicate why good lighting is an asset in factories, offices, stores, and homes; in fact, wherever persons work or use their eyes in serious work or wherever there is traffic. Therefore, light is not only essential to human beings who depend so much upon vision, but is a great economic factor. The best will not be obtained from light until the lighting conditions are adequate and proper and that means they must approach natural lighting in certain fundamental aspects.

Unfortunately light is not a novelty; in fact, it is a common experience from the time we are born and throughout our lives. For this reason it is accepted as a matter of course and no serious thought is given to it by most persons. It is almost as omnipresent as the air we breathe. But we are learning that plenty of fresh air is healthful; perhaps we will learn that good lighting is just as important to us who depend so much upon vision. Most of our experiences and activities depend upon the doorway of vision and therefore light and lighting are intricately associated with most of our accomplishments and other experiences.

Most persons whose consciousness has been awakened in some manner to light and lighting, doubtless will not sense the important difference between bad and good lighting. It may not be difficult for them to realize the differences in direct results. They may readily admit that glaring lights or feeble illumination may increase the likelihood of accidents, but it is not so easy to sense the physiological and psychological effects. These are less direct in their manifestations. The entire psycho-physiological realm is not as susceptible to analysis and appraisal. The eye endures much abuse without complaining directly, but all these abuses of inadequate and improper lighting are recorded eventually on the loss side of the human ledger. We cannot, without risk, subject our sense-organs and mental being to conditions radically different from those for which they have become tuned. This is one of the premises of this book and it is the aim of chapters which follow to discuss the lighting conditions of Nature and to indicate how they can be approximated and even improved upon by means of artificial light.

Chapter II

DAYLIGHT OUTDOORS

TO civilized people daylight outdoors is apparently of chief interest from the viewpoint of its influence upon daylighting indoors. However, from the point of view of the relation of lighting to human activity — production, safety, and happiness — natural lighting conditions outdoors are of great fundamental importance. As has been pointed out, these were a prominent part of the environment to which our body, sense-organs, and mind became attuned through ages of evolution. On coming indoors we cannot wipe out these imprints in a few generations, although some of them may not be as deep or as resistant as others. Doubtless some of them are now being altered by the changes which civilization has introduced and they may be obliterated in time. However, from what is known of evolution and environment, it is safe to state that most of the imprints of outdoor environment are still plainly visible and that they will remain so for a long time.

The chief factors in the distribution of light and of brightness outdoors are the sun, the sky, the atmosphere, the clouds, and the colors and the reflection-factors of various areas. These are important individually and in combinations and their influences are far-reaching.

Sunlight

Notwithstanding the sun's great distance, the intensity of illumination at the earth's surface due to it is enormous. That most persons are unconscious of the difference between the intensity of sunlight illumination and that ordinarily encountered in artificial lighting, is evidence of the extreme range of sensibility of our visual sense-organ and its attendant psycho-physiological processes. The intensity of illumination due to direct sunlight on a very clear day when the sun is near the zenith is nearly 10,000 foot-candles. Inasmuch as a foot-candle is the illumination produced by a standard candle (about one inch in diameter) at a distance of one foot, it is seen that we must have the equivalent of 10,000 burning candles concentrated at a point one foot from a surface in order to equal this intensity of sunlight illumination. Only one-tenth of this intensity of illumination is obtained on a surface by means of a 1,000-watt gas-filled tungsten lamp even when the surface is placed as close as one foot to the filament. Taking into account the distance of 93 million miles to the sun and the fact that the illumination varies inversely as the square of the distance, we find that the sun is a light-source equivalent to 2.5 billion billion billion candles. This is only of passing interest; however, it emphasizes not only the tremendous scale upon which the universe is built, but also the great magnitude of natural lighting compared with which man's achievements so far are feeble indeed.

The candle-power of a light-source in a certain direction is due to its brightness and to the area of this brightness in the particular direction. The sun is not only of great area, but it is much brighter than any light-source that man has devised for lighting purposes. It is true that by "exploding" wires by means of electric current far in excess of their safe carrying-capacity, temperatures equalling, and even far exceeding, that of the sun have been produced. But among the present-day practicable light-sources there is none which approaches the brightness of the sun although this is one of the goals of light-production. Inasmuch as the spectral character of light is closely associated with brightness and temperature of a hot body, other means have been adopted by man to reproduce sunlight and skylight artificially. These various phases are discussed in later chapters.

There is a natural variation in the intensity of sunlight illumination at any point on the earth due to the variation in the altitude of the sun. For example, if a white surface is held perpendicular to a " stream " of light-rays from a source it will be seen to have a certain brightness. If it is now tilted somewhat the brightness will diminish. In other words, the illumination intensity depends upon the density

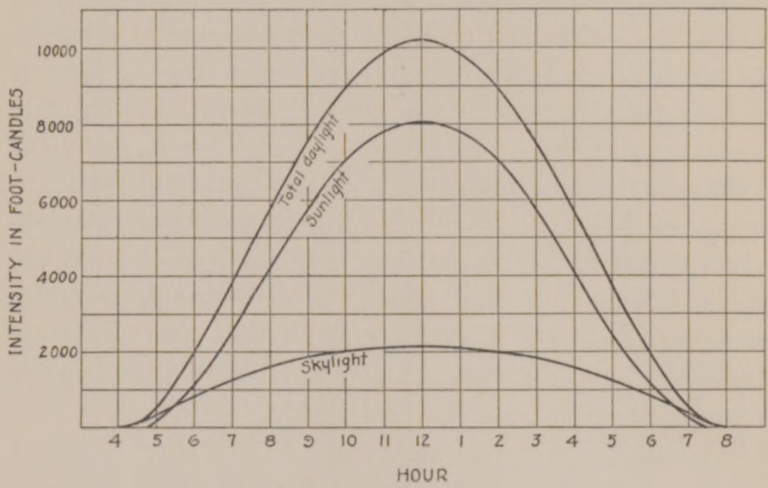


Fig. 2. Variation of skylight, sunlight and total daylight on a horizontal surface throughout a typical clear day in midsummer.

of light per unit of area of the surface. A horizontal surface receives no direct sunlight at the instant of sunrise and it receives a maximum amount of direct sunlight at noon on a clear day assuming all other conditions are constant.

The variations in the quantity of light [3] and of total radiation [4] emitted by the sun have been extensively studied. At most they are only a few per cent and therefore are of no importance from a lighting viewpont, although they are of considerable scientific interest in many ways.

From a lighting viewpoint we are chiefly interested in the quality and the great intensity of sunlight, in the variation in the sunlight illumination due to latitude, sky-conditions, the altitude of the sun and in the *single* shadow which it casts.

The general relations of intensity of illumination on surfaces horizontal, or nearly so, due to sunlight and to skylight throughout a typical clear day in midsummer, are shown in Fig. 2 for the middle latitudes. If the total illumination intensity at noon is 10,000 foot-candles, it is seen that artificial lighting intensities, which are commonly only

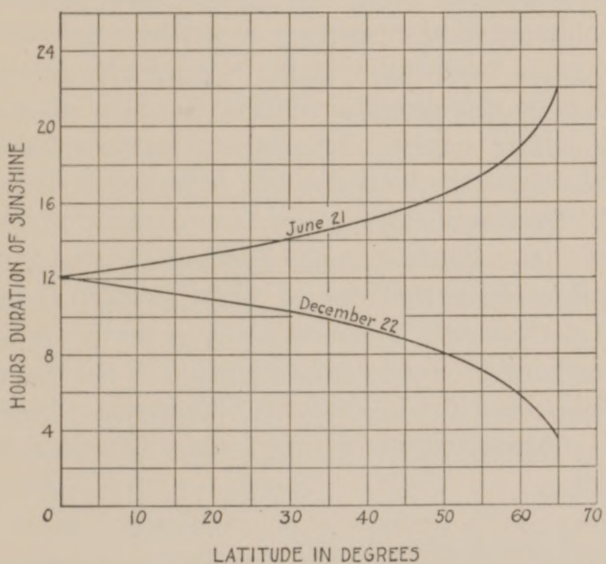


Fig. 3. The maximum possible duration of sunlight in midsummer and in midwinter for different latitudes in the northern hemisphere.

a few foot-candles, would be represented by *only a portion of the thickness of the base line.* Twilights are represented by the skylight which appears before sunrise and persists after sunset. On a typical clear day in winter the relations are similar but the intensities of illumination are less owing to the generally lower altitude of the sun.

The maximum duration of direct sunlight on a horizontal surface (interval between sunrise and sunset) varies, of course, with the season and the latitude. These are shown for midsummer and midwinter in Fig. 3.

Direct sunlight at the earth's surface on a clear day in middle latitudes, when the sun is at its maximum altitude, varies generally from about 7,000 foot-candles in winter to about 9,000 foot-candles in summer on a surface perpendicular to the sun's rays. Owing to the inclination of the sun's rays, the intensities on a horizontal surface are slightly less than those for normal incidence presented above. Throughout the entire year on clear days the total daylight illumination intensities on surfaces not more than thirty degrees from horizontal are generally greater than 1,000 foot-candles excepting during the hour after sunrise and that before sunset. Throughout most of the day on fairly clear days, the total daylight intensity of illumination is several thousand foot-candles, approaching 10,000 foot-candles for two hours during midday. Of this total daylight on clear days, that due to direct sunlight is about 80 per cent of the total. Even on surfaces nearly vertical and facing north (exposure to only a portion of the sky and not to the direct sun) the intensity of illumination, during most of the day throughout the year, is generally several hundred foot-candles.

Effects of the Atmosphere

From the viewpoint of light and of radiation, the atmosphere performs important functions. We live at the bottom of this ocean of atmosphere and are adapted to its presence just as fish in their " oceans " of water are adapted to the properties and influences of water. Even though we supplied ourselves with oxygen from another source and could likewise supply plant-life with the constituents of the atmosphere which it needed, all life as we know it would quickly disappear if the atmosphere ceased to exist. No better example of the adaptation of life to environment is available. The protection of the atmosphere is necessary because we are used to it. From the viewpoint of lighting we are interested in the atmosphere chiefly because it filters solar radiation, scatters light, and causes great variations in daylight intensities. (See Fig. 1 and Table I)

In general, any material body or fluid is not transparent to radiant energy of all wavelengths. Clear glass is quite transparent to visible radiation or light but is opaque to ultraviolet radiation of the "middle" ultraviolet region (wavelengths shorter than 300 mμ). Likewise the gases of the atmosphere [5] are transparent to visible radiation but they absorb invisible radiations (ultraviolet and infra-red) of certain wavelengths. Water-vapor, carbon dioxide, and ozone absorb infra-red radiation, although most of this absorption is attributed to water-vapor in the layer of atmosphere near the earth. Infra-red radiation is of no use to us from the viewpoint of lighting and vision and, therefore, that which is absorbed by constituents of the atmosphere is of no direct interest. However, infra-red radiation is absorbed by the eye-media and too much of it may be harmful, although there is no experimental evidence of any harmful effect of infra-red radiation under ordinary natural or artificial lighting conditions.

It is worth noting that the absorption of the atmosphere does reduce the amount of radiant energy accompanying the daylight which enters the eye. Inasmuch as present-day artificial light-sources emit relatively much greater quantities of infra-red radiation per unit of light than the sun (or the sky), much more heating effect results from equal illumination intensities of artificial light than from natural light. This presents a formidable difficulty in simulating natural lighting conditions by means of present-day artificial light-sources. For example, some provision must be made, such as a layer of water for screening out the infrared radiation, when hundreds or thousands of foot-candles of artificial illumination are desired as an adequate substitute for sunlight, as in the case in experimenting in plant growth, therapy, dye-fading, etc. However, even with present-day artificial light-sources this problem will not be met in ordinary lighting problems until the prevalent intensities are increased many fold. Therefore, great improvements can now be made without this difficulty and it is likely that eventually "colder" light will be produced. This is the goal of the scientist in light-production.

In the ultraviolet region the absorption of the atmosphere is very important. A body as hot as the sun emits ultraviolet radiations very generously, throughout the near, middle, and extreme regions. However, for many years it was a mystery why solar radiation reaching the earth did not contain energy of wavelengths appreciably shorter than 290 mμ in the ultraviolet region. The human body is not adapted to these radiations which are absent; hence, it is not surprising to find them irritable to and even destructive of pigment cells, eye-media, etc. Various artificial light-sources, such as the carbon arc, the magnetite arc, and the quartz mercury arc, emit ultraviolet radiations shorter in wavelength than the shortest found in daylight and these are harmful to the eyes. Many serious results have been due to carelessness and to ignorance, but when these sources are surrounded by ordinary glass, harmful amounts of ultraviolet radiation are not transmitted. Even with the protection of glass one should not look steadily at the light-source. The mystery of the absence of the ultraviolet radiation of the shorter wavelengths from solar radiation which reaches the lower regions of the atmosphere has been explained by attributing the absorption of them to the ozone in the extreme upper regions of the atmosphere.

These ultraviolet radiations to which we are not adapted and which, therefore, are harmful have good uses. Here man extends his independence from natural conditions by manufacturing what is not found in Nature. He uses these radiations, which are harmful to the eyes, in killing germs, in therapeutics and in many chemical processes. Fortunately, germs succumb to ultraviolet radiation as long as 310 mμ in wavelength and this narrow range of germicidal rays found in solar radiation is efficacious owing to the great abundance of daylight. The same is true of other biological effects of radiation. Our skin is tanned but quickly develops or loses resistance because of the superficiality of the effect in the pigment cells.

It is seen that the atmosphere by absorption shortens the extent of the spectrum of solar radiation in the ultraviolet region and reduces materially the amount of infra-red radiation without appreciable absorption of visible radiation. Thus we have a human eye most sensitive to the range of wavelengths of the most plentiful radiation. No other result of adaptation to environment could be expected.

There are many other important parts that the atmosphere plays in respect to life on earth, but the only other one of primary interest here is the scattering of light by it. This is what produces skylight.

Clouds, of course, produce the greatest variation in the intensity of daylight illumination at any given time and place. These variations are enormous; in fact, at any hour of the day or year they may cover a range from zero daylight to the maximum possible. This great variation is the most undesirable feature of daylight from the viewpoint of our activities indoors. The variations of direct sunlight on a horizontal surface outdoors are indicated for a few typical days[6] in Fig. 4. In this respect man is able to improve upon daylight by means of artificial light. However, the great variation is less noticeable and less annoying owing to the great intensities of daylight than it would be in the case of ordinary artificial lighting intensities. Such variations would be dangerous, very annoying and even unbearable in the case of prevalent artificial-lighting levels of illumination.

Skylight

Apparently every medium scatters light, even the most transparent solid, liquid, or gas. The purest water of great depth appears bluish green and it has some brightness only

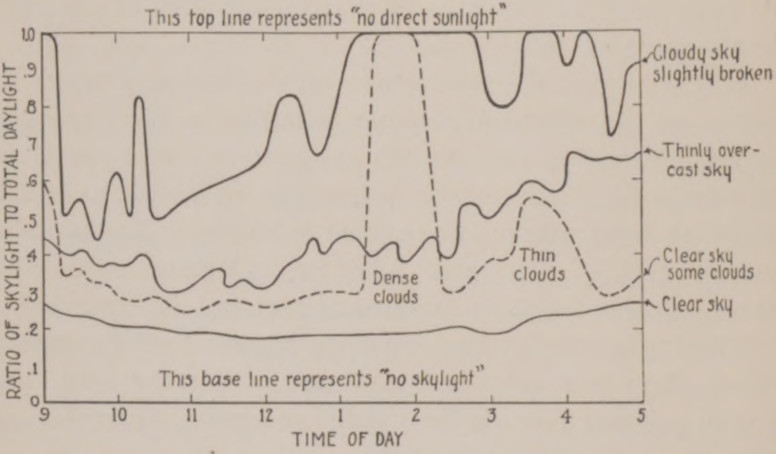


Fig. 4. Showing the variations in the ratio of the intensity of skylight illumination to that of total daylight illumination on a horizontal surface throughout four typical days. These different days may be described respectively as dense, slightly broken clouds; thinly overcast sky; clear day with few clouds; and clear day.

accounted for by scattered light. This is true of the atmosphere, although, as seen from the earth's surface, most of the sky's brightness on a clear day is due to the illuminated particles of dust, smoke, and water. Of course, atmospheric conditions are changing continually but, for example, measurements made by the author on a certain clear morning showed that the sky was ten times brighter as seen from the earth than from altitudes of ten to twenty thousand feet. The scattering in the lower layers is due largely to solid or liquid "foreign" particles, but that of the high regions is perhaps chiefly due to molecules of gases. Certainly little or no water-vapor (in the form of ice crystals) can remain suspended in the extreme upper regions even if it should get there occasionally.

As one proceeds upward the sky gets darker and darker, so, to one who has had this experience, it is obvious that the sky is bright merely because it scatters sunlight. In fact, if water, smoke, dust, and ice particles were absent and the atmosphere was purely gaseous, the sky would be a very dark blue. If the atmosphere did not exist at all and the void of outer space began at the earth's surface, we would have a brilliantly harsh sun shining in a "night" sky studded with stars. Adapted as we are to a bright sky, its absence would leave a most unbearable lighting effect which begins to be suggested at very high altitudes (when there are no cirrus clouds) and is partially demonstrated by a street-light or lantern outdoors at night at a considerable distance from objects such as trees and houses. Cover the ceiling and walls of a room with black velvet and one has a fair reproduction of the condition which would be unbearable to us adapted as we are to the bright sky.

The blue color of the sky is due to the fact that very small particles and molecules scatter the light of short wavelengths (and particularly blue light) more than light of longer wavelengths. The direct sunlight, being robbed of more of these violet, blue, and green rays than of the yellow, orange, and red rays, appears more reddish than it would at the outer layers of atmosphere. As the sun decreases in altitude, it penetrates greater and greater layers of atmosphere, hence the orange or red setting sun. The variation in the color of the setting sun is due largely to the variation in the amounts of smoke, dust, water, and ice particles and total depth of atmosphere. (See Figs. 18 and 19)

An interesting demonstration of the selective scattering of light by small particles may be made with a lighted cigar. The smoke curling upward from the end is decidedly bluish. That expelled from the mouth is more nearly white. The particles in the latter case are larger owing to the condensation of moisture upon them. The larger particles do not scatter the light of short wavelengths as predominantly as the smaller particles do. The shadow cast by the cloud of smoke on a white paper is of a ruddy color showing that it is selective in transmission at least, thus providing a demonstration of the chief reason for the red appearance of the setting sun.

These various factors which give us a blue sky and a reddish sun at low altitudes are important. We are particularly interested in the color or quality of daylight which as we have seen is variable and due to a combination of lights from the sun, the sky, clouds, etc. Quality of light is discussed in Chapters V and VI.

From a lighting viewpoint we are even more concerned with the lighting effects due to the large area of sky. This not only subdues the harshness of the sun but also of the lighting effect. The sky sends light into the shadows and by brightening them renders them less harsh. On an average clear day the brightness of a shadow cast by an object in direct sunlight during midday, is about one-fifth as bright as the sunlit surface when the shadow is receiving light from an entire sky. As the sky "thickens" or grows more hazy, the brightness of the shadow increases until it no longer exists. The approximate percentages of skylight and sunlight for various sky conditions are shown in Table II.

TABLE II

Percentages of direct sunlight and of skylight in the total light reaching a horizontal surface at noon for various sky-conditions.

	Skylight	Sunlight
Outside of atmosphere	0	100
Very clear day	10	90
Average clear day	20	80
Very thin haze	30	70
Moderate haze	50	50
Thickly overcast	100	0

The ratios of total skylight illumination on a horizontal plane at the earth's surface to the illumination due to total daylight are shown in Fig. 4 for four typical summer days in a middle latitude. These show that the illumination due to skylight is less variable than that due to direct sunlight. Although the average illumination intensity due to skylight varies somewhat, the illustration serves very well to indicate the extreme variation in direct sunlight due to moving clouds and to haziness of the sky.

On partially cloudy days the percentage of light from the sky is extremely variable but it averages somewhere near the conditions obtaining when there is a thin haze.

As haziness or cloudiness increases, skylight becomes an increasing percentage of the total until when the sun is obscured, obviously all the light comes from the sky. As the sky brightens, the total light reaching the earth diminishes so that outdoors the maximum intensities of illumination are found on clear days. However, this is not true indoors where the sky is more important as a light-source than the sun. Hence, indoors the highest intensities of daylight, where skylight is depended upon solely, as it usually is, are found on days when the sky is the brightest. The moderately hazy skies are the brightest and, therefore, are the best from the viewpoint of indoor daylighting.

The actual brightness of the sky is of importance both in computing the intensities of illumination obtainable from given sky-areas and fundamentally in obtaining an idea of the brightnesses to which we have become adapted. Brightness can be expressed in several ways, but one of the simplest is in terms of candles per square inch. If a square-inch opening is cut in a cardboard and the sky is viewed through it, the luminous intensity or candle-power of this light-source (the square-inch of sky-brightness) can be determined as easily as that of any light-source. The sky-brightness varies considerably but it is usually less than four candles per square inch. An attempt has been made to express the approximate average brightnesses of the sky under various conditions in Table III.

TABLE III

Average brightness of the sky under various conditions.

	Candles per square inch
Outside of atmosphere	0.0
Very clear day	0.5
Ordinary blue sky	1.0
Thin haze	2.0
Moderate haze	3.0
Dense haze or thin cloud layer	4.0
Medium cloud layer	2.0
Thickly overcast	0.5
Densest overcast approaches	0.0
Maximum brightness of sunlit clouds	20.0

The sunlit surface of clouds varies in brightness, depending upon the thickness of the clouds. Thick clouds have been found by the author [8] to reflect as much as 78 per cent of the incident light. It is readily computed that the maximum brightness of sunlit clouds is approximately 20 candles per square inch. The sunlit portions of clouds are usually from 5 to 10 times brighter than an adjacent area of sky.

These brightnesses of the sky and of the clouds are interesting from the viewpoint of their relations to illumination intensities outdoors and indoors. They also indicate the approximate maximum brightness to which the human eye was commonly subjected throughout the ages. Under the lighting conditions outdoors, the bright areas of clouds and sky can be viewed with comfort and they appear to be safe maximum brightnesses in the consideration of artificial lighting. Of course, these brightnesses indoors can be very annoying if the lighting conditions (level of illumination, adjacent brightnesses, etc.) are greatly different from those outdoors as they often are.

Without skylight we would have no periods of twilight before sunrise and after sunset. Day would come abruptly and night would close down almost instantly. Accustomed to these modulations from night to day and from day to night, skylight is playing an important rôle in natural lighting. In the foregoing we find fundamental lessons in lighting which must be taken into account in developing a science of artificial lighting. Natural lighting conditions teach us that large areas of relatively low brightness are desirable adjuncts to direct light in reducing the harshness of direct lighting and in providing light which penetrates shadows. Twilight periods also remind us that our eyes are used to modulations in intensities of light, that is, that our visual organs have been accustomed to certain time-intervals in which to become adapted to extreme changes.

Daylight intensities are usually less than 100 foot-candles at sunrise and sunset, but they are much greater than maximum artificial illumination intensities in general use for some time before sunrise and after sunset. When twilight has decreased to a few foot-candles we usually think it is too dark for serious visual work. After turning on the artificial light we generally experience annoyance or a feeling of inadequate illumination for some time. This feeling persists until daylight is practically zero and our eyes are adapted to the low level of artificial illumination. Usually twilight becomes insufficient for outdoor activities when the sun is six degrees below the horizon. This is about a half-hour before sunrise and after sunset in middle latitudes.[7]

Smoke has a very marked effect on the intensity of daylight illumination. In smoky cities, direct sunlight and total daylight are often decreased 50 per cent by smoke. If not too dense, smoke causes the sky to be brighter than when the atmosphere is clear but, of course, even then the net result is a marked decrease in the total amount of daylight reaching the earth.

The amount of scattered sunlight is greatest near the location of the sun in the sky. For this reason the sky-

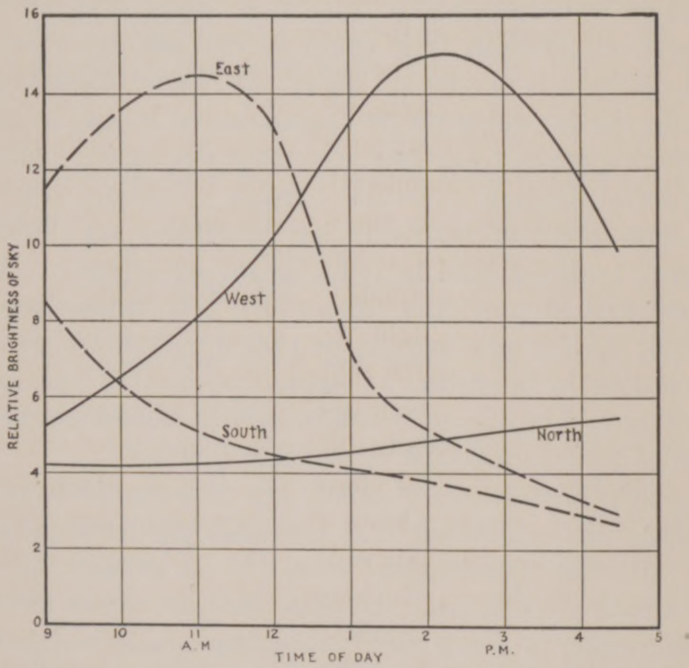


Fig. 5. Variations in the brightness of patches of sky about 20 degrees above the horizon in the north, east, south, and west respectively, throughout most of a clear day in August at 40 deg. north latitude.

brightness is much greater in this region and the sky as a source of light is much more variable in those regions traversed by the sun's path than in other parts. This is well illustrated in Fig. 5 where the variations in the brightness of a patch of sky about 20 degrees above the horizon at four points of the compass — north, east, south, and west

— are shown for a clear day. The measurements were made in a middle north latitude (40 deg. N) between 9 A.M. and 5 P.M. It is seen that the eastern sky was brighter in the morning than in the afternoon after the sun had moved into the west. Conversely the western patch of sky was brightest in the afternoon. Thus the eastern and western skies are seen to vary greatly in brightness. The north and south skies are much less variable in brightness (exclusive of clouds) and of the four the north sky is more nearly constant in brightness than the others.

This reminds us that the north sky has been chosen by colorists, painters, photographers and others who had need for daylight as constant as possible. In developing artificial lighting we should remember that north skylight has been used for centuries largely for its steadiness rather than for its spectral character or color. There are many obvious cases where light of a quality of noon sunlight is better than that of north skylight, but it is difficult to convince those who have used north skylight as a standard that this is true. Having been driven to a north window because of a need for reasonably steady light, they have become used to the quality or spectral character of north skylight and have forgotten or never knew that it was not the spectral character but the constancy of north skylight that made them turn to the north. Incidentally the north skylight also varies less in spectral character than any other areas of sky in a north latitude. This is further discussed in Chapter V.

Moonlight and Starlight

If there were no moon or stars it is likely that there would not have remained in the human eye the receptors which are sensitive only to very feeble light. After twilight failed completely we would have only the suspicion of light extremely faint in comparison with starlight which is itself so weak as to be almost inexpressible in comparison with daylight. Nature has a way of eliminating useless things and it is likely that our retinal receptors — termed "rods" because of their shape — which enable us to see in moonlight and starlight, would have vanished. We say vanished because it is possible that they might have been inherited from animal ancestry which needed them. Prehistoric or very early animal life lived in the sea where amid its dark depths it was advantageous to have receptors which were sensitive to feeble light. Other animals may have needed these sensitive receptors owing to their life in caves. So we cannot say just what the human eye inherited from the past.

At any rate moonlight and starlight are a part of Nature and we can see under these faint illuminations. Moonlight intensities of illumination are of the order of magnitude of a few hundredths of a foot-candle, a matter of a few millionths of maximum intensities of daylight. Starlight is of the order of magnitude of a billionth of maximum daylight. Of course, our ability to see under these natural night illuminants is much more restricted than under the high intensities of daylight. We cannot distinguish color at all and we cannot see fine detail or brightness differences that we can see in the daytime. Nevertheless, the fact that we can see at all under illumination intensities only a millionth or a billionth of maximum daylight marks the human visual process as a marvel in range of sensibility.

These very low intensities were of use to primitive man and are also to us but they are not safe intensities for the complex activities of civilization. We cannot see with sufficient certainty to engage the eyes in serious work. In fact, the chief interest is that we can see at all. However, moonlight is a good example of direct lighting without any appreciable apparent general lighting from the sky. It is like sunlight without much skylight, for the brightness of the sky at full moon is so feeble as to contribute scarcely any apparent light in the shadows. What light we see in the shadows is chiefly reflected from nearby objects. As a consequence we have harsh lighting effects.

The color of moonlight is practically the same as noon sunlight notwithstanding many opinions to the contrary. On the stage moonlight is commonly represented as of a conspicuous blue-green hue. In reality it is practically white. It is sunlight reflected from the moon's surface which is practically colorless.

Nature's Landscapes

The distribution of brightnesses and of colors in Nature is important from a lighting viewpoint. In every respect the human being became adapted to these and one would find it difficult to defend any radically different conditions as being better to live with. The predominant light-source, the sun, is so very bright that we cannot look at it without serious discomfort. Hence, we avoid it and Nature has helped us to avoid it readily by providing us with " visors." We go further in this respect and provide extensions on our hats and caps to screen the eyes from sun and sky. The latter is of a brightness which does not leave serious blinding after-images and it may be looked at directly outdoors without discomfort. The general high level of brightnesses makes the brightness of the sky endurable outdoors. But indoors where the general level of brightnesses is much lower, we cannot view contrasts and brightnesses of the same magnitude as outdoors with the same comfort. Still, indoors we find little attention paid to these matters and mankind is responsible for bare light-sources of very high brightness, extreme brightness-contrasts and low levels of illumination, all contrary to Nature and, therefore, contrary to conditions to which our psycho-physiological processes are adapted.

The fact that we have very generally adopted decorative schemes to live with, in which the brightnesses increase from floor to ceiling, is significant. This is like Nature. Some may say that such a distribution of brightnesses is logical because it is more stable. That is, the dark floor seems to support the brighter walls and these in turn seem to support the brighter ceiling. But, we may ask, why does such a decorative scheme appear more stable? Why does the darker seem to support the brighter? Surely we can find the answer only in natural surroundings which not only made us physically what we are but also what we are physiologically and psychologically. No matter which way we turn or how we struggle for independence, we find Nature's influences and even shackles. But they are kindly shackles if we do not resist them. We must recognize them and be guided accordingly. If we desire independence we must recognize the fact that we cannot materially hasten Nature's processes. They are altered slowly, imperceptibly slowly. All the thousands and thousands of years of mankind's history since the early primitive men are but a second or two in the hour of animal history as written in the geology of the earth.

The reflection-factors or the amounts of light reflected by earth areas[8] are very small so that in our landscapes the foreground and middle distance are of low brightnesses compared with the sky. The average range of the amounts of perpendicularly incident light reflected by earth areas is given in Table IV.

TABLE IV

Reflection-Factors of Earth Areas

Deep clear water	3– 5 per cent
Shallow inland water	5–10 " "
Grass and green crops	5–10 " "
Woods	3– 5 " "
Barren soil	8–20 " "
Clouds	78 " "
Snow	70–80 " "

It is difficult to believe that the range of brightnesses in a landscape is as great as it is. If the artist were to represent the relative brightnesses or "values" accurately, he would have to use black for grass and woods and white for clouds. It is difficult to believe that woods, for example, are only as bright as a flat area painted black but this is true, for black paint commonly reflects as much as three or four per cent of the light falling perpendicularly upon it. The very high intensities of illumination make these low reflecting areas seem relatively brighter than they are. Indoors with our extremely low levels of illumination we should reduce the range of values by using materials having much greater reflection-factors than these areas outdoors.

A sunlit snow-covered landscape is an example of very trying conditions. Outdoors such bright areas, below the horizontal line or plane of vision, are much less usual than areas of low brightness. Over much of the area of the earth which is appreciably populated, snow-covered landscapes are never seen. In most places occupied by man great snow areas are at best relatively rare. They are unnatural. The eye is not adapted to high brightnesses below the horizontal and they are trying to the eyes. Furthermore, sunlit snow is as bright as the brightest sunlit cloud and, therefore, from five to ten times brighter than the average brightness of a clear sky. Snow also reflects ultraviolet radiation, and, although solar radiation which reaches the earth contains only a narrow range of wavelengths of ultraviolet energy which is irritating to the eyes, the great quantity emitted upward into the eyes from sunlit snow is sufficient to do damage. Snowblindness is the inevitable result of these various factors.

It is a matter of optics that if a surface could reflect all the incident light it would be as bright as a hemispherical dome if it received light from all parts of this dome.[6] For example, if the sky were uniformly overcast, such a surface placed horizontally on the earth's surface would be as bright as the sky. If the sky was clear and the sun was contributing four times as much light to this surface as the sky, the surface would be five times brighter than the sky. This is practically the case with sunlit snow. However, snow which reflected only 80 per cent of the incident light, would be only 80 per cent as bright as a uniformly bright overcast sky. Thus we see that an object under sky illumination alone can only approach the sky in brightness as close as its reflection-factor approaches unity. The best mirror can be only about 95 per cent as bright as a uniformly bright overcast sky; whitest powder only about 98 per cent, etc. It is easy to estimate the brightness of a horizontal surface receiving both sunlight and light from the entire sky by making allowances for the amount of sunlight falling upon it besides reasoning as in the foregoing with the skylight illumination.

Another interesting phase of environmental influence is the psycho-physiological imprints that Nature's color-scheme has made upon us. This subject is more specifically interesting in the home and in decoration in general, but it does have some bearing on human activities in work-places, such as office and factory. It is difficult to believe that colors have any innate powers. It is easier to attribute our reactions to them to their location, area, novelty, and commonplaceness in the natural environment which made us largely what we are.[9] It is well known that green is more or less neutral or soothing. Why should it not be so? Nature's vegetation confronted mankind almost everywhere throughout ages of adaptation. That green acquired a neutrality is a most natural consequence of this continued adaptation. Therefore, what better color could we choose for environment for our daily work in office and factory?

Blue sky has been with mankind for eons, but in a position not quite as conspicuous. What is more serene than a blue sky! Perhaps we feel that it is cool up there. Skylight illuminates shadows and penetrates into Nature's solitudes. Why should not blue be cool, serene, quiescent, or even depressing?

The sun appears yellowish by contrast with the blue sky. Yellow is a bright color. Why should it not suggest light and cheerfulness? Yellowish-orange and orange-red were associated with fire ever since mankind used fire and certainly that has been for countless centuries. It is not surprising that these various hues should be " warm " and stimulating.

These are barest glimpses into a complex but extremely interesting subject.[9] They reveal or at least indicate the power of environment. We should have some color even for the surroundings where we work. Nature is colorful and we cannot justify drabness even where we work. When in doubt as to the color for walls and other surroundings in office and factory we can do worse than to heed Nature's color-scheme. Of course, where we specifically aim to utilize the powers of colors we may go much further than Nature.

In calling forth the *powers* of colors we can get the most effect by being *different* from Nature. We can reverse the color-scheme, use large areas of pure colors which Nature does not do, upset Nature's distribution of brightness, etc. This is a phase of color quite the opposite to that which should interest us in our work-places.

Fundamental Lighting Principles

There are many lighting principles which we may well adopt from natural lighting outdoors on the safe assumption that we are best adapted to Nature's environment. Obviously, outdoors we have a compromise of conflicting conditions, but certainly man's egotism, admittedly and obviously gross as it is, cannot muster argument that the human being is not best suited to it or that this compromise is not the best suited to living things in general. There are obvious opportunities for improvement. For example, the great variation in daylight due to sky-conditions, and particularly to moving clouds, is not necessary. It adds charm to landscapes, but it does not aid vision. On the other hand, outdoors it does not hamper vision. The great intensities of daylight compensate for the variation and make it unfelt, for there is usually enough daylight outdoors notwithstanding the variation. Coming indoors has placed limitations on daylight which are man's responsibilities, but in developing an art of artificial lighting we should heed the great environmental factors which are really fundamental lighting principles. Therefore, let us select from the foregoing discussions what appear to be fundamental principles. We find in natural lighting conditions certain outstanding characteristics. The fourteen points are as follows:

a. Great intensities of illumination averaging thousands of foot-candles throughout most of the day are characteristic of natural lighting. These values are literally a thousand times greater than mankind commonly provides by artificial means. It will be seen in Chapter VIII that the visual processes are divided into two regimes. The normal ones are operating under daylight intensities of illumination and the subnormal ones are operating at illumination intensities commonly found in artificial lighting. In other words, the eye may be said to be in " high " under the former conditions and in " low " under the latter conditions.

b. Direct light from the sun is reduced in harshness by an appreciable percentage of light from a large area — the sky. Skylight is commonly 20 per cent of the total light on a clear day. The light from this large area illuminates the shadows and not only reduces the harshness but also provides satisfactory visibility in them.

Physiological laws indicate that as the level of illumination decreases even a greater percentage of light should reach the shadows. Outdoors generally there is plenty of light *everywhere*. This eliminates uncertain and faltering attitude, thereby making greater speed possible in work and in traffic with increased safety.

c. Light coming solely from a large source such as an overcast sky is not as satisfactory as the combination of direct sunlight and diffused sky-light. Definite shadows are generally essential to satisfactory visibility and on overcast days the shadows are not well enough defined. Furthermore, comparatively shadowless illumination is characterless, uninteresting, and even depressing.

d. The brightnesses of objects on an overcast day are not great enough relative to that of the sky for the best concentration of attention and the best visibility. The extremely high level of illumination outdoors usually obscures this characteristic of overcast days but it is apparent to one who will search for it. It is particularly important under the lower levels of totally indirect artificial lighting indoors.

e. Outdoors an object casts only a single shadow. This is a fundamental principle of satisfactory visibility. It is too often ignored in lighting indoors. There need not be only one light-source — window or artificial source — but the best visibility will be obtained where there is one that is *predominant*.

f. The predominant light-sources are overhead and the eyes are so located and protected that they can avoid seeing the light-sources. In other words, the sun and most of the sky are generally out of the direct line or field of vision.

g. The sun is so extremely bright that even careless and indifferent mankind can not bear to look at it directly. The brightness of the sky is of such a low value that at the levels of outdoor illumination it can be viewed with comfort. The highest brightnesses in the sky besides the sun are sunlit clouds (and white objects) and their brightnesses do not exceed 20 candles per square inch. It is well to aim at lower maximum brightnesses indoors and certainly not to exceed this which can be taken as the maximum to which the eye is really adapted.

h. Generally there are no excessive contrasts that are trying to the eyes. Those that would be trying, such as the sun and the adjacent sky or the image of the sun reflected from water and other "mirror" surfaces, are so great (and so few) that they are avoided.

i. Nature's distribution of brightness is such that objects in the foreground and general field of view are of much less brightness than those (sky and clouds) in the upper part of the field. This is a "natural brightness distribution" which it is well to retain indoors.

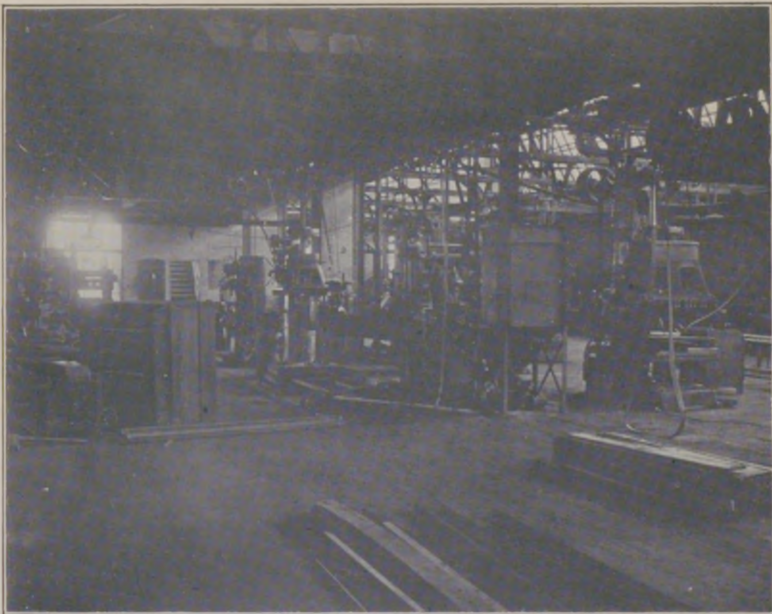
j. The spectral composition of noon sunlight is such as to be approximately a true white. It is logically the best quality of light for color discrimination. It may be said to render colors properly for it does not appreciably "favor" any colors.

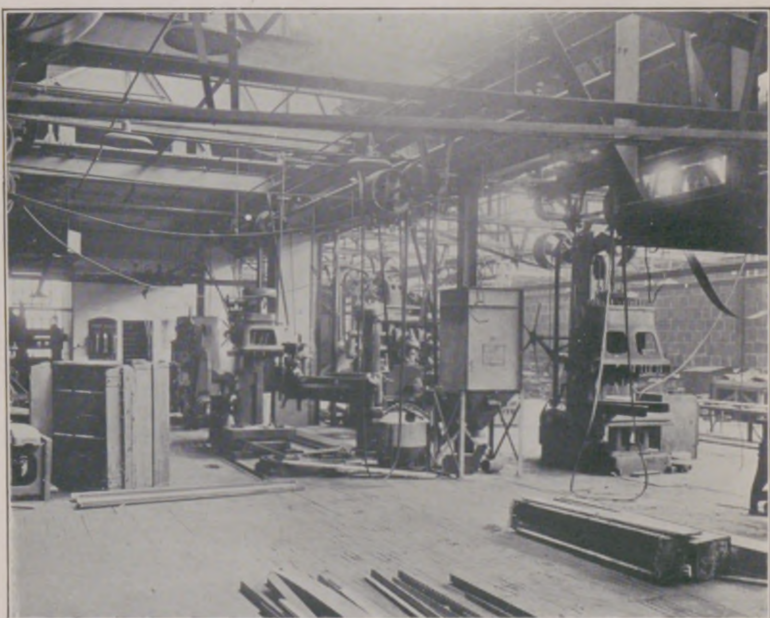
k. North skylight in north latitudes is the least variable skylight available, both in intensity and in spectral character. For this reason it has become the standard for color-work, but it is not the best from the viewpoint of spectral character. It being decidedly bluish, it " favors " colors reflecting blue light such as violets, blues, blue-greens, and purples. Sight has been lost of the fact that north skylight was chosen primarily for steadiness and not primarily for spectral character or color-value. In establishing an artificial illuminant for color-work where steadiness can be easily attained noon-sunlight or a spectral character close to it which gives white light should be standardized.

l. Daylight is a combination of sunlight and light from the blue sky. Inasmuch as the blue sky does not contribute over 20 per cent of the total light, average daylight does not depart radically from noon sunlight. Certainly this light is the best in spectral character for normal eyes because of the eons of adaptation to it. This quality of light should be more appealing to the eyes and to the entire psycho-physiological process of vision than light of any other spectral character, assuming all other lighting conditions are equal. Experiments and experience indicate that this is true so that the ideal artificial illuminant should be one approaching the quality or spectral character of average daylight. In consideration of color-work a white light is desirable. Therefore, from all angles light of the quality of noon sunlight or of average daylight, which is approximately the same, is the ideal artificial as well as natural illuminant.

m. The visual sense-organ is not only adapted to the visible radiation in daylight but has developed resistance against harm from the accompanying invisible radiations. Certainly an artificial illuminant which emits radiations not found in solar radiation should be under suspicion until these other radiations are proved to be harmless.

n. If there are radiations missing from the artificial illuminant that are present in the visible spectrum of solar radiation it is not safe to assume that this is a satisfactory illuminant until adequate proof is available.





Before and after cleaning the glass skylights. The photographic exposure was the same in the two cases.

Chapter III

DAYLIGHT INDOORS

AS civilization advanced, activities were developed indoors and, in the absence of powerful sources of artificial light, it was necessary to bring daylight indoors. However, many handicaps were imposed upon daylight when mankind came indoors. Some of these are not appreciated at the present time because we have long accepted them through necessity. In the consideration of daylight indoors, the sky becomes the primary source of natural light. The sun cannot shine into all our windows and, furthermore, it often fails to shine at all. For this reason it cannot be depended upon in the design of natural lighting indoors. When it does shine indoors it is a mixed blessing. Direct sunlight is cheerful, but it often causes glare and visual discomfort amid the conditions indoors.

Solar radiation has generally been considered valuable as a germicidal agent but this may be questioned after it passes through glass. Owing to the construction of buildings most of our daylight openings are vertical windows in the walls. The result is very non-uniform distribution of light throughout the room. The daylight intensities of illumination indoors are very much less than outdoors and the variation, therefore, is more noticeable and unsatisfactory than it is outdoors. Indoor daylight not only varies with the variation of outdoor daylight but it depends upon exposure, glass area, location of openings above the ground, adjacent buildings and other obstructions to skylight, and to other factors, many of which are not under the control of the owner of the building or of the occupant of the room.

Finally, by bringing daylight indoors, it begins to cost us something. It is no longer furnished free as it is outdoors. Considering the matter from all viewpoints, daylight indoors has so many handicaps imposed that artificial lighting has become a formidable competitor from nearly every viewpoint. In fact, it will be shown that there are many conditions where artificial light is better and even cheaper than daylight indoors.

Daylight Openings

If we had to consider only the problem of admitting daylight into a room, this could be done simply and very well by means of a hole in the wall or roof. But such an opening would expose the room to weather, smoke, and dust and would also permit the escape of a large amount of heat. Nevertheless, many early buildings were daylighted in this manner before the general use of glass. These open " skylights " were common even where civilization reached such heights as in classic Greece. Some of the early temples were mysteriously lighted from " above." The evolution of building is a complex subject. Superstition and religion, as well as intelligence and available building materials, affected design and construction. Perhaps no factor was more influential than climate. For example, in Persia, a land of sunshine, open courts were commonplace in 450 B.C. The temples were open to the sky, for in their ceremonies light, the sun, the moon, and the elements were important. Clerestory windows appeared in early centuries in Assyrian temples. In Grecian and Roman temples, light was admitted in many cases solely through doorways. In the sunny climes of the Mediterranean shores, close to the cradle of modern civilization, daylight openings could be relatively smaller than in the countries to the north.

As the art of glass-making developed, window-openings could be extended in area. It is interesting to note how much greater the window areas became in northern Europe, where the intensities of daylight were less than in the sunny southern portion. Glass and fireplaces did much to diminish the handicaps of severe climate. The great Pantheon, which still stands as the most perfect preservation of ancient buildings in Rome, is lighted by a circular unglazed opening (27 feet in diameter and 143 feet above the floor) at the top of the hemispherical dome.

As the complexity of civilization increased, buildings were constructed of a greater number of stories, so that the vertical skylight in the walls became more practicable from the viewpoint of construction. Therefore, the daylight opening most familiar to us is the vertical one located so we can see out of it. For the sake of simplicity these openings in the walls will be termed "windows." Daylight openings in the ceiling or roof will be termed "skylights" regardless of their slope.

From the viewpoint of uniform distribution of light over the floor or other important horizontal plane, the overhead skylight is generally superior to so-called windows. Only on top floors or in single-story buildings are they particularly effective. Being overhead, they are out of the direct visual field. On the other hand, windows are often in the visual field and these are commonly sources of glare and visual discomfort amid the relatively dark walls of interiors. From almost every angle, natural lighting indoors, by means of windows, is extremely unsatisfactory when one considers it in terms of outdoor daylight or of what can be done with artificial light. Where fairly high intensities of daylight can be obtained indoors, some of the unsatisfactoriness of non-uniformity of illumination is neutralized. However, natural lighting indoors in our cities is generally far from ideal in direction, distribution, steadiness, intensity of illumination, and duration of adequate illumination intensities.

Windows, besides letting light in, "let vision out." It is a pleasant relief to look out of a window provided the outlook is at all desirable. It must be largely for this reason that windows extend so far down into the lower walls. The lower portion of low windows is not as effective in lighting a horizontal work-plane as the upper portion. In our crowded smoky cities it is often a problem to obtain enough glass area, so that nearly all the exterior wall is used for windows. However, there are conditions where the natural lighting would be better if only the upper area of the walls were used for windows. This reduces glare by eliminating sky-areas from the ordinary visual field and tends to keep the dominant direction of light from being too close to horizontal. Clerestory windows or openings high in the walls have excellent applications in interior lighting.

There are many forms of overhead skylights designed chiefly to admit skylight without admitting, or at least diffusing, direct sunlight. The simplest is the flat (or nearly so) skylight. This utilizes direct sunlight as well as skylight. If the glass is of such a character that it diffuses the sunlight, the lighting is improved for a sunny day but at a sacrifice of light on the overcast day when this loss of light can be least afforded. Any skylight glass which diffuses light sends light back outdoors as well as diffusing that which passes indoors. Skylight does not need to be diffused, hence, diffusing glass robs the indoors of some light that it would obtain if the glass were clear. There are clear glasses with ribs which spread the light. These glasses are more efficient transmitters of light if the ribbed side is toward the light-source but this is impracticable to the extent that greater accumulation of dirt becomes an economic factor. Prism glass is also available for diverting the direction of the light by refraction. All these have excellent applications in daylighting as well as artificial lighting but they must be used with understanding.

Much study has been given to roof skylights,[13] particularly for factories. Sometimes direct sunlight is desired but often the glass areas are deliberately faced to the north in order to admit only skylight. Furthermore, advantage is taken of light reflected from the roof areas, walls, etc. adjacent to the glass areas. These adjacent areas contribute little light unless they possess reasonably high reflection-factors. We have many designs of roofs for admitting daylight. The chief types are flat, monitor, saw-tooth, opposed saw-tooth, and opposed monitor. These have various advantages and disadvantages depending upon the character of the surroundings and of the work. They have value as ventilators in factories but they can be applied only to one-story buildings or only to the top floor. No factories today can operate on a regular full shift throughout the year without a supplementary artificial-lighting system. Hence, in consideration of such factors as the cost of elaborate daylighting equipment, the other costs chargeable to natural lighting, the undependability of daylight throughout the period of factory operation, the application of roof-skylights to only one floor, the non-uniformity of natural lighting from windows in large rooms, and the decreasing cost of artificial light, it is reasonable to expect a growing interest in artificial lighting and a decreasing expenditure in elaborate daylighting equipment in many cases, particularly in congested districts.

Intensity of Illumination

Intensities of illumination indoors are of a different magnitude than outdoors. Of course, they vary considerably, but where intensities are measured in thousands of foot-candles outdoors, they are not generally measured even in hundreds indoors. Although it is difficult to devise an accurate statement for something so variable as daylight illumination indoors, it may be safely stated that the intensity of illumination seldom exceeds 100 foot-candles excepting close to a window or skylight. Throughout rooms lighted by means of windows, the intensity of illumination varies enormously.[14] Measurements show this range to be from almost zero to 100 foot-candles in many cases, but generally the average is less than 10 foot-candles.

The foregoing values are for rooms lighted by windows on one side of the room from a sky whose skyline is fairly free from obstructions. In many places in our congested cities, daylight indoors is so feeble and of such a short duration, that it is not worth even the extra heat-loss from the glass areas. The operation of artificial lighting in many stores and offices throughout the day is evidence of the inadequacy of daylight indoors even during midday. Economic aspects are not immune from change any more than the other phases of civilization. Today many daylighting installations are yielding little or nothing on the investment represented. In many places money is spent on natural-lighting equipment where artificial-lighting equipment must provide lighting all day long. Such expenditure is largely wasted but this waste is still going on just because it has always been the custom to supply daylight openings.

The low intensities of daylight illumination indoors are easily accounted for if we stop to think that direct sunlight is not a factor and that only a small portion of the entire sky is visible from a given point in a room. If on a clear day the entire sky outdoors contributes twenty per cent of the total light reaching a certain area on the earth's surface, the maximum skylight illumination of the area would be about 1500 to 2000 foot-candles in middle latitudes. This is based on the assumption that the area receives light from the entire sky — a hemispherical angle or a solid angle of 180 degrees. If one thinks of the "pyramid of light" with the eyes at the apex and the skylight area seen through the window as a base, it will be obvious that this solid angle is but a small portion of a hemispherical angle. It is also easy to visualize the window in terms of an entire hemispherical dome of sky, the latter being suggested by the walls and ceiling of the room. Either method will convince one that the sky-area visible from most points in a room is generally only a few per cent of the total sky. For example, if only five per cent of the sky is visible, the intensity of illumination at the point where the eye is would be 100 foot-candles on a clear day at noon when the sky is contributing 20 per cent of the entire 10,000 foot-candles outdoors. If there are several windows the total percentage of sky area visible from a point indoors would increase, other conditions being equal; however, waning daylight, city smoke, dense clouds, and other factors also must be taken into account. When all the factors are considered, it is easy to account for the low intensities of daylight illumination indoors.

Although this book does not aim to discuss the details of design of lighting installations, it is so easy to gain an idea of the results from a patch of sky that it seems worth touching upon. The illumination in foot-candles produced on a surface (perpendicular to the path of light directly from the source to the object) is found by dividing the candlepower of the source by the square of the distance (in feet) from the source to the surface. This "inverse-square" law does not hold accurately unless the distance between source and object is at least ten times the maximum dimension of the source. However, for approximations the distance can be as little as twice the maximum dimension of the source.

In the case of a window the visible area of the sky is the actual source [15] but in effect it is the area as shown in Fig. 6, of the window-opening "occupied" by sky as seen from the point in question. The candlepower of the source is easily found by multiplying the area in square inches of the portion of the window occupied by the sky, by the brightness of the sky in candles per square inch. This product is divided by the square of the distance in feet from the window to the point in question. It should be noted that this is the maximum illumination intensity at the point in question because the surface was considered to be perpendicular to the general direction of light from the source to it. If the surface is inclined to this perpendicular plane, the illumination intensity at the surface is diminished in proportion to the cosine of the angle of this inclination. Inasmuch as horizontal surfaces in a room are very much

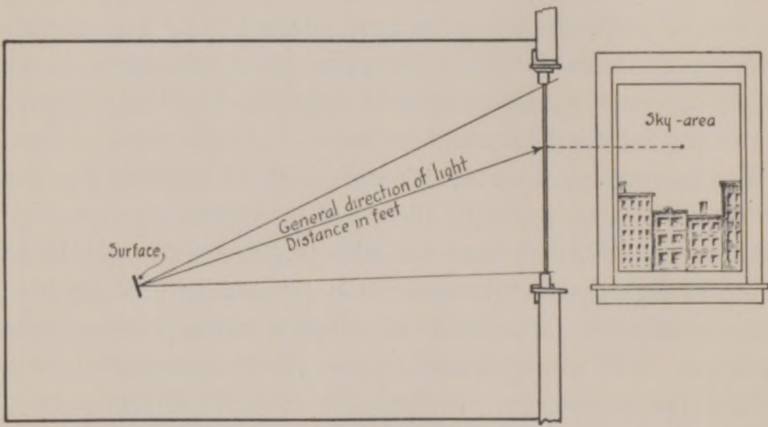


Fig. 6. Showing the effective sky-area at a surface at some distance from a window and also showing the general direction of light from the sky-area to the surface.

inclined to the direction of the dominant light from windows in the walls (particularly low windows), the illumination intensities of these surfaces are very much less than surfaces perpendicular to the general direction of the light from the sky-area to the surface. That is, they are much smaller than they would be if the surface " faced " the window. Anyone interested in the least in the production and working conditions of even a few persons should have available a " foot-candle meter " which is not expensive.

The sky is not uniformly bright so that an average brightness must be used in estimates and computations. Clear skies are generally brighter near the horizon than near the zenith but the converse is generally true of cloudy skies.[3] The values of brightnesses for different kinds of sky given in Table III will be found quite useful.

The intensities of illumination on a horizontal plane obtainable from overhead skylights are generally much greater than from windows. This is chiefly due to the facts that the light-sources are overhead and illuminate the horizontal plane directly, and there need be no floor-areas far distant from a skylight area.

Reflection from Surroundings

In the preceding discussion the lighting value of a daylight opening is based on the visible area of sky and its brightness. Earth-areas are generally of such a relatively low brightness compared with the sky that they need not be considered. This is usually true of most buildings and adjacent roofs which are so located that they could reflect considerable light into interiors if they possessed moderate or high reflection-factors. In many cases much improvement can be effected in daylight indoors by painting important exterior areas white, although as already pointed out, first it should be determined if the result will justify the cost. The construction of buildings of permanent white or " light-colored " materials is due to a recognition of their contribution to daylight indoors in congested cities. However, the lack of universal enforcement of the use of such material in cities indicates that there is no general feeling that the results are eminently worth while. Certainly artificial light must still be used in many congested districts even where there are " white " buildings.

An area of white wall receiving direct sunlight can be much brighter than the sky on a sunny day. It can readily have a brightness of 10 candles per square inch. This value is so much greater than the average of the sky that if appreciable portions of this area are visible from skylight areas, a great improvement in lighting on sunny days results. However, on cloudy days when this additional light is particularly desirable, it is much less. A white surface illuminated by only a portion of the sky and no direct sunlight can never be as bright as the average brightness of the sky. In fact, it seldom is more than a small fraction of a candle per square inch on cloudy days. At best, a vertical surface can receive light from only one-half of the sky and inasmuch as the directions of light rays are inclined to this vertical surface, its maximum brightness possible on an overcast day, and also generally when it does not receive direct sunlight, is much less than one-half of the average brightness of the sky.

Snow on the ground contributes much light indoors. This light is reflected upward against the ceiling and is diffused throughout the room. Snow often greatly increases the amount of natural light indoors and it is particularly welcome in this respect in the season when daylight intensities are generally much smaller than in other seasons. Light-courts, having more than one side, are additionally effective owing to the reflection of light from one surface to the other.[16] This is particularly true when they are painted white.

The reflection of light from floor, walls and ceiling in a room improves the lighting by diffusing the light and by increasing the illumination intensities on work-places. The reflection-factors of floors and walls are quite important in natural lighting from windows because much of the daylight entering windows falls on the floor and walls and reaches the work-places after various reflections. Thus, it is seen that natural lighting indoors is a very complicated matter and at best is far from ideal.

Quality of Light

Although this subject is discussed in detail in Chapters V and VI, a few remarks are not out of place at this point.

Skylight being the primary light-source from a general indoor viewpoint its quality or spectral character is important in natural lighting indoors. It has already been pointed out that, in the northern hemisphere, north skylight is the most uniform in intensity and spectral character because the sun does not influence the north sky as much as it does the portions of the sky in the east, south and west which lie in or close to its path. This has attracted many workers, particularly those engaged in color-work, to north light. However, it is easily shown that light from the clear north sky is bluish white and therefore is not the best quality of light for color-work. It favors certain colors and this should not be a characteristic of a " standard " light.

Light is modified by reflection from colored objects. For example, light reflected from green foliage is greenish; from red brick is reddish; and from yellow walls is yellowish. Such colored surfaces are often adjacent to daylight openings and, therefore, they add tinted light to the light direct from the sky. This amount is often quite appreciable especially if the colored surfaces receive direct sunlight. This adds another variation to daylight whose uncertainty and particularly a lack of recognition of it have often caused difficulty in accurate color-work. Furthermore, this vitiation of daylight is not constant throughout the year or even throughout the day. In temperate zones, we have green areas of vegetation in summer which undergo changes in the other seasons. The progress of the sun throughout a day is such that an adjacent red brick wall may be in sunlight during a certain period, thereby contributing reddish light, and when this is in shadow this contribution is greatly reduced. At this time another surface of a different color may receive direct sunlight and thereby contribute its particular influence. Where accurate discrimination of color is involved these effects are annoying, inconvenient, confusing and often costly. Artificial daylight is the logical solution because it can be accurate and constant in spectral distribution and invariable in intensity — another desirable characteristic of lighting for such work.

Colored surroundings in interiors also influence the color of the light reaching the work. Colored walls, floor, and various objects are, in general, more influential in this respect in daylighting from windows than in artificial lighting. In the latter case usually much of the light comes directly to the work from the luminaire and the nearly colorless ceiling. In natural lighting from windows a great percentage of the light generally reaches the work by reflection from the interior walls, etc. Needless to state, rooms in which accurate color-work is done should be finished in neutral colors not only from a lighting viewpoint but also from a color-vision viewpoint.

Hot-house Effect

This effect is useful or undesirable depending upon the conditions and requirements. It is explained by a trapping of radiation. Glass is transparent to most of the solar radiation; that is, throughout a long range of wavelengths extending much further into the infra-red than shown in Fig. 1. Therefore, these radiations pass through the glass and are absorbed to a great extent by the interior walls and various objects. The result is an increased temperature of these absorbers. They then radiate energy but, being of a relatively low temperature in comparison with the sun, this radiation is of very long wavelength. Glass is opaque to these rays of long wavelengths; hence, the temperature of the interior increases considerably until an equilibrium is reached when the rate of loss of energy from the walls, floor, ceiling, and glass area to the outdoors equals the rate of flow of energy indoors. The walls, roof, and other bounding areas play some part in this effect. They absorb the solar energy and re-radiate the energy in long wavelengths as relatively low-temperature bodies, just as the objects in the interior do. In re-radiating this energy in long wavelengths, some of it enters the interior from which it has the same difficulty in escaping as already explained.

This " hot-house " effect is made use of in growing plants indoors. In other buildings it raises the temperature with a saving of coal in winter and often with an increase in discomfort in summer. Many experiments have been made with the hope of developing a skylight glass which would not admit the infra-red of solar radiation but at best only a minor advantage could accrue from the use of such a glass. A large percentage of solar radiation is in the visible region which could not be absorbed without a corresponding loss of light. Even a greater portion of sky-radiation is in the visible region. If a glass did absorb the portion of sky and sun radiation which was in the infra-red region, the heated glass would re-radiate most of the energy as radiation of very long wavelengths. Approximately one-half of this re-radiated energy would be emitted indoors by the glass and would contribute toward a rise in temperature. Therefore, the net advantage of a special glass of this sort would be slight.

As seen in Fig. 1, a layer of water 0.9 inch in thickness completely absorbs infra-red radiation of wavelengths longer than 1400 mμ (1.4 μ). Such a layer would " cool " direct solar radiation appreciably without reducing the amount of light only very slightly. A few inches of water would be still more absorbent of the infra-red. Some further cooling of the interior would result by increased conduction of heat from the glass to the water if they were in contact. However, by absorbing all the infra-red much heating effect is still possible because the maximum energy in the solar spectrum is in the visible region. The absorption property of water and the hot-house effect are useful in specific cases.

It was pointed out in Chapter II, that water-vapor in the atmosphere absorbed considerable quantities of infra-red radiation. Water-vapor is somewhat more transparent to solar radiation than water. The amount of water-vapor in the atmosphere is generally equivalent to a layer of liquid water somewhat more than one-half inch in thickness.

Hygienic Value of Solar Radiation

It is well known that certain ultraviolet rays in solar radiation are germicidal. This has already been discussed for such radiation outdoors. The radiation which kills germs effectively is not efficiently transmitted by glass. In fact, the spectrum of solar radiation, ending abruptly at a wavelength of about 290 mμ owing to absorption of the shorter waves, probably by the upper atmosphere, contains only a narrow range of wavelengths which are germicidal. These are almost completely absorbed by ordinary glasses as indicated in Fig. 1. Hence, solar radiation indoors after having passed through glass has been very much over-rated in hygienic value. Most glasses begin to absorb radiation considerably at 350 mμ and become opaque to it at about 310 mμ, although there is a good deal of variation among glasses as to the wavelength at which they become opaque to ultraviolet radiation. However, ordinary window and skylight glass may be said to transmit little radiation that is effectively germicidal. In making this statement it is realized that many on first thought will consider it heretical; nevertheless, the data available can not be interpreted otherwise.

It has been well known to many investigators that germicidal rays were confined to a definite region of the spectrum but apparently it has occurred to no one that ordinary glass filters out practically all these from solar radiation before it arrives indoors. Verhoeff and Bell [10] found that radiation of longer wavelengths than 305 mμ did not damage living cells to the point that their ability to repair the damage was overcome. Others have found that radiations longer than 310 mμ in wavelength have no germicidal power. In fact, it has been found that the maximum of germicidal action is at 280 mμ beyond the limit of solar radiation. The powerful effect of solar radiation is due to the great intensity of radiations relatively weak in germicidal effect. Some experiments with the quartz mercury arc showed that the germicidal action of this radiation was reduced to at least one thousandth of its original value when ordinary glass was interposed between the arc and the bacteria. These are just a few glimpses of the evidence which indicates that the germicidal value of solar radiation outdoors is greatly reduced and even practically eliminated when that radiation reaches indoors through glass.

The therapeutics of radiation are not completely understood. There are many conflicting opinions but it seems safe to conclude that direct sunlight has some therapeutic value aside from germicidal action. These beneficial effects are not necessarily confined to the short wavelengths of ultraviolet radiation; if not, they would still be produced by solar radiation which had passed through glass. However, the science of radiation-therapy is not sufficiently developed, or at least there is still too much disagreement, to warrant an extensive discussion here.

Fading of Materials

This point is of passing interest excepting for those who are concerned with materials whose colors are fugitive. In general, only the light or radiation which is absorbed can be responsible for fading; however, it may be stated that ultraviolet, violet and blue rays are somewhat more active than radiation of other wavelengths. Moisture and heat generally hasten fading although radiation seems to be necessary. Direct sunlight is quite injurious to delicate colors owing to its great intensity and to its ultraviolet radiation. Even when filtered through ordinary glass it is still very injurious. Skylight is also very injurious but its lesser intensity causes it to escape with much less credit for fading than direct sunlight. Where delicate fugitive colors are concerned the solution is to exclude powerful daylight and to substitute the electric filament lamp with the "daylight" bulb. This bulb does not transmit very far into the ultra-violet. But the chief advantage of artificial daylight is that, with daylight excluded, a lower intensity than is usually found in museums on bright days would be satisfactory for seeing and appraising the colors or the objects wearing them. Furthermore, artificial light can be turned on only when desired. This is not so easily accomplished with natural lighting. This is a problem that has seriously confronted many persons. Its very obvious solution is by means of artificial lighting of proper quality and intensity and under thorough control.

Cost of Daylight

Daylight has been accepted for so long as a matter of course, that most persons are surprised to learn that it costs something. Of course, this is not true outdoors, but among the handicaps which man imposed upon natural lighting in bringing it indoors is the matter of cost.[11] In general, natural lighting indoors costs as much as artificial lighting and in some cases in crowded cities it costs much more.

The chief items which contribute to the initial net cost of the natural lighting equipment are,—

a. The difference in the cost of the building with and without windows and skylights.

b. The ground-area sacrificed for light-courts and in other ways to obtain effective daylight openings.

c. The cost of extra heating system to supply the excess heat-losses from the glass areas over those from equal areas of walls, ceiling, etc.

The chief items which contribute to the operating cost of natural lighting equipment are,—

d. Interest on initial net investment.
e. Depreciation of natural lighting equipment.
f. Repairs.
g. Cleaning glass.
h. Depreciation of extra heating system.
i. Extra fuel.

There are a number of other items which may be charged to natural lighting but they are largely a matter of judgment so that they were omitted from consideration in obtaining costs.[11] From the viewpoint of this book the actual cost figures of natural lighting indoors are not as interesting as a comparison of costs of natural and artificial lighting for the same room, house, or building. Quite a number of different cases were investigated and it was found that in nearly all cases natural lighting cost more than artificial lighting. Artificial lighting, considerably above the present average and available at any time in constant quantity, costs less, in general, than variable, non-uniform natural lighting whose availability depends upon the whims of nature.

As a matter of interest to everyone it may be stated that the initial net cost of natural lighting in seven-room houses of different construction averaged about $600 and the total annual operating cost was about $100. These figures were closely approached by artificial lighting of a high standard considerably above average conditions.

After having made the comparison on the basis of the items listed in a previous paragraph it may be of interest to present other items which could be charged to natural lighting indoors. Some of these items are window-shades, spoilage due to dust and leaks, fading of materials, sacrifice of floor space, and wall-areas, and cost of artificial lighting used during the natural lighting period when daylight is inadequate.

Windowless Buildings

In our congested cities daylight indoors is often inadequate and the investment in natural lighting equipment is not paying dividends. In many factories, glass areas are so dirty that they are practically useless. The central portions of buildings now given over to light-courts could be utilized as floor space and artificially lighted and ventilated. On every hand there are conditions which would be economically improved by eliminating daylight and substituting artificial light. The psychological effect of the absence of windows is well recognized, but in our congested cities we must work under inadequate natural light reinforced by artificial light, one of the least satisfactory lighting conditions. Many persons work all day long under a total absence of daylight. Our complex civilization demands the services of thousands of night-workers who get along without daylight on their work. Artificial lighting installations are necessary in most places, so it would be an economic measure in many cases to divert the outlay for inadequate and undependable daylight to the rehabilitation of the artificial lighting. In some cases, such as museums, the cost of natural lighting is so great and the result so unsatisfactory, that really wonderful artificial lighting could be supplied by combining both expenditures in artificial lighting. As it is, we often have inadequate natural lighting. By no means is this an advocation of a wholesale elimination of natural lighting. It is meant merely to call attention to the many cases where economics, if carefully studied, would show that natural lighting should be abandoned in favor of expenditure solely for adequate and proper artificial lighting.

The question of ventilation naturally arises. The answer is that ventilation is a growing art which, like artificial lighting, can stand firmly upon its own. Ventilation does not need to be an adjunct to natural lighting. It and heating are best achieved for all and everything concerned by not having to contend with the uncertainty introduced by the opening or closing of windows haphazardly. What makes these suggestions feasible, radical though they may appear, are the great developments of artificial lighting. Buildings are now being constructed or planned in some portions of which no daylight will be provided.

We want daylight where we can obtain it adequately and at reasonable cost but we should recognize its cost and shortcomings. Our complex city life calls for many compromises and also for much night-work. Almost everywhere we need artificial light at night and in many places in the daytime. Those interested in building, particularly in congested districts, where land is expensive and the effective sky is already greatly reduced in area, will do well to consider seriously the growing demand for adequate and proper lighting. Artificial-lighting possibilities are far ahead of those of natural lighting indoors in our crowded districts and to some extent everywhere. The economics of lighting indicate that we are at a turning point. Natural lighting in many places is bound to give way to artificial lighting because of the great handicaps imposed upon it by indoor civilization.

Glasses for Daylight Openings

Daylight openings as a rule should not be glazed with a diffusing glass such as an opal or " milk " glass. As already pointed out this highly diffusing glass diffuses about as much light outward as it does inward. If it is perfectly diffusing, it reflects *more* light outward than inward. If one holds a piece of highly diffusing glass in the path of light rays, it is readily seen that the glass is fully as bright, when viewed in the direction of the light rays as when viewed in a direction toward the light-source. In other words, a window glazed with this glass is fully as bright on the outside as on the inside. This means that about as much light is diffusely reflected outward as is diffusely transmitted inward. This loss of light is particularly undesirable when there is no direct sunlight. This is true to some extent, but not to the same degree, of sand-blasted or so-called "frosted" glass. Furthermore, this finely rough sand-blasted surface cannot be cleaned easily.

For the foregoing reason, crystal glass is best for daylight openings but this glass does not need to be plain glass excepting for windows that it is desirable to see out of. Ribbed and pebbled glasses are the best kinds of glass for breaking up the rays of direct sunlight without an appreciable loss outwardly by diffusion. The irregularities are smooth and can be easily cleaned. Ribbed glass *spreads* the transmitted light in a direction perpendicular to the ribs. The pebbled glass spreads the light in an irregular manner. Both these types are generally very satisfactory where high transmission, ease of cleaning, and the breaking-up of direct solar rays are desirable characteristics. In Fig. 7, four typical glasses — pebbled, coarse ribbed, fine ribbed, and wavy — are illustrated from prints made by placing them in contact with photographic paper and making prints by transmitted light. Their actual cross-sections are also shown. Illustrations made from actual photographs of the transmitted light are shown in Fig 8 for these four typical glasses. The transmission of light for the pebbled and for the wavy specimens are shown for two cases each. In one the rough surface is toward the light-source, in the other the smooth surface is toward the light-source. These illustrate very well the manner in which the light rays are broken up.

When light falls perpendicularly on clear plane glass about 4.5 per cent of the light is reflected from the first

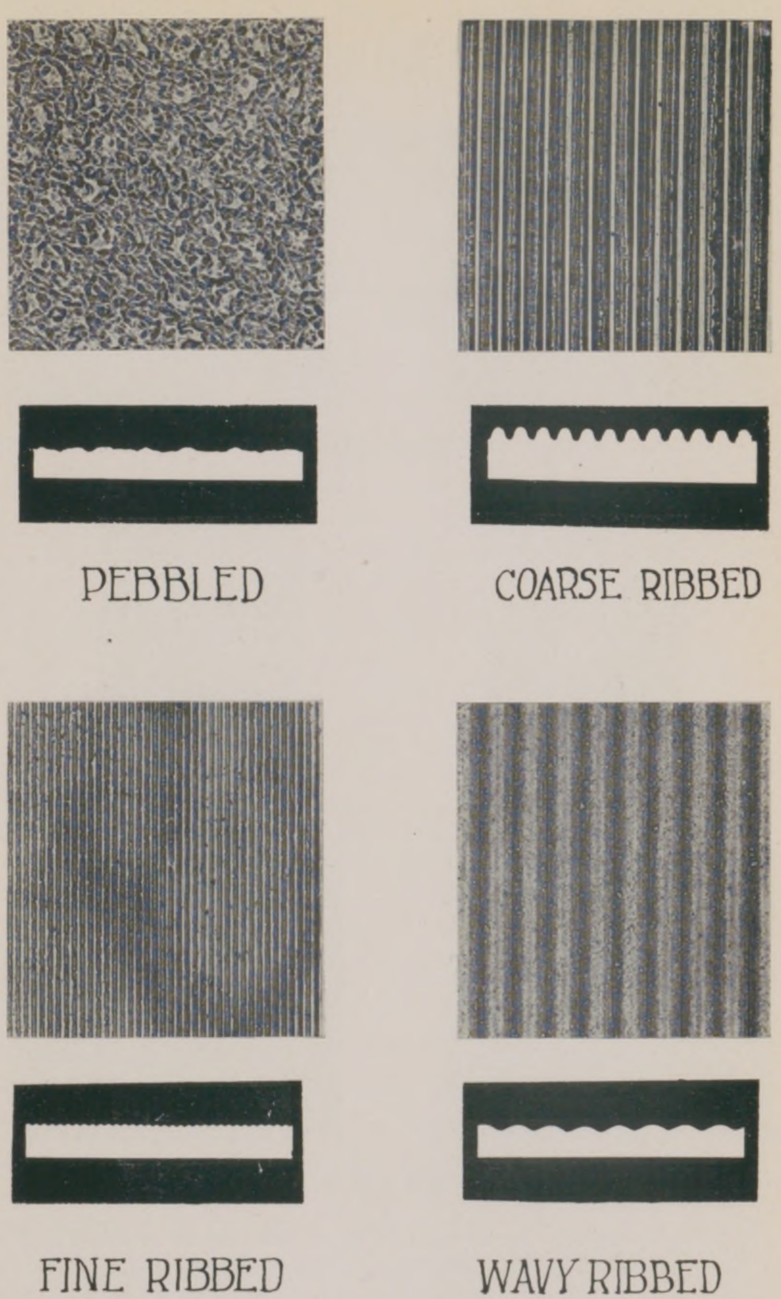
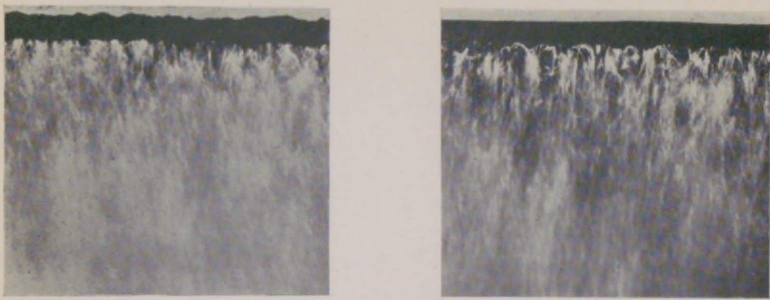
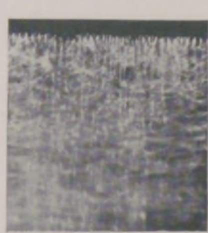


Fig. 7. Four typical crystal glasses having different surface characteristics as indicated by their respective cross-sections.

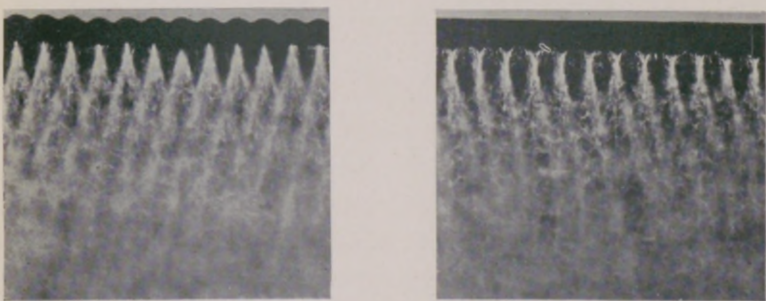


PEBBLED

COARSE RIBBED



FINE RIBBED



WAVY RIBBED

Fig. 8. Showing the actual transmission of light through the four typical crystal glasses having surface contours as shown in Fig. 7.

surface and about 4.5 per cent is reflected from the second surface. The percentage of light reflected increases with the angle of incidence as shown in Fig. 9 for three angles of incidence, nearly zero degrees, about 45 degrees, and about 70 degrees. The principal reflections from the first and second surfaces are shown.

The percentage of light reflected increases very gradually up to about 45 degrees incidence. It then increases rapidly, becoming 100 per cent at 90 degrees incidence. This is shown in Fig. 10 for one smooth clean surface and for the two clean surfaces of an ordinary plain and plane glass.

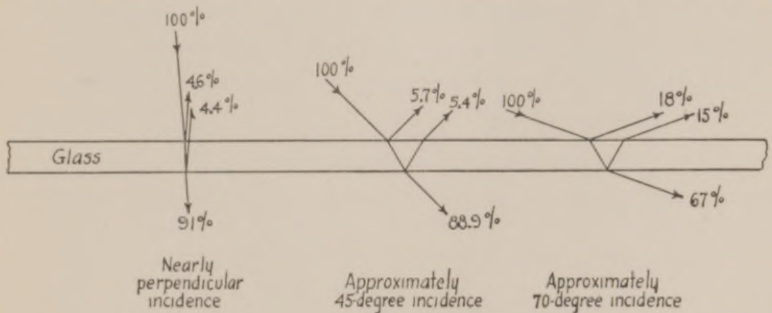


Fig. 9. Showing the approximate percentages of light reflected by the first and second surfaces of clear plane glass at three different angles of incident light. The net transmissions are shown approximately, assuming no absorption of light within the glass.

The amount of reflected light varies with the optical property of glass, known as refractive index, but this variation is a minor factor in the consideration of ordinary glasses, because of the small range in refractive index.

It is seen from the foregoing that no ordinary glass can transmit more than 91 per cent of the incident light and that at large angles of incidence (angle between the light ray and a line perpendicular to the surface) the transmission is reduced very greatly. This is a very considerable loss in daylighting equipment. Furthermore, it should be obvious that the transmission-factor of even a plain glass is less for light reaching it from many angles than for a perpendicular beam of light. For this reason in Table V the transmission-factors for various typical glasses are given for both a perpendicular beam and for light reaching the glass from a uniformly bright hemisphere, such as a uniform overcast sky. The pebbled, ribbed, and wavy-ribbed glasses are the same as those illustrated in Figs. 7 and 8. Inasmuch as the transmission-factor of a glass which is rough

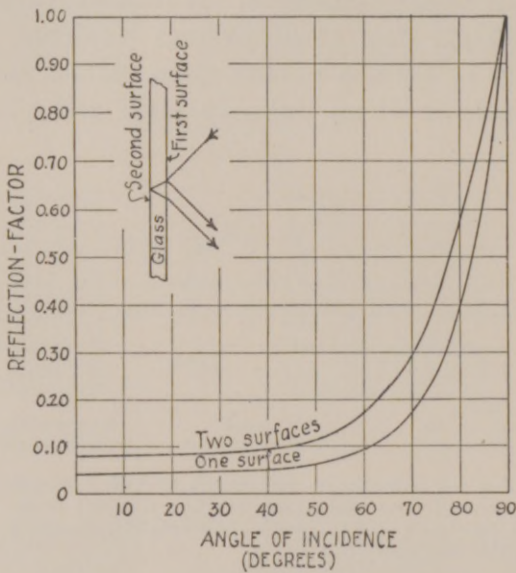


Fig. 10. Showing the percentage of incident light reflected by one and two surfaces of clear clean plane glass for various angles of incidence.

on one side (sandblasted, pebbled or ribbed on one side) is appreciably less when the smooth side is toward the light-source than when the rough side is, the transmission-factor is given for both conditions.

Other considerations being equal, ribbed, pebbled, and sandblasted glasses should be used with their rough sides toward the light-source, but unfortunately this is impracticable in many cases.

TABLE V

Transmission-factors of Typical Glasses for Direct and Diffused Light.

Specimen of glass	Side toward light-source	Transmission-factor Perpendicular beam	Hemispherical illumination
Plane	......	0.90	0.80
Sandblasted	rough	.78	.70
"	smooth	.74	.70
Pebbled	rough	.85	.75
"	smooth	.79	.75
Coarse ribbed	rough	.77	.62
" "	smooth	.52	.62
Fine ribbed	rough	.86	.79
" "	smooth	.79	.79
Wavy	rough	.88	.82
"	smooth	.86	.82

When a beam of light enters glass obliquely from air, the direction of its path is abruptly changed. The amount of this "*refraction*" depends upon the *refractive index* of the glass. Advantage is taken of this property of glass to alter the course of light rays in the making of so-called prism glass. The refraction of light by prisms of glass is illustrated in Fig. 11. Many designs of glass having pris-

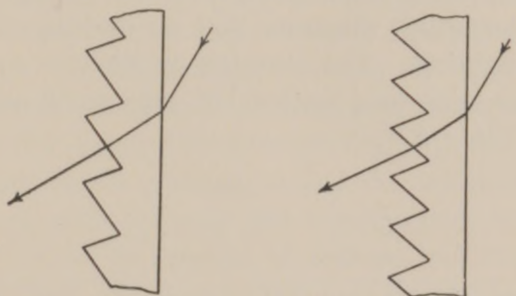


Fig. 11. Illustrating the refraction of light by a "prism" glass.

matic forms are available. When such glasses are properly designed and installed, and also kept clean, an appreciable control of natural light entering interiors is obtained. They are usually employed for the purpose of gathering oblique light from the sky and sending it in a general horizontal direction into the parts of the room at some distance from windows. Unless kept quite clean prismatic glass loses its value.

It is also possible to reflect all the light by means of glass prisms as shown in Fig. 12. After a ray of light enters glass it is totally reflected at a bounding plane if it is incident upon this plane at a sufficiently large angle. As seen in Fig. 12, the path of the light ray is altered 90 degrees

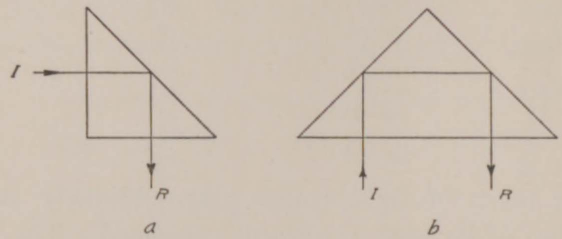


Fig. 12. Illustrating total reflection within glass prisms.

in one case and is completely reversed in the other case. This total reflection within glass has many uses in the art of lighting.

The foregoing is just a glimpse of a few important optical principles which illustrate that an optical science is involved in lighting. The cleaning of window and skylight glasses is an important matter, but very much neglected, as shown in Table XV.

Chapter IV

ARTIFICIAL LIGHT

IN preceding chapters, the salient characteristics of natural lighting have been discussed, and, before entering upon comparisons of it with artificial lighting, the development of artificial light logically demands discussion. Doubtless many readers are surprised that artificial lighting can be considered as a competitor of natural lighting. With due respect for natural light as a powerful environmental factor and an important element in Nature's world, artificial light is now superior in many ways to natural light, handicapped as it is by the shackles which man's artificial world has imposed upon it. If readers are surprised at what appears rank heresy, or at least extreme temerity on the part of the author, in attempting to discuss the merits of artificial lighting on the same level with natural lighting indoors, it must be due largely to unfamiliarity with the wonderful developments in the production and the utilization of artificial light or with the cost and handicaps of natural light indoors. For the present let us inquire into the evolution of artificial light and particularly into developments of the present century.

Fire

Fire was the source of artificial light for countless centuries. The first primitive men who utilized fire will ever remain unknown, because the early utilization of fire for heat and light began long before mankind made permanent records of his achievements. In fact, the earliest use of fire was doubtless long before man devised weapons, vessels, or tools, so that even these "records" are unavailable. From the viewpoint of this book we are not interested in speculation or even in the details of early light-sources. However, the use of fire for countless centuries, as a source of light as well as of heat, is an important factor. It is difficult to imagine primitive men as being any more than beasts until fire was discovered and utilized. It is logical to believe that the use of fire really established the earliest home and family circle.[17] A cave remained a den until fire brought light, heat, and cheer and also protection from Nature's elements and perhaps from animals. Certainly by converting a cave into even a crude home, early primitive beings took the first important step up the ladder of civilization.

For countless centuries, light from the flames of burning material was associated with cheer, comfort, and protection of home. This yellow-orange light could have had little influence as an environmental factor upon the physical and physiological processes of vision, for daylight was still incomparably more powerful in this respect. But we cannot avoid the conclusion that light of this yellow-orange tint left its psychological imprint, for it was present in homes, however crude, during thousands of years when the foundations of our present civilization were being laid. Hence, it has become a symbol of comfort, of rest, of cheerfulness, of warmth, of home. Its feeble light could not replace the powerful light of the sun and sky and make night a period of activity comparable with day. Daylight continued to be the primary light for the growing activities of advancing civilization while firelight was the light of security and comfort of the home and leisure. It is not surprising that the visual processes operate more efficiently and effectually under the high intensities of illumination with light of daylight quality. Indeed, it would be surprising if the feeble intensities of illumination with the yellowish light from flames were effective from a visual viewpoint. Nevertheless, no conception of light and its possibilities is complete without recognizing that, in some respects, the light of flames is deeply woven into the experience of evolving mankind. This is discussed further in Chapters V and VI.

Primitive Light-sources

In those earliest centuries of primitive man, just as with primitive races today, the materials of nature were burned in their " natural " state. Later, as man developed observation, memory, and reasoning sufficiently, he began to select materials which burned better and gave more light. Gradually he scoured nature for materials and then he thought of refining them. Vegetable and animal fats and oils were pressed into service of light-production. Vessels were shaped from rocks or clay to contain these fuels and a wick was devised. Receptacles of this sort are found in the earliest civilization of which we have a record. Even the origin of the candle, which is still a very convenient light-source, is obscure. It antedates the Chrisitan Era many centuries. It is a logical refinement of the principle of the early oil-lamp. It consists of a wick surrounded by hard fuel which is liquefied by the heat of the flame. It is little different in principle than the pith of a rush soaked in grease or oil. It is merely a refinement of the rush-light which still burns in the peasant homes of hinterlands.

Oil-lamps

For centuries upon centuries the light-sources were wood-fires, pine-knots, wood-splinters, oil-lamps, rush-lights, and candles. It seems incredible that civilization was to progress for thousands of years until a very recent period before these crude light-sources of exposed and flickering flames were to be radically improved. Receptacles and fuels were refined but it was not until 1783 that Argand, a French chemist, placed a chimney upon a lamp. This is said to have been an accident. He was heating a bottle over a flame and the bottom cracked and fell out. It was hot and he set it down suddenly, by accident, over the flame. The flickering flame became steady. Pondering over the matter and experimenting further resulted in his invention of the lamp-chimney. All these details of past developments seem simple to us now and we wonder why a civilization which had constructed the Pyramids, the Grecian temples, the Roman aqueducts or the Gothic churches of the Renaissance, did not invent the lamp-chimney.

The seven seas were scoured for whales to furnish the whale oil for the most satisfactory light-source of Colonial days. The pools of petroleum in the earth were hidden from mankind until Drake tapped them in Pennsylvania in 1853.

Gas Light-Sources

We begin to see some experiments in the sixteenth century which supplied the knowledge leading to the manufacture of artificial gas from coal. Murdock distilled gas from coal, piped it into his house, and had gas lighting for the first time in 1794.

This led to a period of gas-lighting by means of open flames until 1885 when Welsbach invented the mantle. It gave more light per unit of burned gas than was yielded by the open flame. This was due to a peculiar property of certain oxides such as ceria, thoria, and zirconia. If one will burn a piece of magnesium ribbon in the bunsen flame of a gas stove, a white ribbon of ash (magnesia) remains. Hold this in the bluish flame of the gas burner and it will glow brilliantly, with a brilliance quite out of proportion to its temperature. In doing this we shall have witnessed the principle of the gas-mantle and shall have repeated, approximately, the experience which led Welsbach to develop the gas-mantle.

Electric Light-Sources

Until 1800 practically nothing was known of electrical phenomena excepting that gained by rubbing a glass rod and producing a static charge. Some little work had been done along the line of stimulating electrically a leg of a dead frog, and noting that it twitched. No powerful source of electricity was available. Volta in 1800 created a sensation in the small and uncertain scientific world of that time, by announcing that a pile of plates, alternately zinc and copper, separated by means of wet cloths, was a source of appreciable current. This Volta's pile was improved and was the forerunner of the voltaic cell. Sir Humphrey Davy, by means of these "chemical" sources of electric current, extensively studied electric sparks and arcs and also obtained light by heating filaments of wire and of carbon. Here we see crude electric light-sources merely as scientific demonstrations. Their general use had to await, for more than a half century, the development of a more practicable — a mechanical — source of electricity.

Organized scientific research was now just beginning. Faraday, a pupil of Davy's, thoroughly investigated electromagnetics and the effects of cutting a magnetic field by means of an electrical conductor, such as a copper rod. He laid bare these laws between 1830 and 1840 and at the same time established the foundation upon which electric dynamos were developed a score of years later. Thus we see that all the tremendous developments of electricity have taken place in the past hundred years.

When the efficient and adequate source of electrical energy appeared about 1860, the stage was perfectly set for the development of electric lighting. Not exactly the first, but at least the best known and most accomplished, actors to appear on this stage were Charles F. Brush with the electric arc-lamp, in 1877, and Thomas A. Edison with the electric filament-lamp in 1879. They must be credited with the development of the entire lighting systems, including electric generator, distribution lines, electric light-sources. Now civilized man for the first time ceased to burn something directly in obtaining artificial light. However, the idea of burning something became so deep-seated that we still speak of burning electric filament lamps when, as a matter of fact, the filaments are not "burned" at all in the ordinary sense of the word.

From these electric lamps and the Welsbach gas-mantle which appeared soon after, lights were obtained which were whiter than the yellow-orange flames which had served mankind throughout uncounted centuries. With the development of electrical science and art, various electric illuminants appeared. These became more and more efficient. The eye demands that the quality be within a certain range, as discussed in Chapters V and VI. Furthermore, light-sources must be practicable, safe, and of reasonable sizes, both physically and as to luminous output. Thus there have been several factors which have determined the superiority of a light-source for general use.

Electric Arc-Lamps

After the generation and distribution of electricity became highly practicable, various electric light-sources appeared. The gas-mantle arrived at an opportune time to keep gas-lighting for some time in the field against electric lighting. However, it is now giving way generally to electric lighting and its future is not promising at present. The electric arc-lamp and the electric filament-lamp appeared at about the same time and, for many years, they were keen competitors. The arc-lamp reigned more or less supreme for a long time where light-sources of large luminous output and efficiency of light-production were primary factors. On the other hand, in such places as the home where smaller luminous output per light-source was desirable and efficiency of light-production was of secondary importance, the electric filament lamp was supreme. Both types of electric lamps were steadily improved.

The carbon arc was enclosed in a globe. This *enclosed arc* was more steady and the carbons lasted longer than in the earlier *open-arc*. Next certain chemicals were introduced into the carbons with an increase in efficiency. Much of the light now was emitted by the arc flame; hence, these were called *flame-arcs*. The open and enclosed arc-lamps emitted light chiefly from the hot spot on the positive carbon called the *positive crater*. Of the flame-arcs the *yellow flame-arc* was the most generally used. Finally came the *magnetite arc* or *luminous arc* consisting of a positive electrode of copper and a negative electrode which is an iron tube packed with iron and titanium oxides. This is the only arc-lamp (excepting the mercury-arc) which is playing a lighting rôle in this country. It is in use chiefly in high-intensity street-lighting but even here the electric filament-lamp is doing most of the lighting.

Mercury-arcs

Perhaps the first mercury-arc was produced by Way in 1860. He permitted a fine jet of mercury to fall from a reservoir into a receiving vessel, the reservoir and the receiver being connected between the poles of a battery. Between the drops of mercury arcs were formed. However, it remained for Peter Cooper Hewitt to develop the modern mercury-arc consisting of a transparent tube of glass or quartz from which the air is exhausted and in the ends of which electrodes are sealed. Liquid mercury covers the negative electrode. Current passing through the vaporized mercury makes it luminous. In fact, here we have the true arc. The light is lacking in red rays. In fact, the visible radiation is of very few wavelengths and, therefore, the appearance of colors generally is very much distorted. The mercury-arc is used for lighting to some extent in the industries and in photographic studios. It has many interesting special applications, particularly the quartz mercury-arc which is used for sterilization, therapy, and in many cases where powerful ultraviolet radiation is desired.

Electric Filament-Lamps

Edison's first lamps of this type and those of his contemporaries possessed a filament of carbon and it was very inefficient compared with present-day filament lamps. For twenty-five years improvements were made but it was not until 1906 that a radical increase in efficiency was achieved. Then, Dr. W. R. Whitney developed the metallized carbon filament with a surface so modified that the filament could be heated continuously to a much higher temperature than previously, with a consequent increase in efficiency of light-production. Incidentally, efficiency increases rapidly with increasing temperature, so that the scientist in light-production is on the lookout for materials or methods of treatment for filaments which will make it practicable to operate them at higher temperatures. Carbon does not melt until a very high temperature is reached, but its evaporation limits the operating temperature in a practicable filament lamp. Dr. Whitney's process retarded evaporation.

Tantalum withstands a higher temperature than that at which the carbon filament could be operated so the tantalum lamp appeared. For the same reason the tungsten filament superseded the tantalum filament. The Nernst lamp should be mentioned in passing. It was a fine achievement but too complicated to compete with the tungsten lamp.

All this time filaments were operated in a vacuum because, even in an inert gas, heat was conducted rapidly from a fine filament with a corresponding reduction in temperature and in efficiency. After Coolidge succeeded in making tungsten ductile it could be drawn into fine filaments. This led Langmuir to make a helical coil of fine tungsten wire, thereby getting the equivalent of a filament of relatively large diameter. Having found that the cooling effect of a gas did not increase as rapidly as the light-output increased from the increasing area of filament, he produced the gas-filled lamp. It had long been known that a vacuum facilitated the evaporation of the filament material and that the presence of gas pressure would greatly diminish the rate of evaporation. Thus it is seen that a combination of simple principles with the development of ductile tungsten produced the gas-filled tungsten lamp. By diminishing the rate of evaporation the filament can be operated at higher temperatures with a resulting increase in efficiency.

The tungsten filament lamp can be made of almost any desired luminous output from the tiniest spark to sources of such luminous intensities that there is little or no application for them. Tungsten lamps have been made as large as 30,000 watts and there is no reasonable limit to the size from a manufacturing standpoint. This extreme flexibility as to size, combined with the fact that the filament is sealed safely in a glass bulb, makes the tungsten lamp adaptable to a great variety of situations.

Luminous Efficiency

As already stated, luminous efficiency, expressed in lumens per watt, has steadily increased and in recent years has increased markedly. The average luminous efficiencies of electric filament lamps in use each year from 1905 to 1923 are shown in Fig. 13. Improvement was very slight for a long period up to 1906. It then increases rapidly owing to new developments. It is the recency of the great increase in luminous efficiency that has found the user of light unprepared in attitude to take advantage of lighting now possible. Certainly we can afford to use much more light now than even a few years ago. It is this increase in the efficiency of light-production that makes it possible for artificial light to compete with natural lighting indoors.

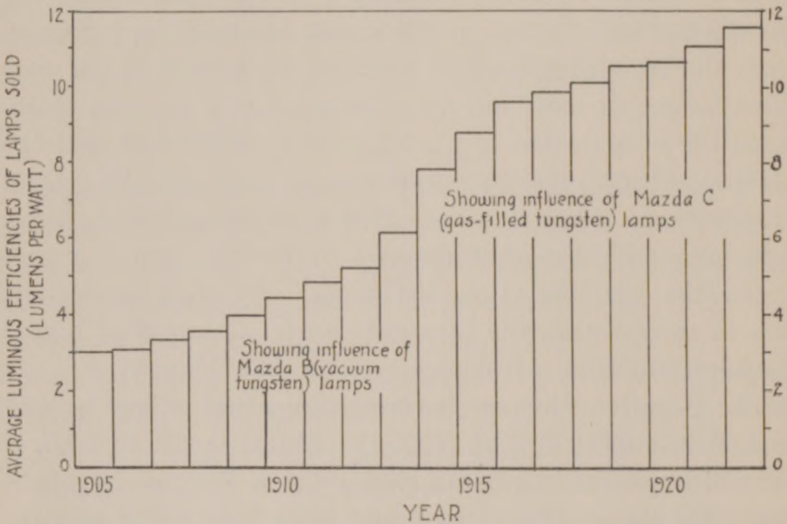


Fig. 13. Average luminous efficiencies in lumens per watt of electric filament lamps in use each year from 1905 to 1923.

Now, as never before, we can have adequate and proper lighting at a reasonable cost. It will be noted that the values in Fig. 13 are for average luminous efficiencies of filament lamps in use. The lamps of large wattage are generally much more efficient than those of small wattage. Inasmuch as the electric filament lamp is almost universally used at the present time, more details of luminous efficiencies in lumens * output per watt are of interest. These are presented in Fig. 14 for the various electric filament lamps. The efficiencies of the gas-filled tungsten lamps of various sizes are particularly interesting, so that these values are given for lamps as manufactured in 1923. It is seen that

* A source of one candlepower in all directions emits 4π lumens.

the luminous efficiency of a 1,000-watt gas-filled tungsten (Mazda C) lamp in 1923 is 7 times that of the carbon filament lamp of 1905 and about 2.5 that of the vacuum tung-

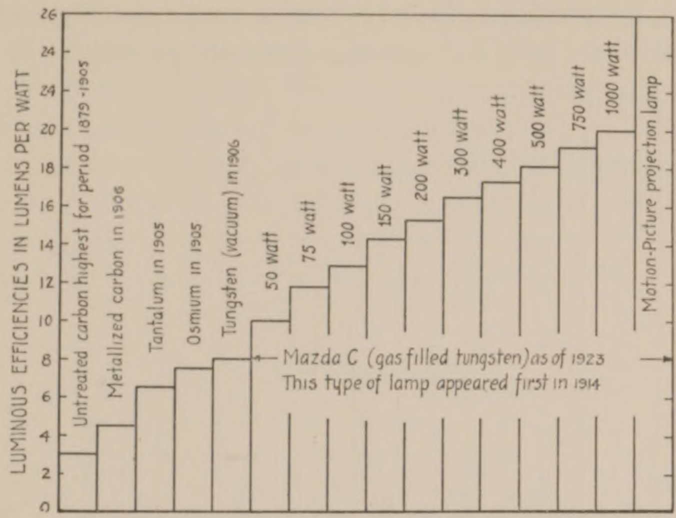


Fig. 14. Luminous efficiencies of various electric filament lamps.

sten filament lamp which appeared in 1906. The gas-filled tungsten filament lamp first appeared in practice in 1914.

Cost of Artificial Light

The attitude of the user of light toward the cost of this fundamental necessity is interesting. The householder complains of a cost for artificial lighting which does not exceed, on the average, $2.00 per month. Perhaps it is unfortunate that this bill comes regularly and clearly defined. Daylighting costs fully as much, but its cost is so completely submerged that it is not even suspected of existence. The interest on "decorative" bric-a-brac within sight of the householder, as he or she sits in comfort under artificial lighting in the evening, often greatly exceeds the lighting cost. The cost of artificial lighting for the manufacturer and the merchant also glares at them in the form of a bill, but they little realize what that artificial lighting does for them or what great costs are piled up by dark corners or inadequate general lighting. These advantages are discussed in other chapters.

It is interesting to look backward over a century and see how artificial light has steadily decreased in cost.[17] In Fig.

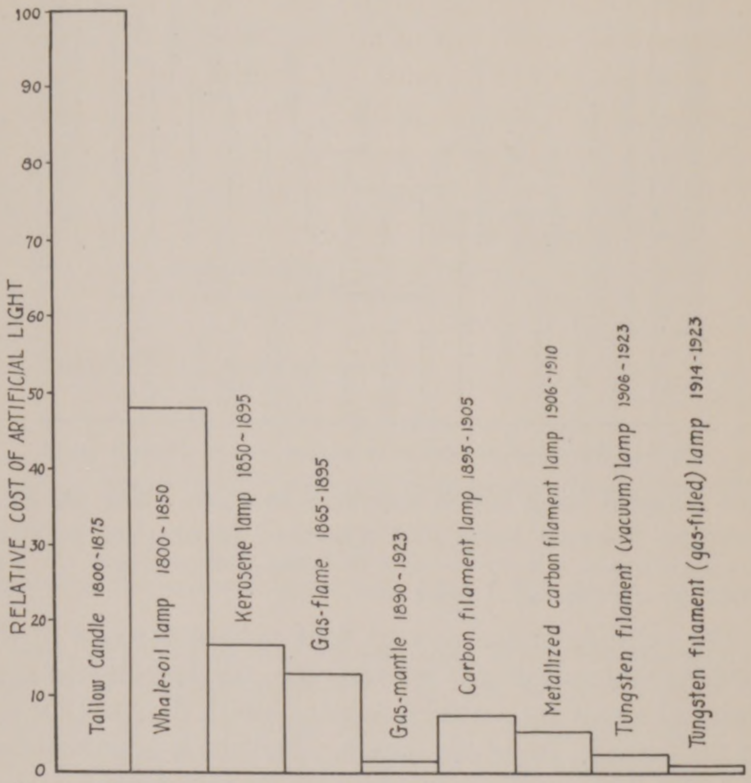


Fig. 15. Relative costs of artificial light during various periods of the past century.

15 approximate relative costs of artificial light are presented for various illuminants during the periods of their extensive use. It is seen that the cost of artificial light is now only one or two percent of its cost less than a century ago. This is a very wonderful achievement which has greatly extended the possibilities of artificial light and has made it a formidable competitor of natural light indoors in

every respect. The items which contribute toward the total cost of daylight indoors have generally increased in cost throughout the past century. Similar influences have been retarding the decrease in cost of artificial light but the scientific developments have so greatly increased the efficiency of light-production, that the net result has been a tremendous decrease in the cost of artificial light.

The great economic value of scientific developments is scarcely realized by the public. In fact, it is difficult to

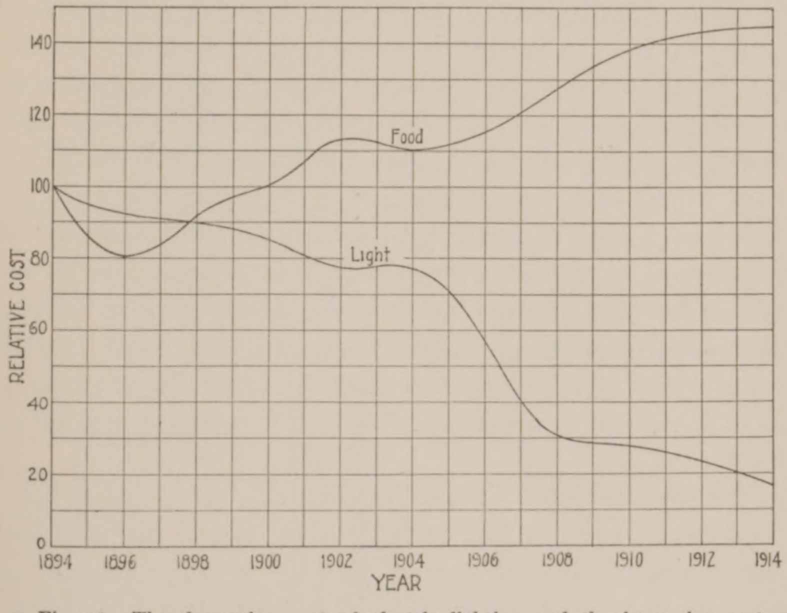


Fig. 16. The decreasing cost of electric lighting and the increasing cost of food for the twenty years preceding the World War. The war period is left out of consideration, owing to the abnormal conditions; however, it is interesting to note that the cost of electric lighting since 1914 has steadily decreased while the cost of food has greatly increased.

illustrate this value in dollars. This is equally true of lighting because there is so much value in increased safety, production, and happiness that can scarcely be appraised in terms of money. However, the relative decrease in cost of electric light compared with the relative increase in the cost of food as shown in Fig. 16 is elucidating, because the cost of food is at least a rough gauge of wages and the cost of necessities for all of us who work. The period was chosen between 1894 and 1914, the war having introduced such an economic disturbance that it seems best to stop at 1914. It may be stated, however, that electric lighting has not generally increased in cost since 1914 and everyone knows that the cost of food increased very much. The great decrease in the cost of electric lighting during the twenty years preceding the war, while the cost of food and of many other things increased steadily, is striking testimony of the economic value of scientific research. It is evidence of the benefits reaped by the consumer through the expenditures of resources by manufacturers in the development of their products. The cost of artificial light has now reached a point where adequate and proper artificial light can be obtained at a cost equivalent to a very small percentage of the payroll of workers for which it is supplied. The increased benefits of good lighting over those of poor lighting are many times the additional cost. In fact, good lighting can often be obtained for less than the cost of poor lighting. In such cases it is a matter of proper knowledge applied to the design.

The United States leads other countries in the use of light, but lighting even in this country is far below the standard that it should be. It is true that the average amount of artificial light used per inhabitant is increasing, but this increase is approximately in proportion to the decreasing cost of light. In Fig. 17 the approximate average lumens of artificial light used per inhabitant per year in this country are shown for a period of years from 1912 to 1923. During this period most of the artificial lighting has been done by electric filament lamps. Gas-lighting has relatively decreased and lighting by means of electric arcs has fallen to a very low percentage. The population of this country has been increasing at a uniform rate since 1900 and the lumens output of electric filament lamps has been increasing also at an approximately (but much greater) uniform rate. Making estimates of the relative decrease in lighting with gas and with electric arcs, the rate of increase of consump-

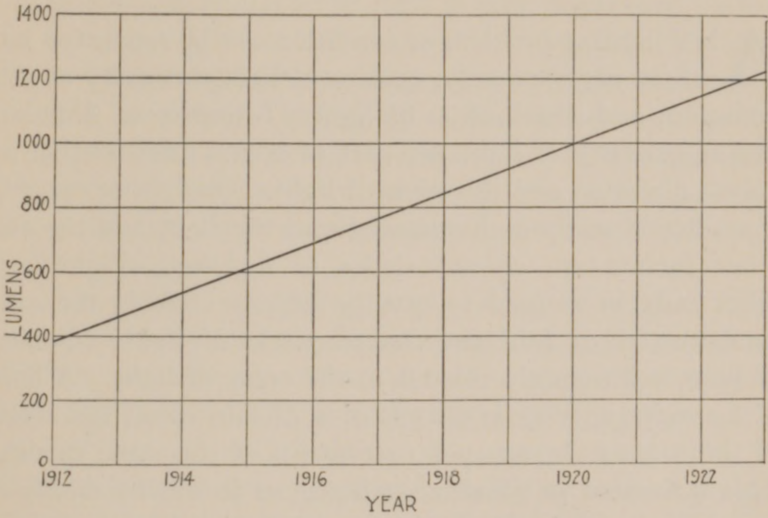


Fig. 17. The approximate average lumens of light used in the United States per inhabitant each year from 1912 to 1923.

tion of artificial light per inhabitant was found as shown in Fig. 17. It is seen that the rate for the period shown is only approximate but it can not be far from correct. The rate will become much greater as the user of light comes to realize the importance of adequate and proper lighting.

Chapter V

ILLUMINANTS AND COLOR

ANY lighting problem or condition can be separated into three parts, namely, quality of light, intensity of illumination, and distribution of light. Intensity of illumination is quantity of light per unit of area. Distribution involves direction and diffusion of light. Quality or spectral character is solely a characteristic of the *light* and the two other factors are characteristics of *lighting*. Lights can differ only in respect to quality because this is the only fundamental or inherent characteristic of light. Quality of light is intimately related to the color of light. A light of a specific quality is always of a certain color, but lights of the same color are not necessarily of the same quality. This is treated in detail elsewhere,[1] so it will be discussed here with brevity. It should be noted that the visual process is a " synthetic " process. The eye may receive visible radiations of all wavelengths from the sun, for example, by reflection from a colorless surface, and, although these radiations of different wavelength cause various hue sensations (violet, blue, green, yellow, orange, red and intermediate hues), the combined sensation is white. If we mix a blue-green light and a red light, of just the right colors and in proper proportions, a colorless gray surface will appear colorless when illuminated by this special mixture. These two white lights (the sunlight and the special mixture respectively) would be far different in quality or spectral character. This is discussed later and is introduced here only to aid those unfamiliar with the meaning of quality or spectral character of light.

This is a phase of light whose importance and effects are less obvious to the average person than intensity of illumination. Even many lighting engineers are less familiar with this aspect than with intensity and distribution. The reason in both cases is because it is less evident than intensity of illumination or distribution of light. Nevertheless, quality or spectral character of light is very important, not only in everyday lighting but also in the scientific and artistic fields of light and vision. By quality of light is meant the relative amounts of energy of various wavelengths present in the visible radiation of an illuminant, or in other words, the spectral distribution of energy in the visible spectrum. By extension, the term may be applied to the ultraviolet and infra-red regions.

This spectral distribution of energy of various wavelengths is something we do not see. If we are familiar with certain scientific aspects we can often judge the quality of light by its color. It must be determined by means of a special instrument known as a spectrophotometer.[1] The light to be studied is dispersed (usually by means of a glass prism) into its spectrum; that is, the radiations of various wavelengths are spread out into a band which we see colored progressively from violet to red as indicated in Fig. 1. The same is done for a standard light, whose spectral distribution is known. Then the intensity of radiation of any wavelength (or hue) can be measured in terms of the intensity of radiation of the same wavelength (or hue) by the usual photometric procedure. Progressing throughout the spectrum we obtain the spectral distribution of energy of the light under consideration. Thus we determine something we cannot see directly; however, if we are observant, we do see the effect of spectral character of an illuminant upon colored objects.

Spectral Character of Illuminants

The distribution of energy of different wavelengths throughout the visible region is shown in Fig. 18 for sunlight at different times of the day. At noon it is seen that the maximum energy is in the middle of the visible spectrum — the yellow-green. In Fig. 1 and Table I, it is pointed out that this is the region of maximum sensibility of the eye. It was also suggested that this is one of the imprints of daylight as an environmental factor during the evolution of man and his visual sense-organ. In fact, it is a most natural consequence of adaptation that the eye

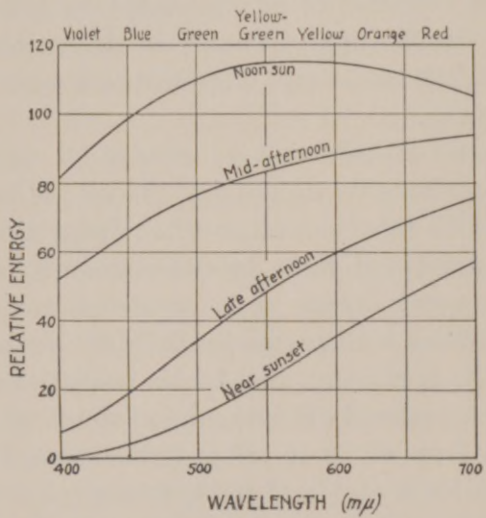


Fig. 18. The spectral character (spectral distribution of radiant energy) of the visible radiation reaching the earth from the sun at different altitudes or periods of the day. It is seen that the sun appears reddish toward sunset owing to the predominance of yellow, orange and red rays.

should be most sensitive to those wavelengths of radiation in daylight that are the most plentiful. In Fig. 1 is shown the evaluation of radiation of the various wavelengths by the eye; that is, the relative luminosities produced by equal amounts of energy throughout the range of wavelengths which causes the sensation of light. The various sensations are of different hues and brightnesses as shown by this *spectral luminosity curve*. In Fig. 18 only the relative amounts of *energy* of different wavelengths are shown for the different sunlights. This energy has not been evaluated as light by the eye. In fact, it is best to show the spectral energy distribution because it is not always the eye that we are concerned with. The photographic emulsion or any other photochemical process might be of interest, and its evaluation of the radiations of various wavelengths differs in general from that by the eye. Therefore, the spectral character of the radiation is best shown in terms of relative energy.

As the sun leaves the meridian and decreases in altitude, sunlight must pass through increasing thicknesses of the atmosphere and amounts of smoke, dust, water, and ice particles that are suspended in it. Owing to the selective transmission of the atmosphere, sunlight reaching the earth grows yellower toward sunset (or sunrise). This is well shown in Fig. 18 by the lower curves. Finally, the sun may appear quite red. Its spectral character when nearly setting is shown by the lowest curve. Thus these data not only show the change in the spectral character of sunlight with altitude of the sun but they illustrate very well what is meant by spectral character.

In Fig. 19 the spectral distributions of energy in the visible region are shown for several illuminants [1] of interest from the viewpoint of this book. The spectral character of noon sunlight is again shown for the sake of comparison and because it is approximately white light. Skylight from a clear blue sky is seen to have relatively more radiation of the shorter visible wavelengths (violet, blue, green) than sunlight. The spectral character of the light from a candle-flame is seen to be quite the converse of blue sky; that is, it has relatively more radiation of longer wavelengths (yellow, orange, red). It is much yellower than noon sunlight. The relative abundance of the yellow, orange, and red radiations in the light of the candle-flame makes it a yellow-orange tint instead of a colorless white light. It is common experience that light from the carbon filament lamp is yellower than that from a tungsten (vacuum) lamp and that this in turn is yellower than light from a tungsten (gas-

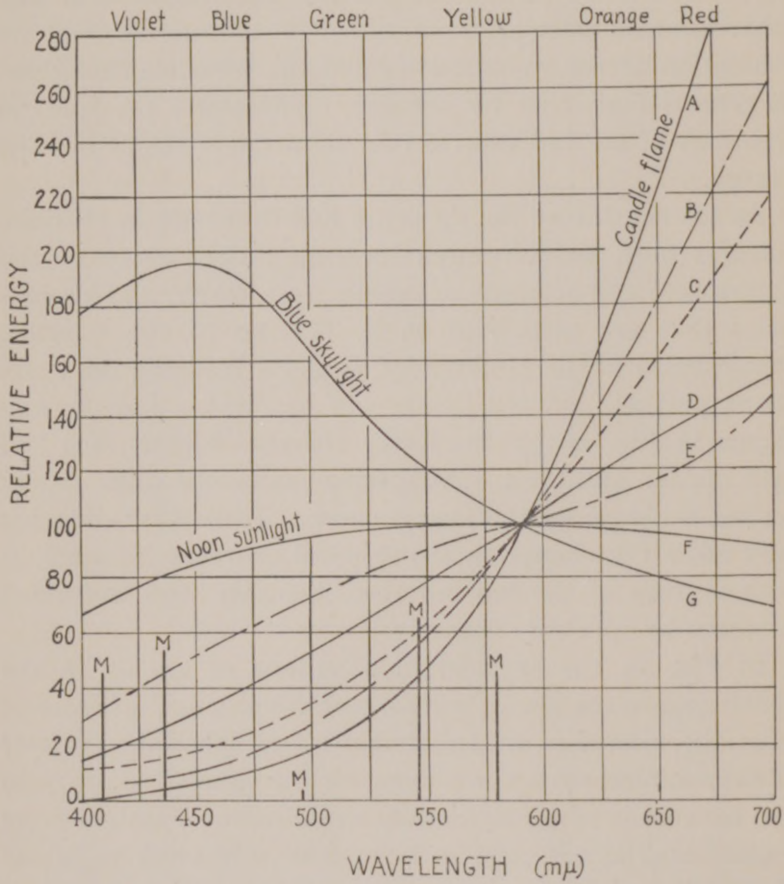


Fig. 19. The spectral distribution of visible radiation in various illuminants.

A Candle flame
B Carbon filament
C Vacuum tungsten filament (8 lumens per watt)
D Gas-filled tungsten filament (22 lumens per watt)
E Mazda daylight lamp
F Noon sun
G Blue sky
M Mercury arc

filled) lamp. These colors are matters of temperature of the filaments and the color of light emitted by virtue of temperature of the solid radiator (filament, arc-crater, etc.) is an approximate indication of the quality of the spectral character of the light. However, this is not true of glowing gases or vapors such as the arc of an arc-lamp or the vapor of a mercury-arc.

Perhaps this may be made clear by means of a tungsten wire heated by electric current. If a rheostat be placed in series with the wire and the room darkened, some current can pass through the wire without heating it to a glowing temperature. If we feel of the wire we will find it becomes warm when sufficient current flows but it does not give off light. If the resistance in series is decreased, more current flows and the wire will become hot. Still no light is given off. All this time radiation is being emitted by the wire but it is all of long wavelengths in the infra-red region, incapable of causing the sensation of light and color. As we increase the current the wire finally begins to glow a dull red. Now some of the long-wave visible radiation is being emitted but the amount of infra-red radiation has also increased. As the current is further increased the wire glows brighter and appears orange in color. More visible radiation is being emitted and a greater percentage of this is of shorter wavelengths. In other words, as the temperature of this wire is increased, relatively more radiation of shorter and shorter wavelengths is being emitted and in greater and greater percentages of the total radiation. Finally, if we could heat the wire to a temperature of the sun we would have a white light of approximately the same spectral character of noon-sunlight as shown in Fig. 19.

All this time the efficiency of the wire as a light-source increased as we increased its temperature. When it did not glow at all its efficiency as a light-source was zero and the electrical energy put into it was wasted if our object was to obtain light. The highest luminous efficiency would be reached when the temperature was approximately that of the sun and from then on the luminous efficiency would decrease as the temperature was increased. This is because at about the temperature of the sun the tungsten wire would be emitting the maximum amount of energy in the visible region. Incidentally, it is interesting to note that the temperature of the sun is approximately the most effective temperature for producing light by means of bodies which emit light by pure temperature radiation. In this connection it should be noted that the range of wavelengths of radiation to which the eye responds is the result of adaptation and the result naturally is a perfect adaptation of the sense-organ to solar radiation.

In the foregoing experiment, we have witnessed the method of light-production which is now generally used. The chief aim in this field of scientific research is to operate filaments at the highest temperatures practicable. No solids have yet been found or developed which can be heated to temperatures approximating that of the sun and still remain in the state practicable for light-sources. The temperature of the incandescent solids used as light-sources has steadily increased and this has been the chief factor in the increase in luminous efficiency.[17] The temperature in Fahrenheit and corresponding luminous efficiencies of a few of these light-sources are in Table VI. The lumens per watt corresponding to the sun's temperature as it appears from the earth is for white light emitted by a solid radiator like carbon if it could be operated at the sun's apparent temperature.

TABLE VI

Approximate Temperatures and Luminous Efficiencies of a Few Light-Sources

	Temperature	*Lumens per watt*
Untreated carbon filament	3300 deg. F.	3.0
Metallized carbon filament	3400	4.5
Tungsten (vacuum) filament	3700	8.0
Tungsten (gas-filled) filament up to	5300	10 to 26
Sun as it appears at noon	8900	(100)

It is not the intention to discuss spectral character here in detail; those who wish to go deeply into the subject will find it adequately treated elsewhere.[1] However, it is of interest to touch upon luminous gases and vapors. The preceding discussion was confined to solids which obey certain laws approximately and emit a continuous spectrum; that is, they emit radiations of all wavelengths between wide limits. In gases and vapors there is more freedom of the atomic radiators and when such materials as gases and solids are excited electrically, they emit discontinuous spectra consisting of lines and bands. Each gas or vapor emits a discontinuous spectrum characteristic of it and it alone. The individual spectrum is just as characteristic of the particular gas or vapor as a finger-print is of a human being. This forms the basis of spectrum analysis. The scientist can recognize the spectral lines of an element when it is emitting radiant energy as a luminous gas or vapor. He finds these lines in the spectrum of a star and can tell what elements exist there in a gaseous or vaporous state.

A number of light-sources have been developed in which gas or vapor are excited electrically. The Moore tube containing nitrogen was used to some extent years ago. The Moore carbon-dioxide tube emitted a white light and has been used to some extent for color-work. Some neon and helium tubes are also in use. Of all these so far the mercury-arc has been used the most extensively. Its visible spectrum consists chiefly of four lines, namely, violet, blue, green, and yellow. The latter is really a double line. These four spectral lines are designated in Fig. 19 by the letter M. The relative amounts of energy of these four wavelengths are represented approximately by the lengths in the illustration, but owing to the greater luminosity of radiation in the mid-spectrum region (see Fig. 1) about 95 per cent of the total light from the mercury-arc is due to the green and yellow radiations, the two lines. Such a light from which most of the spectral colors are absent causes almost everything to appear unnatural. Other phases of the light of the mercury-arc are discussed later.

Natural Illuminants

Daylight and its components — sunlight and skylight — have been emphasized as the natural illuminants. Of these, noon sunlight is the more powerful and represents fairly well the average quality of light throughout most of the day and year. It may be safely assumed to have been the environmental illuminant to which living things and their sense-organs became adapted. It, then, is the fundamental natural illuminant. But we should not overlook another quality of light — that from fire and other common flames — which has been associated with mankind throughout the long period he has struggled up the ladder of civilization. Viewed in this manner, the light from flames or flame-tinted light is a secondary natural illuminant. But in considering this, as has been done in Chapter IV, we must do so in connection with man's activity and its environment. During the countless centuries of civilized progress from the most primitive state of man, daylight was the period of activity and firelight was associated with home and recreation. This psychological aspect is important as shown in Chapter VI.

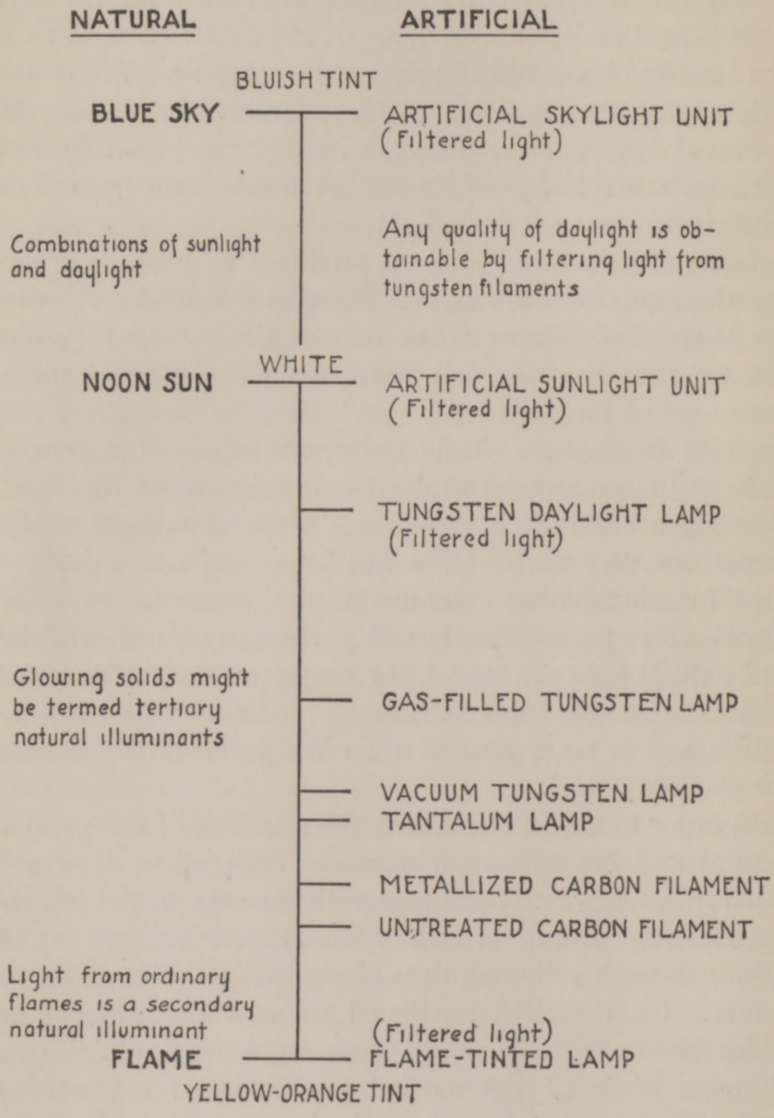
Thus we see on one end of the scale of natural illuminants the yellow-orange light of flames and at the other end blue skylight. Somewhere between is noon sunlight. All these natural illuminants are now duplicated by man so that we may have them where needed or desired. They are obtained by filtering the light from tungsten filaments through specially developed filters of permanent color. The desired quality of light is obtained in this manner by a loss of light, but the high-efficiency tungsten lamps make this method economically possible. Where light of the quality of skylight is needed and skylight is not available, artificial skylight over a small area can be obtained by properly filtering the light from a gas-filled tungsten filament lamp. Surely this small cost for an accurate substitute for daylight is justifiable. Furthermore, if the unfiltered light from the tungsten lamp will not answer the purpose we have the case of subtracting some of the rays and increasing the value of the remaining light. Artificial daylight devices are available which produce any quality of light from noon sunlight to clear north skylight.

Light of a flame tint is now produced by properly filtering the light from a tungsten filament usually by coloring the lamp-bulb. Between the natural flames and the noon sun we have the tungsten filament lamps. One of these, the so-called tungsten " daylight " lamp, is an approximate daylight in quality. It is quite satisfactory for general light and it greatly facilitates the discrimination of colors. For very accurate color-work some artificial-daylight equipments are very satisfactory but these are not ordinarily used for illuminating extensive areas. However, in many places where persons work, and particularly when artificial and natural light are mixed, the tungsten daylight lamp for general lighting is quite satisfactory. It aids color-discrimination and is more natural than the yellower illuminants for everyday work.

In order to aid in visualizing the relations of the various natural and artificial illuminants to each other, they are listed in Table VII. Beginning with blue sky at the top we progress downward toward white (noon sunlight) and thence through yellowish tints of glowing solids to ordinary flames. On the right are listed the artificial illuminants which now cover the entire scale of natural illuminants although some of the natural illuminants are produced artificially by carefully prepared colored glasses or superficial coatings.

TABLE VII

Natural and Artificial Illuminants Arranged in Relation to Each Other along the Natural Scale of Spectral Character from Flames to Blue Sky.



What is Color?

The quality or spectral character of light has already been defined. This term is also applicable to any colored light whether emitted by a light-source or reflected by a colored surface. Then, in general, all lights have a spectral character. In fact, this is the fundamental physical foundation of color. And just as the eye alone is incapable of determining the spectral character of light, so it is incapable of analyzing a color into its components. For example, a perfect yellow can be made by mixing red and green lights and this yellow will appear quite the same as an ordinary yellow. Not recognizing that the eye is synthetic as compared with the analytic ear, is the cause of many errors and lack of understanding of the relation of light to the appearance of colors.

In order to gain a fundamental understanding of color it must be recognized that the color is really in the light. The pigment or dye is merely a selective absorber. It absorbs radiations of certain wavelengths and reflects others. For example, vermilion has the physical property of absorbing most of the visible radiations and of reflecting the red rays. But it, like most colored media, reflects radiation of a certain range of wavelengths. It reflects, besides red, orange and some yellow but the integral sensation caused by these rays is what we loosely term red. It should also be noted that we can not assume that it reflects no invisible radiations. In fact, most colored media also selectively absorb and reflect the infra-red radiations but this is only of secondary importance to us here.

This vermilion pigment appears red only when there are red rays in the illuminant for otherwise it would reflect no red light. This is shown by viewing it under light from the mercury arc. It is now almost black. It does not appear red now because there are no red rays in mercury-arc light as shown in Fig. 19. Our lips are bluish black under this light because they reflect some blue and violet and a great deal of red. If there is no red light in the illuminant but violet and blue rays are present the lips, of course, appear like those of a youngster who has just eaten blueberry pie. This accounts for the unnatural appearance of our surroundings and of our ghastly appearance under the light from a mercury arc. This same process of reasoning can be applied to any colors.[1]

If we illuminate two sets of a number of colors, for example, tints of violet, blue, green, yellow, orange and red, one by skylight and the other by ordinary artificial light, we shall see that the violet, blue and green are more brilliant and colorful under the skylight than under the ordinary artificial light. The converse is true of the yellow, orange and red. A yellow illuminant brightens and enriches the colors from yellow to red and a bluish illuminant like skylight favors the violet, blue and green. The same argument applies to the complex colors. For example, purples reflect predominantly violet and red rays. Under a yellowish artificial light they appear quite reddish as compared with their appearance under bluish light. It is interesting to try these simple experiments. One will learn much of the relation of quality of light to the appearance of colors by this means.

That average noon sunlight is approximately white has been the general conclusion of those experienced in the science of color. However, I. G. Priest [23] has recently confirmed this by a thorough investigation. He found that white light would be produced by a true radiator if the temperature was approximately 8900 degrees F. He found average noon sunlight in Washington corresponded to a color temperature of 9080 degrees F.

Ideal Illuminant for Color-Work

From the foregoing discussion it should be obvious that, for color-work in general, the ideal illuminant is one which is quite neutral; that is, one which does not favor any colors. When we consider that, in a broad sense, we must distinguish between several thousand colors, and between a hundred thousand of them if their variation in shade is taken into account, the problem of color-discrimination is one that demands a proper illuminant. There is only one quality or spectral character of light that can qualify as a standard. This is a white light for it does not favor any colors. Noon sunlight on clear days does not vary appreciably in quality. It is approximately white. It is the most natural of our natural illuminants because of its overwhelming power. It can be fairly well standardized over the world because it visits all the countries concerned with color-work. However, an artificial white light can be standardized by proper color instruments.

As already pointed out, when man came indoors the sky became the source of daylight upon which he depended. But as already explained, in the northern hemisphere, north skylight is less variable in quality and intensity than light from any other portion of the sky. Therefore, color-work gravitated to north windows but even here the light is variable and often insufficient for accurate color-work. Thus the idea that north skylight was the best light for accurate color-discrimination became firmly entrenched. It is so firmly rooted that it will be difficult to dislodge. There will be cases where it is the best quality, but they will be those where violets, blues, etc. are important and where there is an advantage in favoring them. But where true appearance of one color in relation to others is desired, white light will be standardized eventually. This is now possible because artificial white light is available. For accurate color-work the color-expert should adopt artificial white light and use it exclusively. Its cost is insignificant compared with its importance in saving time, in reducing spoilage and in guaranteeing satisfactory product.

Accurate Artificial Daylight

In the appearance of colors, the distribution of light and the color of the surroundings [19] are important. There are surface effects so that light from a brilliant source of small size will cause an appearance different from light from a large source. In general, the light should be diffused somewhat and should come from a source subtending an appreciable angle at the object. This can be achieved by several artificial-daylight units in a special room with white ceiling and medium gray walls.

A color is always influenced by its environment so that the latter should be the best compromise possible. This is a medium gray. A colored area seen amid black surroundings appears relatively brighter than it actually is. Seen against white it appears darker than it is. There will be the least change in apparent brightness of the color under observation when the surroundings are equally as bright as the color. Therefore, in general, a medium gray is the best average or compromise. Besides this brightness-contrast we have color-contrast. If the surroundings are of a certain color they generally tend to induce in the color under observation, a slight color approximately complementary to their color. This is well demonstrated by placing a white or gray area in the midst of a colored field. If the color of this surrounding field is green the white or gray area will be seen to be tinged with a purplish color.

Furthermore, we must contend with after-images. If we look intently at a bright color for a few moments and then look away at a white or gray surface, we shall generally see an area, the size of the bright color, tinged with a complementary hue. If we look at a blue sky for a few moments and then at some colors, they will appear different than they do a little later. The effect of after-images in ordinary color-work is of relatively short duration — a matter of seconds — but when comparing two or more bright colors by looking from one to the other, the effect is noticeable. These aspects of light, color, and vision have been discussed in detail elsewhere.[1]

If only a small spot is to be illuminated, a single artificial-daylight unit is satisfactory. However, for the best discrimination of color, the intensity of illumination should be much higher than is usually found under ordinary artificial lighting conditions. It should be at least 50 foot-candles if possible. In fact, here is a phase of vision where we should obtain the highest intensities practicable, for the eyes should be working under conditions as normal as possible. Although the quality of skylight varies owing to changing sky-conditions, much of the variation of skylight entering a window is due to the changing lighting of the adjacent buildings due to variation of direct sunlight. Furthermore, colored surfaces such as brick walls, at one moment in direct sunlight and at the next in shadow, cause much uncertainty in fine color-work. Satisfactory artificial daylight can be obtained over an area for one worker by means of a few hundred watts. Thousands of these lighting-units are now serving in a great variety of industries involving accurate color-discrimination.[28] Many operators and expert colorists are now independent of daylight which is very uncertain for color-work demanding accuracy. Accurate artificial daylight is now in use in textile mills, stores, cigar-factories, color-factories, paint-shops, garment-factories, cotton-exchanges, fur-industries, color-printing, art-studios, metal-work, refineries, chemical analysis, laundries, paper mills, flour-mills, sugar-refineries, jewel-shops, dentistry, microscopy, medical examination, surgery, woodwork, and in a great many other places. Any industry or human activity calling for the discrimination of color has uses for artificial daylight. Only a few of the different types of artificial-daylight units which have been placed on the market have been scientifically correct. The others have been makeshifts, or impracticable, or far from correct. These naturally eventually disappear from the market, but before they do many of them have found their way into the industries. An accurate artificial daylight is invaluable in many human activities; a spurious one is worse than none.

Approximate Artificial Daylight

The luminous efficiency of our practicable light-sources of the present time is not sufficient to produce accurate artificial sunlight for general lighting at a reasonable cost. However, in a machine-shop all the machinists do not need the finest set of calipers. Their work and their ability do not demand them. So it is with accurate artificial daylight. All workers do not need such an illuminant, but most of them would find advantage in an illuminant which approximated noon sunlight or average daylight in quality. For these reasons the tungsten daylight lamp was made available. Its light is a long step toward noon sunlight and everything appears more natural in proportion to this step toward noon sunlight. Millions of these lamps are in use and there is adequate proof of their desirability.

Few persons who have not studied the subject, realize how much we unconsciously depend upon color in our everyday work. If we carefully study our surroundings or our work we will recognize that color plays an important part. Woods, metals, fabrics, papers and almost everything possess color. In fact, it is difficult to find something that is colorless. For example, we may think a "white" powder is colorless but stick a finger into it and withdraw it. The hole will generally appear decidedly colored. The light entering the hole is trapped and reflected many times. Each reflection colors it slightly until it assumes a conspicuous tint by multiple reflections. A gold-lined goblet appears of a reddish color for the same reason.

Many examples of costly spoilage are found which would have been eliminated even with the tungsten daylight lamp which is designed to give a light as near to average daylight for general lighting as cost of light will permit. It has been in existence for ten years and has invaded many fields of human activity. It is useful not only where color-discrimination is important but also where daylight must be reinforced by artificial light. Here the reduction in color-difference between the two illuminants is satisfying. The dominant directions of natural light and of artificial light are generally quite different. In such cases a marked difference in the color of the lights is very noticeable and quite annoying. This annoyance is much less when the two lights have the same general dominant direction as is the case of the artificial-lighting luminaires being hung under a ceiling skylight through which the daylight enters. Inasmuch as most daylighting is done by windows in the walls and artificial lighting by luminaires overhead, this unsatisfactoriness due to the two lights being different in color is quite common.

Chapter VI

QUALITY OF LIGHT AND THE HUMAN BEING

THERE is a growing conviction in many quarters that the ideal illuminant from the viewpoint of the efficiency of the human being in everyday work, is white light or one approximately white. If we are to give due weight to the influence of adaptation to environment, certainly we cannot avoid the conclusion that light of a daylight quality — whether natural or artificial — is the ideal toward which to strive. Fortunately this is the tendency in light-production by the method of heating solid bodies, because as the efficiency increases a natural step toward white light is achieved. In practically all tests of the relation between the quality of light and the desirability of the light, it is found that the whiter light is chosen for work-purposes. Naturally many would like to know why this is true. To many of these the explanation involving evolution of the sense-organ and of the attitude of the human being toward light is not convincing. Perhaps, here and there, we may find a more material or a physical or an optical reason, but in the main the author believes that the most powerful and reasonable explanation is that of adaptation. This should be convincing to those who have an adequate conception of the invulnerable position that this principle has attained in the biological and psychological realms. We have not attained breadth of view in regard to man and his relation to the world in which he lives, until we recognize the great importance of physiological and particularly of psychological phases of the human being.

Nature's lighting has influenced us physically by having to do with the development of our physiognomy and of the physical properties of the eye-media. It would take countless centuries of slow adaptation to other lighting conditions to alter these physical characteristics so that they would be more suitable to the new regime of lighting. The physiological processes of vision are also a product of adaptation and doubtless would be altered very slowly to the new lighting. Our mental attitude, or more broadly the psychological phase, is more susceptible to change. On every hand we see changes taking place within the short period of our lives. Furthermore, it is in this psychological realm where man differs from other animal life very much more than in the other more permanent or more enduring realms. We must take this into account in any broad and deep consideration of lighting. In doing so we iron out apparent inconsistencies and this is what any successful explanation must do. Our imagination cannot picture primitive man beginning his journey up the ladder of civilization without fire. Taking into consideration his use of fire and of its light and the conditions of its use, it is easy to conclude that this illuminant became *natural* to him under *certain* conditions which are responsible for *certain* associations and attributes. This phase of natural illuminants has been touched upon in Chapters IV and V and is further analyzed in the present chapter.

Light of Natural Quality

Where the discrimination of color is involved there is no doubt of the superiority of light of a white quality. This is subject to demonstration just as it can be demonstrated that it is better to eliminate color-difference when daylight and artificial lights have different dominant directions. However, further questions arise. What quality of light is best where color-discrimination is not involved? What quality of light are we inherently best adapted for? These are questions which will be completely answered eventually by research. We now have some data, a great deal of experience, and certain logical philosophy. In viewing this aspect we should think of an average normal person as two beings psychologically. He is a *day* and a *night* being. With day and daylight, work and serious vision are associated. During the day we expect adequate intensities of light of daylight quality. This expectation is really an unconscious demand inherited perhaps from each ancestor of the long line of them extending far back of the veil of unrecorded history. This expectation or unconscious demand is fostered from the moment we begin to record experiences in early infancy. It becomes a most natural part of our lives and activities.

Day with its high intensities of light of daylight quality is the dominant period of serious work. Our *esthetic* self is submerged by our *working* self. Night is quite the reverse for the average normal person. This is a period of rest and recreation in which the esthetic self may come forth. We may sit in the comfort and cheerfulness and restfulness of home or we may actively recreate. But in all this we have the spirit of home with which has been associated for countless centuries the yellow-orange light from flames. This color of light has been indelibly stamped upon us as "night" beings. If our visual sense-organs are normal or at least not radically defective, our night self predominates and demands the color of light of home — that of flames. In the case of weak or peculiarly sensitive eyes, there is a natural demand for light of daylight quality, for this was the great overpowering environmental light to which the sense-organ became best adapted. Then for the present we will assume that for a perfectly healthy, normal visual sense, the psychological aspect of artificial light of the warm tint of flames dominates in our night environments indoors, at least when we are not engaged in work so serious that our esthetic self is completely submerged. However, for the moment let us consider our " working " or " day " self in which the serious business of doing our part in the world's work is dominant.

The meager data which we have on eye-fatigue and vision, in general, indicates that light of a daylight quality is more favorable to prolonged visual activity than light of other quality. In fact, there is an indication that light becomes generally more and more favorable as the quality approaches white. For example, for serious visual work in which the esthetic sense plays little or no part, as we increase the temperature of a tungsten filament the quality of light improves. Of course, all other conditions are assumed to remain constant. Such a result is to be expected unless we are willing to admit that, only in the case of daylight as an environmental factor in evolution, the well established principle of adaptation fails. This the author cannot do; however, it is well to ascertain, if possible, whether or not actual data support the logic of the principle of adaptation.

For one entire winter the author experimented with lights of different quality for serious work. At one end of the series was approximate daylight from the tungsten daylight lamp and at the other was a deep yellow-orange light. Between these were several steps of yellowish lights of the natural qualities of incandescent solids of different temperatures. In order to eliminate the " night " self or the dominance of the esthetic self, the experiments were conducted only while the author and another adult were engaged in the concentration of writing and computing attendant scientific and technical books and articles. Under such conditions one becomes quite oblivious of surroundings and of the spirit of comfort and cheerfulness of home. In other words, such concentration tends to keep the " working " self dominant. Without any question the results pointed with favor to that illuminant which approached nearest to daylight in quality. The desirability of the different illuminants decreased with increase of yellowishness.

A more recent experiment performed with about 35 intelligent persons seemed to be conclusive for the conditions of the experiment at least. The observers were persons engaged chiefly in clerical or laboratory work and none had any special interest in the question involved in the investigation. Without going into detail it may be stated that the research was conducted in the approved manner of psycho-physiological researches in which extraneous influences, suggestion, and prejudice were guarded against. The visual process chosen was that of reading black print on white paper such as the *Saturday Evening Post.* The surroundings were plain, ordinary, and practically neutral in color and played no important part in the results. The illuminants used were Mazda C (gas-filled tungsten) lamps with colorless bulbs and Mazda " daylight " lamps operating at their normal voltages. The light in both cases was equally diffused and distributed to surroundings and reading matter in the same manner. Thus, there was only a difference in quality with the single exception of intensity of illumination. The " daylight " lamps emit only about two-thirds as much light as the clear-bulb lamp of equal wattage. In order to make the investigation of the most practical value *equal wattages* of the two kinds of lamps were used. This made the intensity of illumination from the " daylight " lamps always only two-thirds of that from the regular clear-bulb lamps. This is not only a practicable aspect from the viewpoint of cost of light, but it was thought that if there was a tendency for superior quality to overcome inferior illumination intensity the results would be convincing.

After a preliminary period of adaptation of the subject to the conditions, he (or she) was requested to read under a certain level of illumination from one of the illuminants. A change from one illuminant to the other could be made at the will of the observer as desired in order to obtain a comparison or judgment. It will be noted that in reading the black print on white paper amid neutral surroundings the problem of discrimination of color did not enter at all. Here was a comparison of desirability of quality, pure and simple, although the factors involved in the chain of events from the stimulus to the retina to the brain and finally to consciousness need not be analyzed here. Notwithstanding the handicap of a lower intensity of illumination, the quality of light emitted by the Mazda daylight lamps was preferred by a majority of the observers as shown in Table VIII.

TABLE VIII

Results of an Investigation of the Preference of a Group of Observers for Two Illuminants, namely that from Regular Mazda C lamps and that from Mazda Daylight Lamps.

Experiment	Foot-candles		No. of Observers	Percentage Preferring Mazda daylight
	Mazda C	Mazda daylight		
1	0.75	0.5	28	75
2	6.0	4	34	62
3	13.5	9	32	54
4	21.0	14	32	54
5	28.5	19	34	77

Five levels of illumination were used and the observers were the same throughout. The research extended over most of a year and the matter of memory was easily eliminated. The levels of illumination extended from 28.5 foot-candles to as low as 0.75 foot-candles for the Mazda C (gas-filled) lamp and respectively two-thirds of these values for the Mazda daylight lamp. It is again emphasized that the latter gives only approximate daylight as explained in a preceding section.

The most significant result is that the majority in all cases preferred the light from the approximate daylight quality over that from the regular gas-filled tungsten lamp even with the handicap of *equal wattage*. No great weight can be given to the variation of the percentages in the last column but it is extremely interesting to find that even a low intensity as 1/2 to 3/4 foot-candles, where *light* might seem to be of more importance than its *quality*, the Mazda daylight lamp was favored by three out of four persons.

Another experiment was carried out whose results even more emphatically favored the light of approximate daylight quality. It has been commonly observed that mixing ordinary artificial light with natural daylight, differing both in direction and quality, is unsatisfactory, particularly when the quantity of one was of the same order of magnitude as the other. The same set of intensities was used, from the same two overhead sources (Madza C and Mazda daylight lamps of equal wattage), but at all times 4 foot-candles of natural daylight from the sky through a window at the left illuminated the reading matter. The results are presented in Table IX.

TABLE IX

Showing the Preference of a Mixture of Approximate Artificial Daylight with Natural Daylight over a Mixture of Light from Equal Wattages of Tungsten Gas-filled Lamps with the Natural Daylight.

Experiment	Foot-candles Added to 4 Foot-candles of Natural Daylight		No. of Observers	Percentage Preferring Mazda daylight
	Mazda C	Mazda daylight		
6	6.0	4	32	75
7	13.5	9	36	67
8	21.0	14	36	72
9	28.5	19	36	89

These results show that the light of approximate daylight quality from Mazda daylight lamps is more favored than even the greater amount of light obtained from Mazda C lamps of *equal wattage*. From previous work it has been proved that, within the range of intensities considered here, persons engaged in reading favor more light in each case if it is available. Therefore, it appears to be well established that, for equal intensities of light from Mazda C and Mazda daylight lamps, the latter light which approximates daylight in quality meets with decidedly more favor than the former for close visual work, assuming, of course, that general conditions are approximately the same.

The results of long experience are valuable to the individual and through them he is guided in practice. Data on the influence of quality of light on us as human beings are very difficult to obtain. Not only is this psycho-physiological realm a trying one for the investigator, but in most cases there are overwhelming difficulties in obtaining a sufficiently large group of subjects who will devote themselves to the ordeals. Furthermore, in this particular field the results obtained from only one or two observers are often unconvincing, owing to the great variation among human beings in their reactions to light. However, the weight of evidence is bound to accumulate with experience and such is the case with the author during many years in this field. These indefinite data will not be convincing to many so that they will not be discussed in detail.

Throughout the past ten years or more, many cases of individuals with over-sensitive eyes have come to the author's attention. Usually the statement is made that artificial light "hurts" their eyes. Knowing how careless most persons are with artificial light, one is always justified in assuming that there is improper distribution, lack of shading or diffusion, or insufficient intensity. However, after eliminating these factors we have plenty of evidence that many persons cannot read with comfort under ordinary artificial light at night who read with comfort under artificial daylight. In most of these cases the approximate daylight from the tungsten daylight lamp is satisfactory. The testimony in this direction is plentiful and authentic.

This leads us naturally to a seeming contradiction but which disappears on analysis. Many persons express dislike for the " white " light from ordinary tungsten lamps and speak in glowing terms of the warm yellow tint of flames or firelight. In the first place, they only *think* the former light is white for it is quite yellowish compared with sunlight or skylight. The same persons make no complaint of the whiteness of daylight during their period of work or serious activity. This inconsistency rules out of consideration the complaint against the " whiteness " of ordinary artificial light unless we recognize that man is psychologically a different being by day than he is at night. Evidence on every hand strengthens this conclusion. Usually this complaint of " whiteness " of ordinary artificial light arises in the home or in environments having the home atmosphere. The period of work has passed and the esthetic self comes forward as already suggested. Now the human being rests, or wants to, even while engaged in definite activities such as reading, sewing, etc. Even in these pursuits the factor of recreation is prominent. After our work-day, our interiors are havens of comfort, recreation, and cheerfulness. Firelight has ever been a symbol of such havens. We cannot easily overcome this instinct for light of warm tint. Of course, there are unsensitive beings to whom this is piffle, but their process of thought and their outlook on life which have made them unsensitive to the esthetic world have also made them so unhuman in so many ways that their opinions are of little moment in comparison with those of *human* beings. Persons who are not developing in a normal manner psychologically are at the rear of the parade of human progress.

On the other hand, super-esthetic persons are interesting subjects. To them firelight is full of charm and ordinary artificial light is garish and harmful. They declare emphatically that the latter hurts their eyes terribly and that they cannot stand it at all. After due analysis and argument one is generally able to conclude that the whiter lights hurt merely their esthetic self but this self is so dominant they think that the light is really physiologically harmful. These same persons actually enjoy full daylight in their summer garden without even a thought of its real whiteness.

It is hoped that these few glimpses of the psycho-physiological effects of light may aid the reader in understanding and particularly in analyzing this complex aspect of light and lighting. The author firmly believes that his assumption of two different beings or attitudes for each normal person is in general correct. Certainly, it explains many observations and irons out some apparent inconsistencies. Long experience and observation have established this conviction and as already stated much of the data is of that indefinite nature which cannot be transmitted to others without laboring far afield.

Light of Unnatural Quality

From the preceding discussions and Fig. 19, it is seen that the chief characteristic of a *natural* illuminant is a continuous spectrum in which visible radiations of all wavelengths within this spectral region are present. There is a great difference between the actual distributions of these radiations throughout the visible region for sunlight and candle-light. But it has been noted in Table VII that the various electric filament lamps take logical places in the series between candle-light and sunlight. These artificial illuminants are due to glowing solids of various temperatures and in a sense arrange themselves in a natural scale as to color. In fact, their color is not conspicuous because of this degree of naturalness. Doubtless, the reader will recall the artificial illuminants which seem unnatural. The gas-mantle after it has been in use for some time assumes a greenish tinge. This is noticeable and has attracted unfavorable comment. However, a redeeming feature of the light from a gas-mantle has been its continuous spectrum; that is, the presence of all wavelengths of visible radiation. It is greenish because of the presence of an abnormal amount of radiations of wavelengths in the green region of the spectrum. However, the light from the gas-mantle is only tinged with " unnaturalness," and having a continuous spectrum it passes muster in any group of illuminants.

The only radically unnatural illuminant in appreciable use at the present time is the light from the mercury-arc. Its total light is bluish white; that is, a gray or colorless surface will appear bluish when illuminated by its light. However, its quality or spectral character as shown in Fig. 19 consists of four principle lines M in the visible region and to two of which, the green and yellow (double), more than 90 per cent of the total light is due. Thus this light is almost as " unnatural " (in the sense of the term as used in this book) as an illuminant could be. The least natural would be one that had a single line in the extreme portions of the spectrum, say, red or blue. Incidentally this would be known as monochromatic light because the light is confined entirely to one spectral hue or line. Therefore, mercury-arc light approaches monochromatism to the extent that the total light approaches in spectral character a very narrow band of a single wavelength. Such a light is bound to have peculiar properties and, therefore, a brief discussion of these is presented.

Perhaps the most noticeable characteristic of mercury-arc light is the peculiar and unnatural appearance which most colored areas assume when illuminated by it. As discussed in a previous section, red objects appear practically black because this light has no orange and red rays in it. It is certain that we would not illuminate everything with a blue light or a green light made by coloring tungsten-lamp bulbs, for example. Fortunately, there are sufficient blue and violet rays in the mercury-arc light, which when mixed with the green and yellow rays give a gray or colorless object a bluish color not differing radically from white. This makes the light from the mercury-arc endurable even though it causes most colors to appear unnatural.

Owing to a certain shortcoming of the eye (chromatic aberration), very fine details near the limit of visibility are seen under monochromatic light at a somewhat lower intensity of illumination than in the case of ordinary light. Dr. Louis Bell [20] and later the author [1] studied this matter thoroughly. It was found that at the limit of visibility, the revealing power of mercury-arc light is superior to sunlight or any light of extended spectral character but that this advantage decreases as larger details are considered. The advantage rapidly decreases as the intensity of illumination increases. It practically disappears for ordinary visual activities such as reading under adequate illumination intensity. Very seldom do we call upon the eyes to distinguish details so small as to be near the limit of visibility. The engraver, for example, is engaged with finest detail more of the time than most other persons; still, engravers often prefer light of a daylight quality. In one of the largest printing establishments in this country where mercury-arcs are used in some parts of the printing plant, the engravers use natural and artificial skylight. The advantage of monochromatic light has been over-rated by ignoring the fact that we generally are not required to distinguish very fine details near the limit of visibility for the particular lighting conditions. Of monochromatic lights it is fairly well established that, for the normal eye, those yellow and green regions are the best from the viewpoint of visual acuity. The mercury-arc is fortunate in this respect because most of its light is due to the green and yellow spectral lines.

There are many special applications of mercury-arc light but it is questionable whether or not a group of workers should be subjected to the unnaturalness of appearance of themselves and surroundings. In special cases a light of such peculiar properties can be utilized for revealing certain things. However, the advantage of such light can best be determined by experiment, although a knowledge of the science of color helps in making predictions.[1] Some claims have been made to the effect that reaction time is less under mercury-arc light than it is under other illuminants; however, the data are not convincing because of the insufficient number of observers and for other reasons. With great respect for the wonderful achievements represented by commercial mercury-arcs, the author believes their place in the world's work is in very special applications and not for general lighting where large numbers of persons must be subjected to the psychological influence of unnatural appearance of people and of their surroundings. Certainly this question should be settled if possible by very careful research involving many workers.

We are subject to influence by our environment. No person even though he has the ability to observe, to think and to remember can wholly resist his environment. This is contrary to the principles of adaptation. It seems reasonable that a person cannot remain unaffected by the ghastly appearance of his co-workers under mercury-arc light. It seems reasonable to expect that depression or distortion of some kind might arise from the general unnaturalness. It seems reasonable that one's idea or appreciation of color would be distorted after hours each day spent in such an environment. All these factors can be studied but the amount of work involved would be very great. One is not encouraged to do this when he is fortified with illuminants which are in the natural scale and with the logic that mercury-arc light is too radically different from natural illuminants to assume the responsibility of using it, when there are no prominent advantages of cost or of general visibility.

There had been so much discussion of the advantages and disadvantages of a light approaching monochromatism, that a simple experiment was devised to see how much light a reader would choose of two radically different qualities.[22] A box with a bottom of diffusing glass and containing gas-filled tungsten lamps was hung overhead by the side of a mercury-arc. Brightnesses of visible portions of light-sources were of the same value and the distribution and dominant direction of light were practically identical for the two illuminants and the surroundings were neutral. In other words, all conditions were identical excepting quality or spectral character of light. The reading material was in all cases black print on white paper. After an adaptation period of reading at a selected intensity of illumination, the reader was permitted to change the intensity of illumination as desired. For each experiment with the two illuminants a certain maximum intensity was obtainable. These maximum intensities were 10, 30, and 45 foot-candles. The condensed data of the investigation are presented in Table X.

TABLE X

Choice of Intensities of Illumination of Lights from Mercury-arc and Gas-filled Tungsten Lamps.

Test No.	Number of Observers	Maximum Foot-candles Obtainable	Average Foot-candles Chosen	
			Mercury-arc	Gas-filled Tungsten
1	22	10	6.3	5.3
2	55	30	14.2	12.7
3	24	45	16.9	16.1
4*	26	30	18.0	17.4

* In this case the paper was dyed gray of 41 per cent reflection-factor.

It is seen that there is no marked difference in the intensity chosen. It seems likely that if one illuminant was very much superior to the other in promoting visibility, less of this light would generally be chosen in comparison with an illuminant of inferior quality. As the maximum available intensity increased the average illumination chosen also increased. Why the maximum intensity was not chosen may be explained in the following manner. Before beginning the investigation, which ran for a period of several months, it was expected that a subject would likely choose an illumination somewhere between the maximum and zero. Not knowing what was the underlying object he might think that the best condition was somewhere between the maximum and minimum available. However, there was no way to avoid this and besides the same attitude applied to both illuminants. The observer made his choice of illumination for each of the illuminants for only one available maximum illumination at a setting. He was tested for the condition of another available maximum sometimes weeks later. Considering this method of procedure, the large number of individuals, the several different " sittings " of each individual, the large total of observations and the fact that he could make his choice of illumination for each illuminant as he desired, it is surprising that there is no marked difference in the average choice of illumination for the two illuminants when their maximum available intensities were the same. If there was a marked difference in the " revealing power " of these two illuminants the results should have shown some indication of it. Besides showing no marked difference in the choice of illumination intensity, the results indicate that there is no marked advantage of mercury-arc light in promoting visibility of details like reading matter under adequate illumination intensities, and that there is no low limit of desired illumination intensity. It will be noticed that slightly more mercury-arc light was chosen on the average than light from gas-filled tungsten lamps.

CHAPTER VII

QUANTITY OF LIGHT

ILLUMINATION intensities have been discussed here and there in preceding chapters but they will be discussed briefly here more specifically, even at the risk of some repetition. In the matter of intensity of light we have a curious anomaly — perhaps we should say inconsistency — in human activities. As has been pointed out, we have enormous intensities of illumination outdoors during the day, but our lighting at night is very close to the other extreme — darkness — by comparison. Still we often hear complaints of " overlighting " and " too much light," when the actual intensity of illumination is only a few foot-candles. The same intensity on our porch a half-hour after sunset seems feeble indeed and unless our book is particularly fascinating we lay it down to await the artificial-lighting period indoors. When we go into the house some time later, we may find a condition which sometimes arouses the complaint of " too much light." Measurements would show the extreme folly of the remark, but there is another way of doing this. If the room is well lighted in the daytime, turn on the artificial lighting and its influence on the illumination intensity will scarcely be noticeable. If it cannot make its influence felt upon this well-daylighted interior it would be insignificant in competition with the daylight outdoors which is hundreds of times more intense than the daylighting indoors upon which it could scarcely make an impression. The truth is that glare from unshaded lamps and undiffused light is confused with quantity of light. It is also interesting to note that fine work generally is located near windows in factories and elsewhere. In actual practice we cannot obtain too much light indoors if the lighting conditions are proper. Nearly every visual law shows that the efficiency of the eye, or at least its ability to see, increases as the intensity of illumination increases up to hundreds and even thousands of foot-candles.

The Sun as a Light-Source

In many respects the aim of human progress is either to improve upon or to become independent of Nature. Owing to the inadequacy of daylight indoors in many places in our congested cities, electric lighting is a great improvement over natural lighting, but when we think of the sun as a light-source, and of the intensity of illumination which it provides over one-half of the earth's surface constantly, the accomplishments of mankind in lighting are feeble indeed. There is such a general misconception of the relative intensities of natural and artificial light that the overwhelming intensity of sunlight compared with ordinary artificial lighting intensities cannot be over-emphasized. As has been pointed out, the luminous intensity of the sun is over two billion billion billion candle-power as measured at the earth. All the artificial light ever made by mankind dwindles to an insignificant spark by comparison. No adequate conception of this enormous luminous intensity can be obtained from the bare figures; however, we may put it in terms of the earth's population of about two billion beings. If we gathered the earth's population into one group and gave each person a billion lamps of a billion candlepower each we would have an aggregate light-source which would compete with the sun in luminous intensity. Even now we cannot conceive the magnitudes, so let us try again. If the present rate of manufacture of artificial light-sources were increased a billion times it would still require 100 million years to accumulate enough lamps for their combined candle-power to compete with that of the sun. Such figures may shock us into a realization that there is no danger of over-lighting this earth with the feeble facilities of mankind at the present time.

Now let us approach the matter differently by eliminating the great distance of the sun and consider illuminating the surface of the earth from a reasonable earthly distance by means of lamps contained in perfect reflectors. Suppose we distribute the population of the earth uniformly over its surface. Each person would alone occupy a 1700-foot square. If present-day, 1000-watt tungsten lamps were used and all the light were reflected toward the earth, each 1700-foot square would require a million 1000-watt lamps to illuminate it to an average daylight intensity during midday. In other words, each person on the average would have to manufacture one million 1000-watt lamps every 1000 hours, or 25,000 lamps each day.

Artificial Lighting and Decreasing Cost

Such figures are staggering but they show what a job mankind has to accomplish before he is going to have the earth overlighted. Of course, the comparison is unfair because outside of streets and a few other places mankind is interested only in lighting indoors. When we consider our indoor world we have an area considerably shrunken as compared with the earth's surface. The lighting expert has been conservative and has had his eye on costs. Perhaps his attitude, even though it has been a fair one, has not been best for mankind. His recommendations for general lighting indoors average only a few foot-candles. He realizes that adequate artificial lighting became possible only recently and that he must contend with the inertia of the people who not long ago accepted the light from candles and have not broken the habits of those relatively dark ages. In one-half century light-sources have developed from feeble flames to sources hundreds of times more powerful.

The cost of light has decreased so enormously that we can purchase today as much light for one cent as we could a century ago for one dollar. We have a flexible dollar which is often in a shrinking mood and we have a steadily increasing standard of living. It is true that we are using much more artificial light than we did a century ago, but this increase is not in proportion to the decrease in cost of light. When we consider the tremendous increase in indoor activities — the great commercial and industrial activities — we can come to no other conclusion than that mankind has not taken advantage of decreased lighting cost in proper proportion. Certainly the workman of a century ago had an intensity of illumination of a foot-candle if he was obliged to do fine work after dark. Would the same workman for the same work, have 50 to 100 foot-candles today even though he could have it at the same cost? The answer is that relatively few workmen are provided with intensities of illumination of this magnitude, although it is very likely such intensities will be common-place in the near future.

Perhaps at this point it should be stated that, with a properly designed lighting system and proper surroundings, there is no intensity of illumination, obtainable today in a practicable manner, that would be too great. Most of the visual processes become more and more efficient as the intensity of illumination increases up to hundreds of foot-candles. Under proper conditions, such as exist outdoors in nature, we shall not have our work-places overlighted even at an illumination intensity of a thousand foot-candles. It is shown in Chapter VIII that our ability to see fine detail and brightness-difference steadily increases up to very high brightnesses and illumination intensities. Let us attempt to compare the present state of affairs with that of a century ago. Let us estimate that the purchasing power of our money is only one third as great as a century ago. Let us guess that our standard of living and working has increased in general five times during the past 100 years. The last item is a guess because it can scarcely be appraised. Of course, anyone is at liberty to revise these two guesses; however, on this basis we should have about 1500 times more artificial light for our work-places than would have been available for workmen 100 years ago.

It requires no unusual imagination or ability to observe, to conclude that artificial lighting has not kept pace with progress as represented by increase in efficiency of light-production and in the standard of living and working. Only by realizing the benefits of adequate and proper lighting will artificial lighting eventually come fully into its own. The lighting expert does not demand at the present time intensities of illumination of a thousand foot-candles. He would be happy to see an average of 20 or 30 foot-candles for work-places at the present time and would be confident that such a standard would convince the manufacturer and others of the great value of adequate and proper lighting. When he is convinced, higher standards will eventually come more or less as a matter of course.

Natural and Artificial Light Indoors

It has been pointed out several times that mankind by coming indoors placed many handicaps on natural lighting. Excepting from overhead skylights of proper design, the distribution of natural light indoors is not very satisfactory. The non-uniformity in large side-lighted rooms is very great and the horizontality of the dominant direction of natural light at some distance from windows is not satisfactory excepting in very special cases.[24] The intensities of illumination are also very much less than outdoors. In fact, they are so low that it is easy to attain them by means of artificial light. Natural lighting indoors costs about as much as artificial lighting. Considering the advantages of control and constancy of artificial light, it is seen that it is a formidable competitor of natural light indoors.

By no means are daylight intensities as great in factories as many are likely to believe from their experience at home or in well-lighted offices. Ward Harrison[25] made a survey of lighting conditions on clear and cloudy days in representative factories of various industries. From his summary it is seen that the average illumination of horizontal surfaces was less than 10 foot-candles. In fact, in only two out of seventeen kinds of industries visited was the average above ten foot-candles. It varied generally from five to ten foot-candles on a horizontal surface at the work-places. The diversity of the illumination on vertical surfaces was greater, being from two to thirty-five foot-candles, with an average somewhere in the neighborhood of ten foot-candles. These are intensities of illumination obtainable at reasonable cost by means of artificial light and as is shown in Chapters X and XIV with a considerable increase in production and other desirable factors quite in excess of the cost of artificial light.

Artificial lighting is necessary for economical operation of a factory because it must be available when daylight fails, as it is likely to do at any time. This should be charged to natural lighting. But we also have the possibility of using the same artificial-lighting installation for night-work. With the increasing standard of living we may be driven to two-shift operation in order to put brakes on the mounting cost of living. It is true that night-work has not been considered favorably in general. A part of this disfavor is due to experience with inadequate artificial light. However, work-conditions can now be fully as satisfactory at night as during the day and perhaps the two-shift plan of eight hours each will be worked out eventually. Such a plan would distribute overhead over twice the output with an obvious advantage to all concerned. Mr. Harrison[25] computed the cost of artificial lighting to equal the average daylighting intensities and his conclusions are presented herewith.

"To produce an illumination varying from 5 to 10 foot-candles in the different departments of a factory would under present conditions require an expenditure of a little more than 1 watt per square foot of floor space, assuming that well-diffused lighting units were to be employed. With current at 2 cents per kw. hr. the total cost of lighting should not exceed 7.5 cents per square foot per year for a night shift of 2,500 hours.

"If, on the other hand, doubling the size of the factory and operating on a day shift only were to be decided upon we would have to compare with the 7.5 cents per square foot annual cost of lighting the annual rental value of the addition to the plant fully equipped with machinery and ready to operate. Typical data on this point show a range for various plants of 30 to 75 cents per square foot per year, annual charge to cover interest, depreciation, and taxes on the plant and its equipment. The rental value depends somewhat on the location and type of construction but largely upon amount of machinery required. Thus the charge for a plant of 100,000 square feet area would fall between $30,000 and $75,000 depending upon the industry. The cost of lighting this plant for night shift operation would not exceed $7,500. This saving $20,000–$70,000 represents the difference between success and failure for many companies. To look at it from another viewpoint, the consumer's viewpoint, rent now comprises from 15 to 30 per cent of the increase which accrues to raw material in passing through a manufacturing establishment. Night operation should effect a substantial reduction in the cost of manufactured articles. But granting these facts, there remain the objections often raised that men do not like to work at night, that good men do not have to work at night, that it is impossible to change the established mode of life, and that really restful sleep cannot be secured during the day. Of the four, this last objection is a valid one; in fact, it is an open question whether satisfactory service can ever be obtained from a shift which begins work at midnight. On the other hand, man's preference for working during daylight is in many cases nothing more than an outgrowth of the fact that until recently effective work could not be done under artificial lighting, and that amusements have gradually come to appropriate that part of the day which was otherwise unoccupied. If factories were operated on a morning and evening shift — the latter ending by midnight — the ordinary hours of rest would be but slightly disturbed, and amusements which are dependent for their success upon a man's leisure time and his money would soon adapt themselves to the change. Under these conditions one would anticipate much less objection to night employment."

Influence of Daylighting on Artificial Lighting

The most striking evidence of the limitations which have been imposed upon natural light by the indoor life of man is the relatively high intensities of illumination outdoors at times when natural light indoors is considered inadequate. In other words, from the viewpoint of our indoor activities, darkness comes much before it does outdoors; that is, " day " indoors is much shorter than it is outdoors. Mr. A. Smirnoff [26] made an investigation of this in Washington, D.C. In this city manufacturing is a small part of the central-station load. Owing to the fact that the business-district supply of electric energy could be recorded independently of the residential supply, he applied his observations chiefly to the former. He obtained continuous records of daylight throughout various days and compared these with the current readings in the central-station. His results apply to the business district as a whole and therefore are interesting as mean values in this particular locality. Mr. Smirnoff by observing the current recorder could observe the variation of artificial lighting with variation in daylight. He found that there was a definite increase in consumption of electrical energy when the records of the Weather Bureau in the city showed that total daylight, at a point where the entire sky was visible, decreased below 1500 foot-candles. As the intensity of daylight illumination outdoors in an unobstructed location decreased below this value the current reading increased, but all variations in outdoor daylight illumination above 1800 foot-candles had only a negligible influence. Some of Mr. Smirnoff's data are reproduced in Fig. 20 where it is interesting to note the general regularity of the current-consumption curve on a clear day (July 25) with that for July 29 when it became quite cloudy in the afternoon. The dotted record below these two ampere-records represents the variation of total daylight illumination on a horizontal surface in the open on

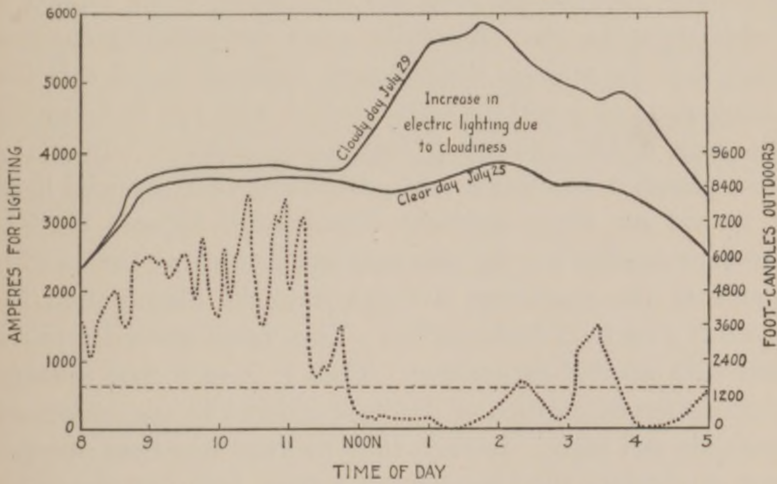


Fig. 20. Showing the influence of cloudiness on the amount of electric current used for artificial lighting. The dotted line represents the daylight illumination intensity outdoors (right-hand scale) on a horizontal surface exposed to the direct sunlight and the entire sky on July 29. The two other curves are total current consumption for a cloudy day (July 29) and a clear day (July 25) respectively.

July 29. The horizontal broken line at 1500 foot-candles indicates the level of outdoor illumination at which daylight becomes inadequate in some portions of the indoors which have been depending on natural light.

It will be noted that the difference between the two records of current consumption on the clear and cloudy days respectively is considerable. It represents expenditure for artificial light during the period that daylight is expected. It is a charge that might legitimately be placed against daylight. This amounts to a great sum in our congested cities. In Fig. 20 it is seen that the consumption of electric energy due to the cloudy afternoon of July 29 was about 20 per cent greater than on a clear day. When costs of artificial lighting are computed, that due to failure of *daylight in the daytime* should be subtracted and should be added to the cost of daylight. Of course, the illumination value *outdoors* at which daylight begins to fail indoors varies extremely for various interiors depending upon exposure, visible sky-area, etc. When the 1500 foot-candle point was reached in the open in Washington, Smirnoff found that the illumination at a certain west window was 360 foot-candles but only 9 foot-candles 6 feet away from it. In many other places it was much less. Assuming that artificial light is turned on when daylight illumination indoors reaches two foot-candles on the average, one arrives at the conclusion that the maximum average daylight illumination indoors is about 10 foot-candles. This value coincides fairly well with general experience. Thus it is seen that average illumination intensities of daylight indoors in our congested cities are not high. In fact, they average less than one per cent of outdoor illumination intensities, being of the order of magnitude of one hundredth to one thousandth. They are of such low value that they can easily be attained by artificial lighting at a comparable cost.

Without considering cost, the ideal system of lighting designed wholly from the viewpoint of the greatest certainty, speed, safety and comfort in human activity will provide an illumination intensity of hundreds of foot-candles (See Chapter XIII). Even considering the matter of present cost of lighting, the indication is that increased production, greater safety, less spoilage, and better *esprit de corps* should justify intensities of illumination many times greater than are now in general use (See Chapter XIV).

In a survey of industrial lighting made in 1919 it was found that about one-third of the total operation of industrial plants is under artificial lighting. This means that an enormous value of products of manufacture is produced under artificial light. The survey indicated that in only 40 per cent of the factories visited was the lighting such as could be pronounced good as judged by standards of 1919. Incidentally, the standard which represents adequate and proper lighting as established by lighting experts has continually increased during recent years. In view of what is known of light and its relation to visual activity, it may be stated with complete safety that there is not a factory in the world today illuminated to the point of maximum productiveness.

CHAPTER VIII

FUNDAMENTALS OF VISION

VISION is accomplished by our ability to distinguish differences in brightness and in color. Although color-vision plays a much more important part in every-day vision than most persons are conscious of, the real fundamental of vision is the discrimination of brightness-difference. If an object has the same brightness as that of its background and the brightness is uniform in both cases, the object cannot be seen. In rare instances this may be true but there may still be a difference in color. In such cases, color-vision makes it possible to distinguish the object. In the absence of color-vision mankind could go about every-day work quite unhampered, but, of course, some other provision would have to be made in those cases where color has been used for specific purposes such as in signals. The color-blind person does not experience the charm and the interest in the magical drapery of color which color-vision makes it possible to enjoy. By no means is it to be understood that the author relegates color to an unimportant place in every-day vision. It is important but not as fundamentally important as brightness. Therefore the discrimination of brightness, of brightness-difference, and of colorless details is emphasized more than color in these discussions and data. The subject of color is touched upon only when it plays a fundamental part but it is so complicated that it can not be treated as completely as it has been elsewhere.[1]

The Eye

Our ability to see fine details, in other words our visual acuity, depends primarily upon certain optical properties of the refracting media of the eye, the structure of the retina, the intensity of illumination, the relative and absolute brightnesses of the object and its background, and the size of the object or the visual angle subtended by it at its distance from the eye. The spectral character of the illuminant, and the colors of object and background, play parts that have been discussed in Chapter V and elsewhere.[1] Our ability to distinguish brightness-differences of relatively large areas is also influenced by the same factors as our ability to see fine details excepting that retinal structure

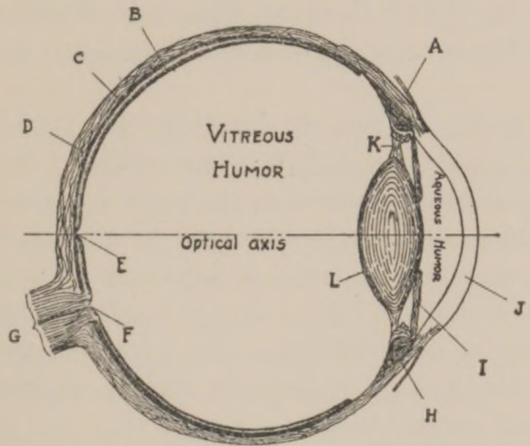


Fig. 21. Illustrating the various parts of the eye by a vertical cross-section along the optical axis.

A	Conjunctiva	G	Optic Nerve
B	Retina	H	Ciliary body
C	Choroid	I	Iris
D	Sclera	J	Cornea
E	Fovea	K	Suspensory ligament
F	Blind spot	L	Lens

and, in fact, the resolving power of the eye as a whole, are generally less important than in the case of distinguishing fine details. A diagram of the eye is shown in Fig. 21 with the various parts indicated.

The eye must focus a fairly accurate image on the retina if the object is to be seen clearly. In this respect the defects and limitations of the optical parts of the eye are those which are to be looked for in any more or less simple optical system. The retinal structure or the smallness of the individual elements responding to light also influences the clearness of fine details and, in fact, limits the smallness of size of details which are distinguishable. Its limitations are similar to the "grain" of a photographic emulsion. When we inquire into the eye as an optical system we conclude that it is far from perfect but when we think of its great range of sensibility, or its adaptability to a great range of brightnesses, we find it a very remarkable sense-organ. In fact, we agree with the great Helmholz when he said that he could make a better optical instrument but not a better eye.

The sensibility of the eye depends upon such factors as the state of adaptation and the visual angle of the stimulus. As the visual angle increases, there is a decrease in the minimum amount of radiant energy of any given spectral character necessary to cause a sensation of brightness or brightness-difference. Under proper conditions the eye can function over a range of brightness of about 10 billion to one.[30] Besides being a marvelous sensory organ the eye is also a motor organ capable of remarkably fine discrimination.

In considering the human eye as a sense-organ we cannot avoid giving weight to the conditions under which it evolved from a lowly sense-organ to the most highly developed one. It is not surprising to find this sense-organ, and the various processes which play parts in transferring its record to our consciousness, adapted best to daylighting conditions. It is not surprising to find the entire visual process better satisfied in general with the high intensities of illumination outdoors and with the quality of daylight.

The remarkable range of sensibility of the eye is explained partially by the assumption of two different kinds of elements in the retina and two corresponding visual regimes.

For very low brightnesses retinal elements termed " rods " (owing to their form) are supposed to be in operation according to one theory which has much anatomical evidence to support it. They and their attendant processes enable us to see the brightnesses resulting from very low intensities of illumination such as those of moonlight, starlight, and feeble artificial light. The rods are relatively insensitive to hue or color as is evidenced by the colorless appearance of colored objects under low intensities of illumination. They do not exist in the central portion (fovea) of the retina; hence, we are unable to see a faint star by looking directly at it, although often we can see it by slightly averted vision.

The other set of retinal elements are termed " cones " (owing to their form). These elements are supposed not to respond to feeble brightnesses. Their range of sensibility does not extend to as low brightnesses as the rods. They are responsible for at least most of our sensations of brightness at ordinary and higher levels of illumination and, if this " duplicity " theory is correct, they are primarily responsible for practically all our color sensations. The cones predominate more toward the central portion of the retina while the converse is true of the distribution of so-called rods.

Rods are absent from the fovea — a central region of the retina of approximately one degree of visual angle — and, in fact, are absent from the surrounding region having a total circular area of about 3 degrees. However, it should be pointed out that the cones in this central region are more rod-like structurally than the cones in the peripheral region. Cones and rods actually exist anatomically and there is evidence that they are the actual receptors or at least they play an important part in reception. Much of the data available point to them as performing the functions described above. Certainly the assumption of these two regimes explains much of the data pertaining to vision. The characteristics of vision over different parts of the retina seem to vary according to the distribution of rods and cones respectively. Incidentally, the smallest object that can be seen is that whose image falls upon only one retinal receptor. This limits the resolving power of the eye if nothing else does. Normal eyes cannot readily resolve two objects nearer together than about 40 seconds of visual angle, which corresponds to a separation of about 0.0025 inch at a distance of 14 inches from the eye. Data in Table XI and Fig. 25 may be interesting at this point.

It is thus seen that the eye or the visual sense-organ may operate in "low" or in "high." The change from one to the other is not as abrupt as that in the transmission of automobiles but the analogy is useful and it may be extended even further. Just as the automobile is not designed to operate continually in "low" but only in emergencies requiring such a gear-ratio, so it is with the eye. For continuous operation the eye should be in "high." Many of the data presented in these chapters show that the eye does its best at high levels of illumination and their consequent brightnesses. At such brightnesses as those of the sun and of many artificial light-sources the eye or the visual process as a whole again becomes less sensitive. However, these brightness-levels need not bother us here because they are of much greater magnitude than even those of objects illuminated by direct noon sunlight.

It will be noted that most of the curves in these chapters which show the increase in visual acuity, brightness sensibility, speed of vision, etc., are of the form of efficiency curves of electric motors, for example. It is not the general practice to operate motors on the lower parts of the curve which represent low efficiencies. It is good practice to operate them at the higher or highest efficiencies. So it is with the eye when economic considerations permit and, fortunately, the present efficiency of light-production and utilization make it economically possible to provide intensities of illumination better suited to the operating characteristics of the eye than those prevailing indoors at the present time. In fact, it is shown in Chapter X that it is profitable to increase the generally existing intensities of illumination and to rehabilitate many lighting systems.

Besides the high and low regimes in the visual process, we have the pupil of the eye as a governor to some degree. It performs the same function as the iris diaphragm in the camera for it regulates the average brightness of the retinal image. Its smallest aperture is about 2 millimeters (0.08 inch) and its largest is about 8 millimeters (0.32 inch). This corresponds approximately to a range from F20 to about F2 on the usual aperture scale of a camera, the values being determined by dividing the focal length by the diameter of the aperture. It should be noted that the size of the aperture determines to some extent the definition of the image. The pupil has a similar influence on the retinal image. But when it is small, definition may be better, but the brightness of the retinal image of the same object under the same illumination is much less when the pupil is small than when the pupil is large. The resolving power of a lens increases as the aperture increases as is well evidenced by the desire for astronomical telescopes of large aperture, but apparently this influence is outweighed by other factors in the eye as shown later.

We are all familiar with the results of adaptation of the visual sense to different levels of brightness or of illumination intensity. Coming suddenly into an illuminated room from the dark we are "blinded" for some time until the eyes becomes adapted. This phenomenon is important in lighting, although lighting conditions to be best for work should be such that this phenomenon is not evident.

Thus it is seen that there are many interesting and important factors pertaining to the eye which have their influence upon visual discrimination. Many others, particularly those involving color, could be discussed, but these would lead us far afield. Only the fundamental factors are considered here; the others may be found adequately treated elsewhere.[1]

Illumination and Brightness of Test-Objects

Many scientists have for years measured their visual test-objects in terms of brightness rather than illumination intensity. This is the correct and safe method. On the other hand the engineer and others are more familiar with foot-candles. Therefore, the diffuse reflection-factors of the different parts of the test-object should be given as well as the illumination in foot-candles. This makes it possible to compute the brightness. In these chapters the author has reduced many values to foot-candles on colorless surfaces diffusely reflecting, respectively, 80 per cent and 8 per cent of the incident light. This leaves the data in terms of foot-candles on so-called white and dark gray surfaces respectively in which form the data are most practicable.

Test-objects are usually black on white. Of course, color plays an important rôle in vision and its influence should be studied in the laboratory; however, the black-white is the most natural combination. In general, this high contrast will be a greater aid to vision than lower contrasts such as black on dark gray, and results with the black-white test-object will be representative more of how well the eye can do rather than of what it may be expected to do in every-day vision, excepting in work such as reading in which black-white contrasts are the rule rather than the exception. Therefore, it is important that low-contrast test-objects be also used in order to approach more nearly to average brightness-differences with which the worker is usually confronted.

It should be noted that what we term *black* reflects some light and what we term *white* absorbs some light. Therefore, black is a very dark gray and white is a very light gray. Dull black paints and inks commonly reflect from 2 to 5 per cent of the incident light; black felt about 1 percent; black velvet usually less than 1 per cent; and a *hole* in a box lined with black velvet emits practically no light. Black velvet surrounding the hole is bright compared with the hole.

White papers and paints reflect from 70 per cent to 85 per cent of the incident light. The purest magnesium carbonate and similar white powders are sometimes found to reflect from 90 per cent to 98 per cent of the total light. However, a good white paint or paper usually has a diffuse reflection-factor of 80 per cent.

Inasmuch as such a white is usually used, it is interesting to know its brightness under various intensities of illumination. Brightness is measured in various units. Candles per square inch or the lambert are convenient units for the brightness of the sky and of artificial lighting units. The millilambert (one thousandth of a lambert) is a unit of convenient size for the brightnesses of objects under intensities of illumination up to 1000 foot-candles. Some of these relations are as follows:

1 lambert = 1000 millilamberts (ml) = 2.054 candles per square inch

1 candle per sq. in. = 0.4868 lambert = 486.8 millilambert

1 foot-candle on a perfectly white surface (100 per cent reflection-factor) produces a brightness of 1.076 millilambert (ml)

1 foot-candle on an ordinary "white" surface of 80 per cent reflection factor produces a brightness of 0.86 millilambert.

1 millilambert = 0.929 lumen emitted per square foot = brightness that would be produced by 0.929 foot-candles on a diffusing surface of 100 per cent reflection-factor.

1 foot-candle = 1 lumen incident per square foot

To find the brightness of a diffusely reflecting surface in millilamberts, the intensity of illumination in foot-candles is multiplied by the reflection-factor of the surface and this product is multiplied by 1.076. This relation is shown graphically in Fig. 54, Chapter XII.

The original definition of the lambert (and the millilambert) involves perfect diffusion, so that the foregoing relations are best confined to surfaces that diffusely reflect or transmit light. In fact, throughout this book the term reflection-factor applies to diffusely reflected light unless otherwise stated.

Brightness Sensation

The most fundamental visual function is the distinction of brightness. It is the peculiar property of the visual sense-organ (and of its lines of communication to the brain and to our consciousness) that radiant energy between a certain range of wavelengths (about 390 mμ to 760 mμ., Fig. 1 and Table I) impinging upon the retina causes the sensation of brightness. As is well known, radiation of various wavelengths within this range causes sensations of certain hues. The combined sensation of radiations of various wavelengths is a result of a complex psycho-physiological process which need not concern us here. It has been seen in Chapter V that various spectral distributions of radiant energy give integral effects such as approximate white for noon sunlight and an unsaturated yellow for the light from tungsten filament lamps.

The minimum brightness of a given visual angle that we can see depends upon the state of adaptation of the eye and upon the wavelength of radiation. It is so very small for the dark adapted eye that it does not concern us in lighting although it is of scientific interest. In every-day vision the brightnesses which we encounter are much greater than this threshold value; therefore, in vision we are not so concerned with our ability to discern brightness as we are to distinguish brightness-difference. This visual function has been thoroughly studied by many investigators. König's data are presented in Fig. 22 for white light, and also

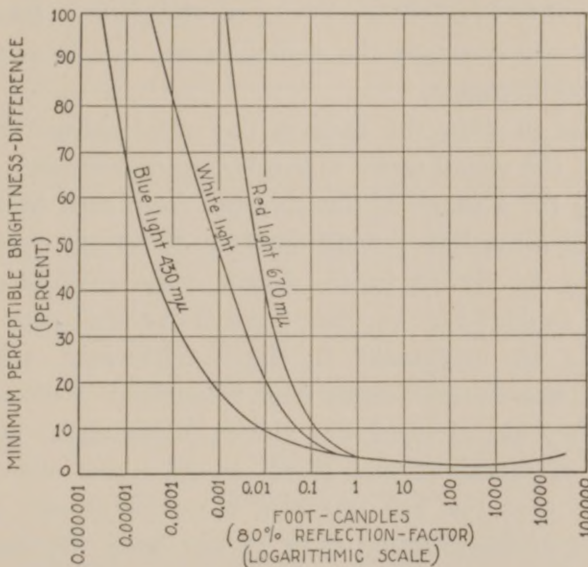


Fig. 22. Showing the minimum brightness that is perceptible at various brightnesses corresponding to those produced by a wide range of intensities of illumination (foot-candles) of a so-called white surface of 80 per cent reflection-factor. The horizontal scale has been expressed in foot-candles on a colorless surface which diffusely reflected 80 per cent of the incident light as nearly as possible from the original data presented by König. The results for white light and also spectral blue and red lights are shown.

for red and blue light, over a very great range of brightnesses far exceeding the range ordinarily encountered in the objects that our work requires us to look at. The scale on the left represents the minimum brightness-difference (in per cent of the greater brightness) which is just perceptible at the various brightnesses obtained by illuminating a so-called white surface (of 80 per cent reflection-factor) to intensities in foot-candles as shown on the horizontal scale. This scale had to be computed from data presented by König. The true sensitivity-curve of the eye to brightness-difference is obtained by plotting the reciprocals of the brightness-differences. The scale of illumination in Fig. 22 is also peculiar in that it is logarithmic. This enables the plotting of a great range of illumination intensities (in reality brightnesses) because the scale is telescoped. By sensitivity is meant the ability of the eye to distinguish brightness-difference.

In order to show the data in the usual manner the sensitivity of the visual sense to brightness-difference is plotted in Fig. 23 for a range of illumination from zero to 25 foot-candles on an ordinary white surface of 80 per cent reflection-factor as shown in the lower scale of foot-candles. It shows, as does Fig. 22, that the eye can see much smaller differences in brightness if the brightnesses are those ordinarily encountered under high intensities of illumination than if they are of the lower values found under lower intensities of illumination. Here, as in many other cases, it is seen that the eye operates more effectively at high intensities of illumination than at low ones. It should be noted that brightness is the factor upon which vision largely depends. However, in practice we deal with foot-candles, so that, in these discussions and illustrations, foot-candle scales are provided, but the reflection-factor of the surface (or background in the case of visual acuity) is also given. This enables one to visualize and even to compute the brightness.

It should be particularly noted that the brightness of a so-called white surface (80 per cent reflection-factor) is ten times greater than a so-called dark gray surface of 8 per

per cent reflection-factor under the same intensity of illumination. Much of our seeing is concerned with surfaces of low reflection-factor whose brightnesses are much lower than surfaces of high reflection-factor under the same in-

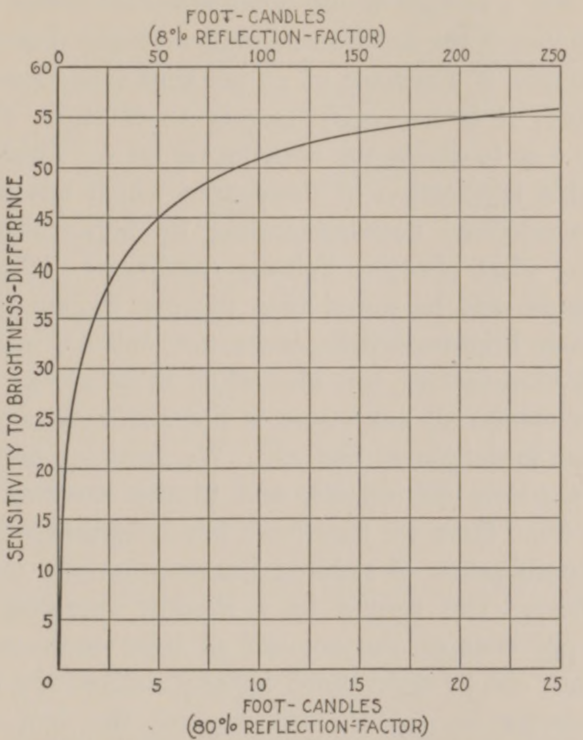


Fig. 23. Showing the sensitivity of the eye to brightness-difference throughout a range of brightnesses corresponding to illumination intensities up to 25 foot-candles on a so-called white surface of 80 per cent reflection-factor. The upper horizontal scale is the same as the lower one when both scales are reduced to brightness values because the upper scale is for foot-candles on a colorless surface that reflects only 8 per cent of the incident light. By sensitivity is meant the ability of the visual sense to see brightness-difference.

tensity of illumination. The data in Fig. 23 are applicable to materials which reflect 8 per cent of the total light by using the upper scale of foot-candles. The curve now tells a different story for it is seen that the eye does not approach its maximum effectiveness within this range until the illumination intensity has reached a value in the neighborhood of

200 foot-candles. The two foot-candle values in Fig. 23 represent at any vertical line, the respective intensities of illumination to produce equal brightnesses of two surfaces having 80 per cent and 8 per cent reflection-factors respectively. For a surface of any other reflection-factor the same curve applies if the foot-candle scale is changed accordingly. For example, if a surface of 40 per cent reflection-factor is considered, it is necessary merely to multiply the lower scale by 2 or to divide the upper scale by 5. This is a very practicable application of these data which has been generally overlooked notwithstanding its importance in determining what effective lighting conditions really are.

It should also be noted that the eye is called upon to distinguish brightness-differences not only of surfaces of low reflection-factors, but also when these are in shadows. In other words, all our vision is not confined to the desk, inspection table, planer-bed, etc. We must see under these, in the shadows on objects, and in the shadows cast by objects, etc. Here we may have low brightness-values due to the combination of reduced illumination and low reflection-factors. The results in a shadow receiving only a certain per cent of the amount of light received by the work-plane can be determined for any surface of a given reflection-factor by taking into account the fact that the illumination intensity is reduced to this certain percentage of the full illumination. These results are those obtained in the laboratory under ideal photometric conditions, where distraction is minimized and where the observer has nothing else to do at the time. The conditions are far different for the worker. Certainly he should have a large factor of safety; that is, the lighting should be such as to promote visibility, and the illumination intensity should be well up in the region of maximum visual efficiency not only for discrimination of brightness-differences of surfaces of high reflection-factor but also of low reflection-factor. Furthermore, shadows should be taken into account. In other words, if the worker is to see quickly and with certainty he must have many times the amount of light necessary under

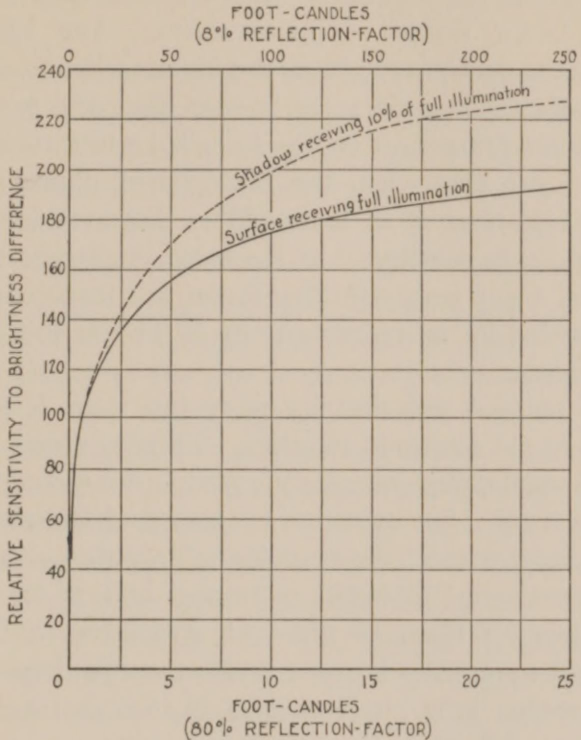


Fig. 24. Showing the per cent increase in the sensitivity of the eye to brightness-difference for surfaces receiving full illumination (solid line) represented by the foot-candle scales and for a shadow (broken line) receiving only 10 per cent of this full illumination. The relative sensitivity is represented by 100 at the brightness of a colorless surface of 80 per cent reflection-factor under one foot-candle of illumination (or a surface of 8 per cent reflection-factor under 10 foot-candles.

the ideal conditions of laboratory researches. There should be a large factor of safety for the worker as discussed in Chapter XIII.

It is interesting to ascertain the per cent gain in sensitivity of the eye to brightness-difference as the intensity of illumination increases. This is shown in Fig. 24 where

100 on the sensitivity scale represents the relative sensitivity of the eye to brightness-difference at the brightness of a colorless surface of 80 per cent reflection-factor under an illumination of one foot-candle (or one of 8 per cent reflection-factor under 10 foot-candles. The solid line represents the surfaces receiving the illumination represented in the foot-candle scales. It is seen that the sensitivity for brightness-differences on the so-called white surface, increases 75 per cent when the intensity of illumination is increased from one to 10 foot-candles (lower scale). This same increase in sensitivity at the same brightnesses, when surfaces of 8 per cent reflection-factor are involved, would be represented by an increase from 10 to 100 foot-candles (upper scale).

It was pointed out that in every-day work it is often necessary to see details in shadows. These shadows are not only those cast by objects upon our work but are also those on the object itself. For example, we may find it desirable to see into complex machinery, under tables, etc., or we may find it necessary or desirable to inspect objects themselves without turning them in different directions so that all sides would eventually be seen under the full illumination. For this reason it is interesting to inquire into sensibility to brightness-difference in a shadow receiving only 10 per cent of the full illumination represented by the foot-candle scales in Fig. 24. This is shown by the broken line. It is seen that a 100 per cent increase in sensitivity (ability to distinguish brightness-difference) accompanies an increase in illumination from one to 10 foot-candles or from 10 to 100 foot-candles respectively for the brightness represented by the so-called white surface or the so-called dark-gray surface respectively receiving the full illumination. This does not take into account the reduced sensitivity of the eye when looking into shadow by the influence of the higher brightness-level of surroundings receiving full illumination.

All this argues for "luminous" shadows obtained by diffused and evenly distributed light and argues for higher intensities of illumination than are now generally used, if we are to operate the eye reasonably close to its highest efficiency.

Many factors besides illumination intensity and brightness-level affect the sensitivity of the eye to brightness-difference. The state of adaptation of the eye and the size of the stimulus are important [31] in many cases of lighting where the intensity of illumination is far from uniform or of low values of the order of magnitude of moonlight or less. Reeves [32] has presented interesting data on the effect of visual angle and brightness of the stimulus (the object) on the ability of the eye to distinguish various brightness-differences after certain periods of time have elapsed since the eye was adapted to another brightness. In fact, a great amount of work has been done which involves the period and degree of adaptation. These data are exceedingly valuable in revealing the operation of the visual sense-organ. When we have adequate and proper lighting the eyes are not subjected to wide ranges of illumination or brightness and the time element of adaptation is not a prominent factor. Therefore, this phase will not be discussed in this chapter. It is important to note that, other conditions being constant, the smaller the visual angle the greater is the contrast necessary to see an object. The data presented in Figs. 22, 23, and 24 are for large visual angles far above the limit of visibility. For small visual angles, the sensitivity of the eye to brightness-contrast would be less; hence, in those illustrations the foot-candle scales would have to be multiplied by factors greater than one to make the data applicable. In other words, for a small visual angle the intensity of illumination must be greater than for large ones if vision were to be equally effective in the two cases.

Visual Angle

An important factor in vision is the size of the object or details to be discriminated. Inasmuch as the size of the retinal image is more important than the size of the object, visual angle is the term in which acuteness of vision is determined. This takes into account both the size of object and its distance from the eye. Small visual angles are directly proportional to the size of the object divided by

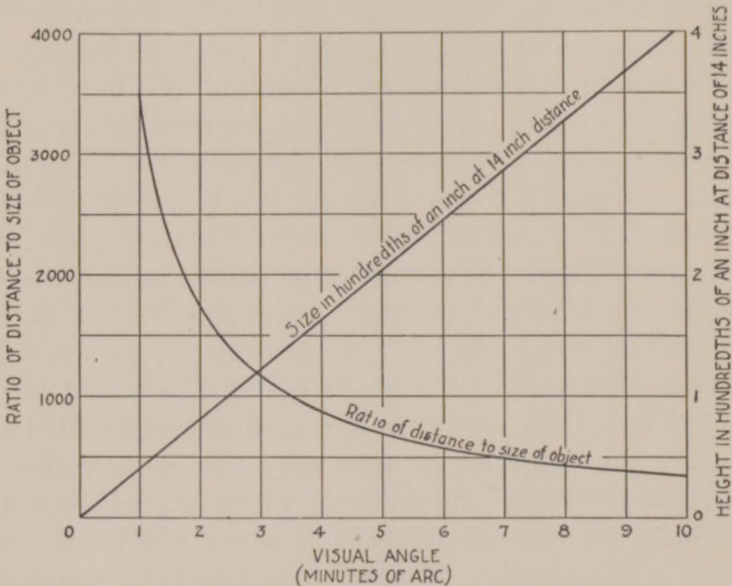


Fig. 25. Showing the relations of size of an object and its distance from the eye for small visual angles. The straight line represents the sizes of objects in hundredths of an inch (right-hand scale) at a distance of 14 inches from the eye for small visual angles. The curve shows the ratio of the distance of an object from the eye to the size of the object in the same units of length (left-hand scale) for small visual angles.

its distance from the eye. It is obvious that an object of a small size at one foot from the eye is of the same visual angle as an object of twice its size at a distance of two feet. Inasmuch as visual angles are so important, some data pertaining to small visual angles are presented in Table XI and in Fig. 25. It should be noted that in the second column of the table the size of the object is given in hundredths of an inch. For example, an object approximately 2 hundredths of an inch in size and 14 inches from the eye subtends a visual angle of 5 minutes. The third column makes it possible to determine visual angle by size of object and distance from the eye in the same units of length.

TABLE XI.

The Relation of Size of Objects and Their Distance From the Eye for Small Visual Angles.

Visual Angle (Minutes of arc)	Size of Object at distance of 14 inches (in hundredths of an inch)	Distance of object divided by size of object in same unit in length
1	0.406	3448
2	0.812	1724
3	1.218	1149
4	1.624	862
5	2.030	689
6	2.450	571
7	2.856	490
8	3.262	429
9	3.668	382
10	4.074	344

Visual Acuity

After the ability of the retina to distinguish brightness and brightness-difference, the next important factor is acuteness of vision. We distinguish a certain minimum brightness-difference between an object and its background and naturally we are curious to know how small the object would have to be to be undistinguishable, other factors remaining constant. The term *visual acuity* is applied to the discrimination of fine detail. It is usually determined as the smallest visual angle between two objects which the eye can resolve under the particular conditions. Some idea of the relation of size and distance for various visual angles may be gained from Table XI and Fig. 25.

A test-object for the study of visual acuity may be any fine detail such as letters, fine lines, broken circles, dots, etc. The visual angle is determined by measuring the dimension of the part to be discriminated and the distance to the eye. The visual angle may be varied by moving the object toward and from the eye, but this is not a satisfactory method for analytical work. It introduces factors such as change of focus. In such tests it is well to have such an object as parallel bars or a split ring which can be rotated about its center so that the observer may be required to state the position of the bars or missing part of the ring, thereby showing whether or not he actually discriminated the bars or two parts of the ring. Some features of test-objects have been discussed in a previous section.

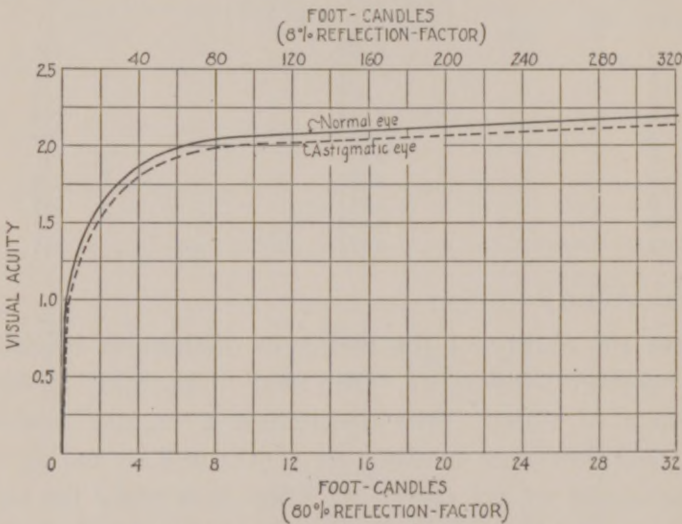


Fig. 26. The solid line represents the general relation between visual acuity and illumination intensity for a normal eye, the test-object consisting of black details on a so-called white background of 80 per cent reflection-factor (lower scale). The upper scale applies to a dark gray background of 8 per cent reflection-factor. The dotted line shows the general relation of the results obtained with a slightly astigmatic eye.

In Fig. 26 the solid line represents for the normal eye the typical relation between visual acuity and the illumination (lower scale) of a " black " test-object on a " white " background of 80 per cent reflection-factor. It is seen that the form of this curve is quite similar to that of many pertaining to vision which are represented in this and other chapters. It is the familiar "efficiency curve." Its actual form depends somewhat upon the character of the test-object but that is a matter more of scientific than of practical interest. The solid line in Fig. 26 is representative of the general form of the visual-acuity curve or general relation of visual acuity and brightness of background of black details.

At low levels of illumination or brightness of background, visual acuity is much less than at higher levels. It should be noted that these results are for the ideal laboratory conditions and for a test-object of maximum contrast and white background. Assuming that the black of the test-object is non-reflecting and that the background is a dark gray of 8 per cent reflection-factor, we now must apply the upper scale of foot-candles. For a surface of 40 per cent reflection-factor the lower scale would be multiplied by 2 or the upper one would be divided by 5. A foot-candle scale can be thus constructed for any other reflection-factor. We see now that the eye even under the ideal conditions of the laboratory does not begin to operate any where near its maximum effectiveness in this respect until the illumination of the test-object is above 10 foot-candles. If we consider the matter of a factor of safety to allow for the less ideal conditions in every-day work and perhaps for discriminating details in shadows, it is seen that illumination intensity from the viewpoint of visual acuity should be a rather high value compared with one foot-candle for example. This is discussed further in Chapter XI.

It is also of interest to ascertain the per cent increase in visual acuity with increasing brightness or intensity of illumination on the two colorless surfaces reflecting respectively 80 per cent and 8 per cent of the total incident light. In Fig. 27 for the sake of comparison the relative visual acuity is represented by 100 at a brightness corresponding to one foot-candle on an 80 per cent reflecting (colorless) surface, or 10 foot-candles on the 8 per cent reflecting (colorless) surface. As already stated, all our seeing is not done on objects and surfaces receiving full illumination; that is, often we must discriminate details in shadow.

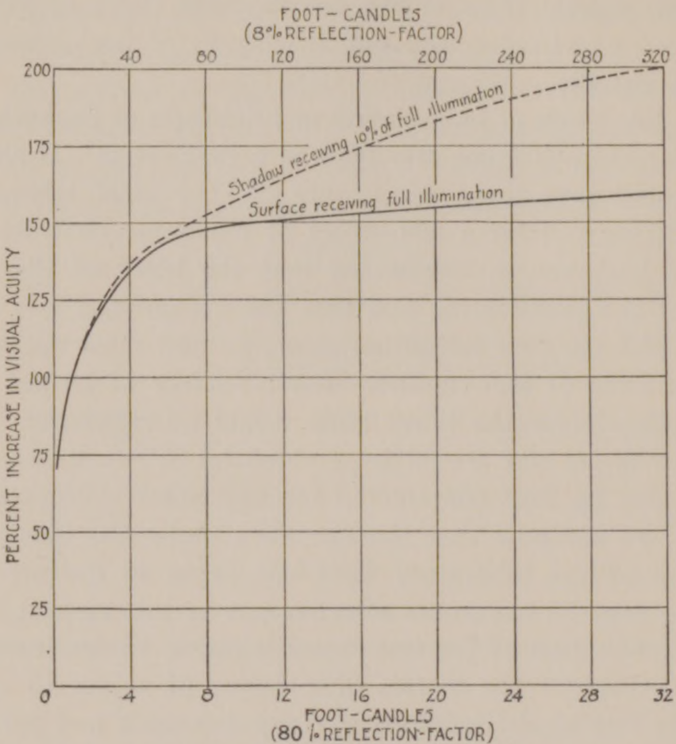


Fig. 27. The solid line shows the per cent increase in visual acuity with brightness of background against which the black details are viewed. The foot-candle scales apply to surfaces of 80 per cent and 8 per cent reflection-factors respectively. The relative visual acuity is represented by 100 for a brightness of background corresponding to one foot-candle on a colorless surface of 80 per cent reflection-factor (or 10 foot-candles on a colorless surface of 8 per cent reflection-factor). The broken line shows the per cent increase of visual acuity in a shadow receiving only 10 per cent of the full illumination represented by the foot-candle scales.

Therefore, the per cent increase in visual acuity is also shown for brightnesses of shadows receiving only 10 per cent of the full illumination represented by the foot-candle scales. For surfaces having reflection-factors other than 80 per cent or 8 per cent, the foot-candle scale can be altered to fit. For example, for a surface of 40 per cent reflection-factor the lower foot-candle scale would be multiplied by 2 or the upper one would be divided by 5.

The foregoing discussion applies solely to normal eyes. Of course all eyes that have defects which can be counteracted by proper glasses should be equipped with such glasses. Nevertheless many persons do not wear glasses, notwithstanding the fact that their eyes need slightly corrective glasses at least. Progressive industries have found that examination of the eyes of workers pays them as well as the workers; nevertheless, in lighting it is well to consider not only the requirements of normal eyes but of somewhat defective ones. If a reasonable factor of safety is allowed for these, subnormal eyes have less of a handicap than if there is no allowance for them. The reduced visual acuity of eyes slightly astigmatic is shown in general by the broken line in Fig. 26. In some industries as many as 50 per cent of the workers have been found to have defective vision.

It is a fact of common observation that we can see fine details of ordinary brightnesses or under ordinary intensities of illumination can see exceedingly more clearly if we look directly at the details than if we look a little to one side of them. The converse is true for abnormally low brightnesses or illuminations. This is well shown in Fig. 28. The broken line shows relative visual acuity for various parts of the retina at levels of illumination under which the eyes are generally used for fine work. The solid line represents the visual acuity under very low intensities of illumination. Zero degrees represents the center of the retina, that is, the center of the fovea. It is seen that for the high-level brightnesses or illuminations visual acuity is very high at the center of the retina but it drops very rapidly in value for the first few degrees. For the abnormally low-level brightnesses or illuminations, such as moonlight and starlight, the converse is true. The central part of the retina is not as effective as an area between 10 and 20 degrees from the axis or center. This shows why we see a faint star better by slightly averted vision.

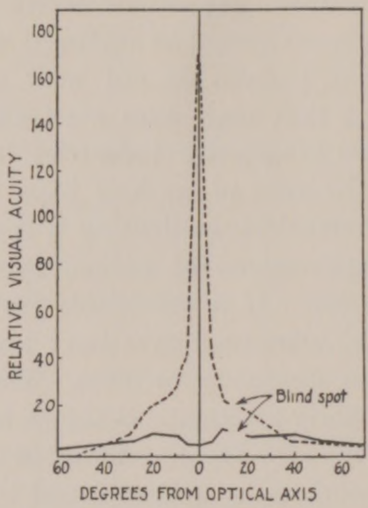


Fig. 28. Showing relative visual acuity for various portions of the retina. Zero degrees is at the center of the fovea of the retina. The dotted line represents the relative visual acuity at ordinary brightnesses of high-intensity illumination. The solid line represents visual acuity for very low brightnesses (low intensities).

The blind-spot in the eye is shown by the gap in the two lines to the right of the axis. This is of no importance excepting in monocular vision because the blind-spots of the two eyes do not overlap in the visual field. The blind-spot can be detected by fixing one eye (the other being closed) on a black dot on a white surface and fixing the attention on another dot on the same surface about two inches from the first. If the white surface be held about a foot from the eye and moved back and forth, a point will be found where the second dot will disappear.

Color Sensation

At ordinary levels of illumination intensity (or of brightness), we can see about the same brightness-difference of colored surfaces as of colorless surfaces. Under the best laboratory conditions this brightness-difference is about 1.6 per cent as seen in Fig. 22. Thus between a perfect white and a perfect black we have about 60 perceptible shades for any given high intensity of illumination. This range is not as great with colored surfaces because, for example, a fairly pure red paint would reflect only about 20 per cent of the incident light. Thus between it and a perfect black we would have only about 12 perceptible shades.

A tint is a color diluted with white light (or pigment). The reflection-factors of tints of a given color vary from that of the original color to the limiting tint which is white itself. Therefore, the number of distinguishable shades of a tint depends upon the brightness of the tint itself. An approximate estimate of the average number of distinguishable shades of white, of tints, and of colors might be taken as 30 or half the number of neutral grays distinguishable between black and white. This is for a given illumination intensity of reasonably high value. A shade of any color (including tints and even white) is merely a lesser brightness. Therefore, we can produce shades in the broad sense by increasing the intensity of illumination. If we have a so-called white under a given intensity of illumination, by increasing the intensity of illumination we produce a lighter shade (in an absolute sense) than the original white. Therefore, the number of absolute shades which we can see is very much greater for any color, in general, than the series of distinguishable shades under any given intensity of illumination.

With sensitive apparatus we can distinguish about 125 hues in the spectrum of sunlight or light from a tungsten filament. (In the light from the mercury-arc there are only four principle hues and a few others represented by very weak spectral lines.) Considering that the purples are not represented in the spectrum, we may estimate that under the best laboratory conditions we can see 150 distinctly different hues. Our ability to distinguish a difference in tint (technically termed difference in saturation) is not as well developed as our ability to distinguish differences in hue or in brightness. Data on large groups of untrained eyes are not available but we will estimate that 20 different tints (or degrees of saturation) represent the average number of tints of a color actually distinguishable. Therefore, by multiplying the number of distinguishable hues (150) by the estimated average of distinguishable shades (30) under a given high intensity of illumination by the estimated average of distinguishable tints (20) we obtain 90,000 as the approximate number of different color sensations that we can distinguish for a given high intensity of illumination. When we introduce absolute brightness, that is, increase the intensity of illumination and thereby introduce an extensive range of brightness, it is seen that the number of distinctly different visual sensations which we can experience (apart from those of form) runs into millions.

P. G. Nutting and L. A. Jones found that the sensibility of the eye to change in tint varied with the depth of tint. That is, to a pure color as much as 4.7 per cent of white light had to be added before the change in tint was noticed. After the color had been diluted so that it was a medium tint (50 per cent pure hue and 50 per cent white) the addition of 4 per cent of white light was just noticeable as a change in tint. As the color became less and less saturated by the addition of more and more white, this percentage, required to produce a just noticeable tint, decreased until it reached a value of 2.2 for the very lightest tints (those very nearly colorless). A pure color is said to be of 100 per cent saturation. Tints are unsaturated colors of various percentages of saturation.

In color-perception at very low levels of illumination the Purkinje effect must be taken into account and also the difference in our sensibility to brightness-difference for various colors.

In very fine discrimination of color, after-images or successive contrast must be taken into account. The portion of the retina fatigued to a certain color will have an after-image of the complementary color.

A central region of the retina is called the " yellow spot " because it absorbs blue rays somewhat and therefore in this small portion of the visual field colors in general are not seen as they are. This spot can be noted sometimes if the eyes are fatigued by bright colors. It is also noticed on viewing shades of colors of peculiar spectral characteristics.

For accurate color-discrimination an intensity of at least 50 foot-candles is more generally desirable than lower intensities often encountered.

Simultaneous Contrast

If we juxtapose two quite different colors, in general, they will both appear more vivid and different than they will under other conditions. If we place a gray paper on a green background of the same brightness, the gray paper will assume a purplish tinge complementary to the surroundings. This effect is the life of color and is in operation everywhere we have color-difference. It can be demonstrated on any colored painting or print. Suppose we have an orange flower-pot amid green foliage. The orange may appear quite vivid under these conditions. Punch a hole in a white or gray paper and place the hole over the orange pot thereby excluding the other colors. The orange now has lost much of its colorfulness. In the photographic darkroom we gradually become accustomed to the red light and it loses much of its redness. If we discover a crack letting in daylight, the daylight appears a blue-green color. If we light a lamp of any other color than red, the red light immediately assumes its redness again.

The effect of simultaneous contrast is also very noticeable with colorless surfaces. A white area on a dark gray appears much brighter than it is. Conversely the dark gray appears darker than it is. This is very prominent in a series of grays. Where a brighter edge meets a darker one the former will appear brighter along the edge than further away from the edge. The converse is true of the dark edge.

We can never see a color as it actually is because we can not escape the influence of its environment.

Irradiation

If we cut a hole out of a white card and place it over a black card the black hole appears smaller than it really is. Conversely a white area of the same size but placed on a black surface will appear larger than it is. When we turn on a light-source, particularly in a diffusing globe, it appears to move slightly toward the observer. This is an interpretation of apparent increase in size (due to irradiation) into an apparent approach. The most striking illustration of irradiation is a glowing fine filament of an electric lamp. It appears many times larger than the actual filament. Even at a low voltage when the fine filament is barely glowing it appears considerably larger than it actually is. It is interesting to note how the size appears to increase from the cold junction to the fully glowing portion. Irradiation is a very important phenomenon particularly in connection with backgrounds as discussed in a later paragraph.

The Pupil of the Eye

A brief description of the eye has already been given and it is illustrated in Fig. 21. It is seen that the pupil offers some protection to the eye against sudden changes in brightness or in illumination levels. If its minimum diameter approaches one millimeter and its maximum about 8 mm., its area at the largest diameter is more than 50 times that at its smallest diameter. Inasmuch as the brightness of the image focused upon the retina is proportional to the area of the pupillary aperture, this brightness is under control of the pupil over a range of about 50 times. Combining with this control the peculiar property of "adaptation of the eye," we have a sense-organ that is fairly well fitted for extensive ranges in brightness.

As already shown, the pupil plays important optical rôles but some of these are at cross purposes. For example, the definition of the image is best for low apertures (small pupils) but the resolving power of any lens increases with the diameter of the aperture. However, definition is more important than resolving power in the optical parts of the eye because the retinal structure limits resolving power. The pupil of the eye under ordinary conditions of lighting is contracted considerably. Apparently its function is chiefly to enlarge at low intensities of illumination to admit more light even at a sacrifice of definition. The area of the pupil having a great deal to do with the brightness of the retinal image, it is important in vision. Inasmuch as glaring light-sources tend to make the pupil contract we not only have a reduced visibility due to glare but also due to a decreased brightness of the retinal image.

It is easy to study the effect of pupillary aperture by using artificial pupils close to the eye. A series of circular openings of different sizes can be made in opaque material like sheets of thin metal. Dr. P. W. Cobb [33] studied the effect of various pupillary apertures on visual acuity. The test-object consisted of fine black lines on a white background. The width of the lines and the intervals between them were equal and could be varied in number per inch without disturbing the equality of width of lines and of the intervals between them. In Fig. 29 Dr. Cobb's data on the relative visual acuity of the eye for various pupillary apertures are shown in the solid line A. The actual visual angles between the center of a black line and the center of the bright interval are given on the right-hand scale.

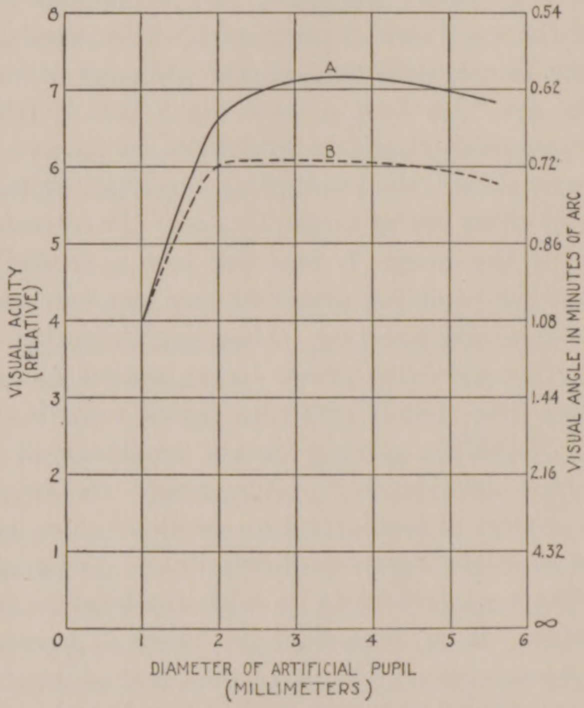


Fig 29. The effect of pupillary aperture on visual acuity. The full line A represents results obtained with various apertures and a test-object of constant brightness. The broken line B represents results obtained with various pupils but with the brightness of the test-object altered in each case to keep the retinal image of constant brightness. The brightness of the test-object was the same for the 1 mm. pupil in the two cases.

It will be noted that this is not a uniform scale. Incidentally the product of the relative visual acuity and the corresponding visual angle is equal to a constant throughout the two scales. It is seen that visual acuity reaches a maximum at a pupillary aperture of about 4 mm. The brightness of the test-object was 189 candles per square meter. However, it is interesting to note that here we have several variables due to the variation in pupil size. As the pupil increases in size, definition decreases but resolving power and brightness of retinal image increase. It has been seen that visual acuity increases as the illumination intensity of the test-object increases. According to Dr. Cobb's data the best size of the pupil from the viewpoint of visual acuity, external conditions being constant, is from 2.5 mm. to 4.5 mm. The diameter of the pupil under satisfactory conditions of lighting is usually in the neighborhood of 3 mm. to 4 mm.

It is interesting to note that over the range of artificial pupillary apertures from 1 mm. to 5.6 mm., the brightness of the retinal image increased over 31 times for the data represented by the solid line A in Fig. 29, although the brightness of the test-object was constant at 189 candles per square meter. Dr. Cobb then conducted the interesting experiment of keeping the brightness of the retinal image constant by decreasing the illumination intensity of the test-object in proper proportion to the increase in pupillary aperture. In other words, when the largest artificial pupil, 5.6 mm., was used the intensity of illumination at the test-object was less than one thirty-first of its value when the 1 mm. pupil was used. The data obtained in this experiment are shown by the broken line B. When the pupil was 1 mm. in diameter, the brightness of the retinal image was the same for each case but the lower visual acuity shows the result of the low constant brightness of the retinal image compared with the continually increasing brightness of the retinal image in the case of the data represented by the solid line. This shows that for a constant brightness of the image on the retina the size of the pupil has little effect on our ability to see fine detail within the range from 2 mm. to 5.6 mm.

This is exceedingly interesting inasmuch as we need not consider the effect of the size of the pupil on visual acuity excepting as it influences the brightness of the retinal image. The latter is a very important factor in lighting because an increase in brightness of the retinal image by an increase in pupillary aperture is just as beneficial to vision as an equivalent increase in illumination intensity when the pupil remains constant in size. The data show that the pupil size does not appreciably alter the standing of the eye as an optical device for seeing fine detail within the range from 2 mm. to about 5 mm. in diameter. This represents a range of brightness of the retinal image of about 6 times. If the pupil could be kept open to a diameter of 5 mm. instead of 2.5 mm. under a certain condition, we would have visual results equivalent to a 300 per cent increase in intensity of illumination. No better argument can be devised against unshaded light-sources, excessive brightness-contrasts and specular reflection of bright images, all of which are glaring and cause the pupil to contract. Well diffused light, properly controlled and distributed, tends to open the pupil and thereby increase the effectiveness of the illumination. It should be noted that even though the pupil may contract upon being exposed to higher brightnesses it also tends to become larger as adaptation to the new condition progresses. Reeves [34] has shown that after a period of 15 minutes' adaptation to darkness, the average size of the pupil for 6 different persons was 8 mm. He repeated the experiment for a number of brightnesses up to 2000 millilamberts (about 4 candles per sq. in.). The average size of the pupil after 15 minutes' exposure to this highest brightness was 2 mm. His subjects were less than middle age. Measurements of the pupil externally yield results slightly greater than the true size of the pupil and, as Reeves pointed out, his values should be decreased by about 7 per cent. In Fig. 30 his data, averaged for six subjects, are plotted to a logarithmic scale of brightness (foot-candles on a surface of 80 per cent reflection-factor) in order to cover an extensive range of brightness. It should be pointed out that the brightnesses of lighting units are ofttimes more than ten times the maximum brightness used by Reeves, and exposed light-sources and

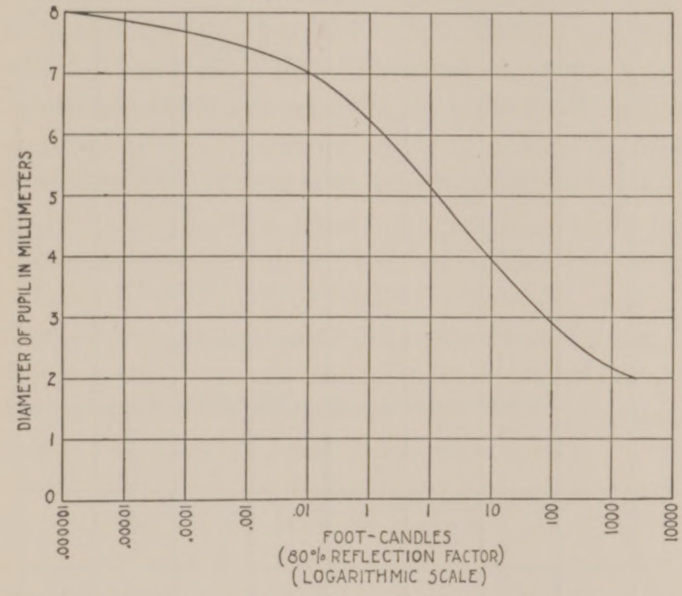


Fig. 30. Showing the size of the pupil after 15 minutes' exposure to various brightnesses from zero to 2000 millilamberts (about 4 candles per sq. in.).

their specularly reflected images are thousands of times greater than his maximum brightness. However, these results are extremely interesting in connection with brightnesses encountered in connection with everyday work under proper conditions of lighting. They show what we may expect of the pupil of the eye. The maximum size of the pupil varied for the different subjects from 7 mm. to 8.7 mm. At 100 ml. the variation was from 2.7 mm. to 2.9 mm.

In Fig. 31 the full line represents Reeves' data on the closing of the pupil after the stimulus was suddenly changed from darkness to 100 millilamberts. These data are the average for six observers. The broken line represents his data on the opening of the pupil after the stimulus, which was a brightness of 100 millilamberts, was suddenly replaced by total darkness. It is interesting to note that the

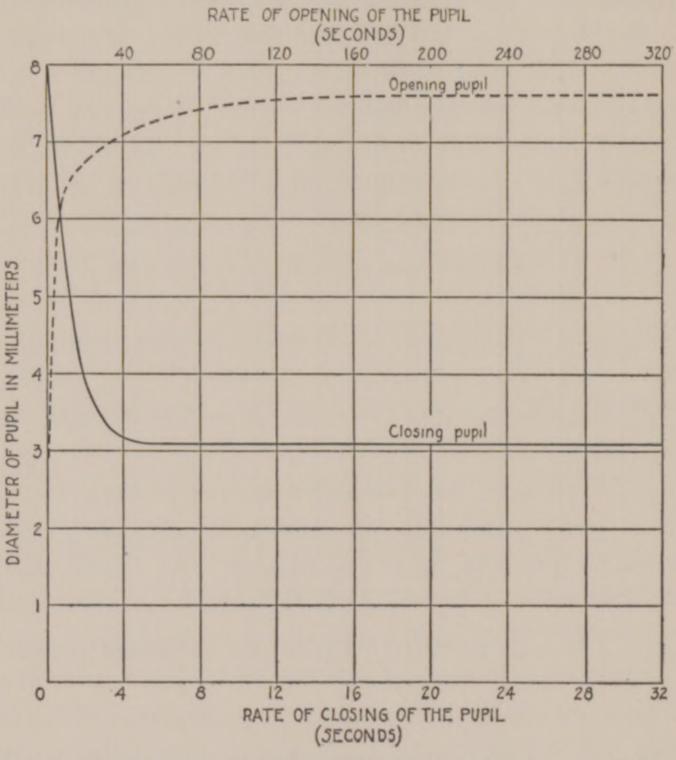


Fig. 31. Showing the rate of opening the pupil after a brightness of 100 millilamberts has been replaced by darkness; and the rate of closing after darkness has been replaced by the stimulus of 100 millilamberts.

pupil requires about as many *minutes* to open to its maximum diameter as it does *seconds* to close to its minimum for the conditions of the experiment. Doubtless, the rate of opening would be increased with very powerful stimuli and possibly the rate of closing would be slower; nevertheless, the great difference between the rate of opening and of closing would not be wiped out. It is such data as these that help us to understand visual results and to predict what we may expect under given lighting conditions.

Adaptation of the Eye

This phenomenon is well known to everyone by experience and, doubtless, everyone knows that it takes time for the eye to adapt itself to changes in brightness. The pupil tries to do its part by changing in size, but there is still a more important adaptation which is retinal or perhaps psycho-physiological. Sometimes in lighting, the question of quantitative data arises; therefore, a brief discussion appears worth while. On coming into a dark room from outdoors

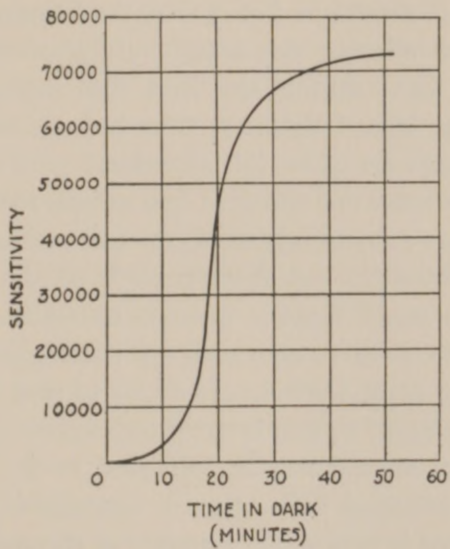


Fig. 32. The increase in sensitivity of the eye with time of exposure to darkness as determined by the minimum brightness perceptible as the time of adaptation to darkness increased.

in the daytime it takes a long time for the eye to adjust itself. The room may not be perfectly dark, but it may seem so for several minutes. The lowest brightness that can be seen at first is many times brighter than the lowest perceptible brightness after adaptation to darkness for ten minutes. The sensitivity of the eye does not reach its highest point until it has been adapted to complete darkness for about an hour. Many have studied the increase in sensitivity of the eye as the period of adaptation decreases. In Fig. 32 the data obtained by Hecht[35] have been plotted. It is seen that the sensitivity of the eye increases very slowly for 5 or 10 minutes and then increases rapidly for the period of 10 to 30 minutes after entrance into a perfectly dark room. It continues to increase in sensitivity up to about 50 minutes. During this entire period the sensitivity has increased over 70,000 times. It may appear from Fig. 32 that practically no change occurs in the sensitivity of the eye to brightness in the early stage of adaptation to darkness, but it should be noted that the large values of the left-hand scale obscure the small values of the first few minutes. In fact, during the first five minutes of dark adaptation, the least brightness that the eye can see drops to about 50 per cent of its initial value.

The slow increase for the first few minutes shows the undesirability of subjecting workers to various levels of illumination intensity for short periods of time. The eye cannot adjust itself rapidly enough to radically different brightnesses to justify tolerance of such conditions even in the same room, if workers are to go to and fro from one level of illumination to another. Furthermore, great brightness-differences should not be tolerated in the visual field. Glare from unshaded light-sources, automobile headlamps, and street-lamps is very much a matter of the state of adaptation of the eye. A lighted match may be glaring to a dark-adapted eye but an electric filament lamp having a brightness and a luminous intensity much greater can be viewed without as much discomfort against the bright sky by eyes adapted to outdoor daylight. An eye adapted to outdoor daylight will tolerate brightnesses thousands of times greater than a dark-adapted eye. The subject is too complex to discuss in detail here but it may be stated as a fundamental of good lighting conditions, that the eyes should not be subjected to sudden changes in brightness or to sudden changes in general levels of illumination of great magnitudes.

The Purkinje Effect

Visible radiations of the shorter wavelengths (violet, blue, green) are relatively more effective in causing brightness-sensation at low intensities than at high ones. The converse is true of visible radiations of longer wavelengths (yellow, orange, red). This phenomenon, discovered by Purkinje nearly a century ago, is of great scientific interest and has some importance in lighting at low intensities of illumination. It is seen in Fig. 22 that the threshold value of blue light is much less than that for red light. This suggests the Purkinje effect. Suppose we equally illuminate a white surface with blue light and one with red light to a brightness equivalent to that of a white surface of 80 per cent reflection-factor under an illumination of one foot-candle of white light. Now if we have some means of reducing the intensity of illumination at exactly the same rate for the blue and red lights, when the brightness becomes equivalent to the white surface under 0.2 foot-candles of white light, the blue will begin to appear brighter than the red. If we continue the reduction, the blue becomes relatively brighter and brighter. Finally, the point will be reached (equivalent to the white surface under 0.001 foot-candle of white light) when the red will be practically invisible but the blue will still be perceptible. If we had increased the intensities instead of decreasing them no such effect would have been found. Perhaps the red would have become slightly brighter than the blue but not very much brighter. Certainly König's data or any data that the author is familiar with do not indicate that this would be true.

It is thus seen that an illuminant that is bluish in comparison with another would be somewhat more effective at very low intensities than the yellowish one. This advantage may be appreciable at intensities of illumination of the order of magnitude of 0.05 foot-candles or less but it is negligible for any commercial illuminants at intensities above 0.1 foot-candle. In signalling and wherever colors of very low brightness are seen by eyes adapted to low brightnesses, this phenomenon may be worth taking into account, but, excepting for very low intensity lighting, it is of little practical interest in general lighting practice. Often claims are made in factory lighting that a yellowish illuminant is not as satisfactory as a white or a bluish one for visibility in the shadows. This is based on the assumption that the Purkinje effect is operative in the shadows while the eye is adapted to high intensities at the work and elsewhere. This assumption is dangerous when it is not supported by reason or by data. The Purkinje phenomenon belongs to the " low " regime of the visual process which can not be appreciably effective when the eye is adapted to high levels of illumination. Furthermore, it has been shown the the Purkinje effect is not perceptible on a portion of the retina when other parts of the retina are subjected to ordinary brightnesses.

It is also of interest to note that there is no evidence of the Purkinje effect in the central portion of the retina over an area at least 2 degrees of visual angle.

Growth and Decay of Visual Sensations

A sensation of brightness or of color does not grow immediately to its full or final value the instant the image is focused on the retina, and it does not immediately decrease to zero when the stimulus disappears. In fact, the brightness-sensation due to a certain stimulus " overshoots " at first if the stimulus is bright enough. Doubtless many persons have noticed this in turning on the electric filament lamps in a room. Those who have not may be interested to note the slight "overshooting" of general brightness of the ceiling, for example, an instant after the switch is pushed. It is more readily noticed if the lighting is of unusually high intensity. This point is not of general interest but it arises in some of the more scientific phases of lighting.

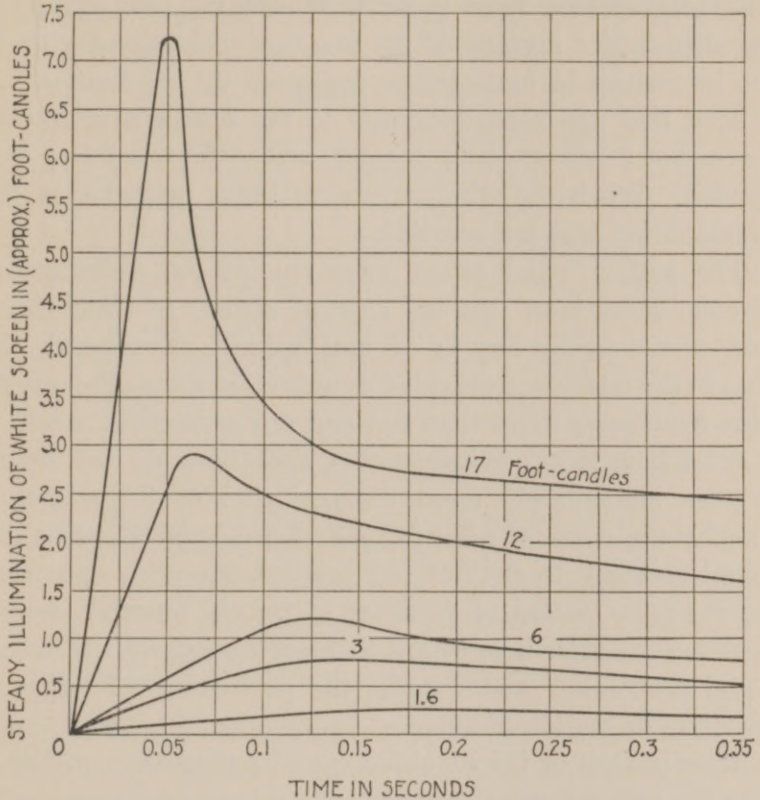


Fig. 33. Illustrating the overshooting of brightness sensation. The figures are foot-candles and the brightnesses are those produced by these illumination intensities on a so-called white surface of 80 per cent reflection-factor.

At any rate, it is of some interest in connection with the operation of the visual sense-organ. It can be demonstrated by means of specially constructed rotating disks and in other ways.

The phenomenon is shown in Fig. 33 by means of data obtained by Broca and Sulzer.[37] They compared the brightness of a so-called white screen under a certain intensity of illumination with a steady brightness at various intervals after the illumination was applied to the white screen. They used five different brightnesses obtained by illuminating the white surface to five different intensities of illumination. The brightnesses were those produced by illuminating a so-called white surface of 80 per cent reflection-factor to the intensities in foot-candles indicated by the figures. It is seen that the sensations due to the higher brightnesses "overshot" about 0.05 second after the stimulus was applied. When the stimulus was of lower brightnesses the overshooting was not marked.

The author[36] and others have studied the overshooting of color-sensations. In the case of signals of short duration this overshooting is of real value. In general, the hues in the mid-spectral region overshoot less than the others. Blue overshoots more than red and red more than green.

After-images are evidence that sensations do not decay to zero immediately upon the cessation of the stimulus. Usually the color of after-images of a colored stimulus are complementary to that of the original stimulus, excepting for the early period of decay of extremely powerful sensations. Such after-images are to be reckoned with in many visual problems. Incidentally, the persistence of vision is the basis of motion-pictures.

After-images of bright objects, and particularly of light-sources, are not only annoying but often are temporarily blinding. Many accidents are caused by glaring light-sources in factories and on the streets. When not actually a source of danger they reduce the ability to see. This is one of the powerful arguments against glaring or unshaded light-sources in lighting systems. The author attempted to measure the duration of after-images by measuring the time it took them practically to disappear. The data are presented in Fig. 34. The highest brightness employed was that of the brightest electric filament lamp at the time. This was the vacuum tungsten lamp and the brightness of its filament was 1080 candles per sq. in. The duration of the after-image increased with the time of exposure to the bright filament. In the case of the highest brightness of filament, looking at the filament for one second caused an after-image that endured for 45 seconds. Exposing the

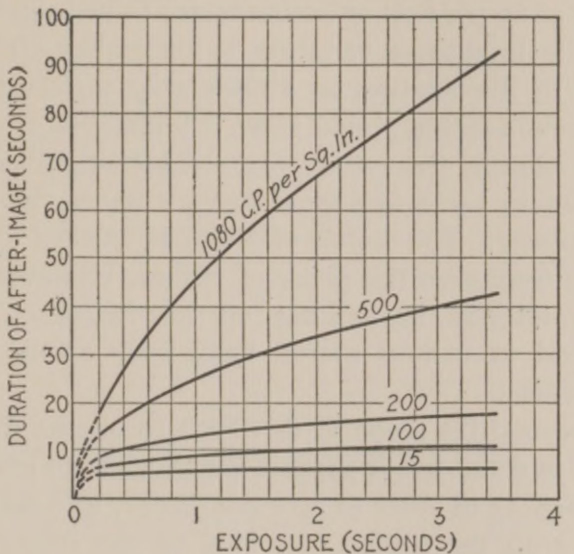


Fig. 34. Showing the duration of after-images from exposures of various lengths to light-sources of different brightnesses.

eye to it for 3.5 seconds increased the duration of the after-image to 93 seconds. As is well known, the after-image is blinding at first and, when it is considered that vision is interfered with for an appreciable period, it is not surprising that production increases in offices and factories when such exposed sources are replaced with suitable shades or diffusing equipment.

The frequency at which a flicker disappears depends upon the maximum brightness and upon the wave-form. The vanishing-flicker frequency increases with the brightness and is greater for a cycle in which the change in brightness is abrupt than for one in which the change is gradual.[36] Owing to the lag in cooling and heating of a lamp filament we generally have a flicker superposed on a steady average brightness and it is invisible excepting at low frequencies. For 25-cycle electric energy this superposed flicker is apparent on surfaces that are relatively bright. For example, a certain intensity of illumination may cause a surface of 80 per cent reflection-factor to be bright enough so that its brightness variation is noticeable. The same intensity of illumination on a dark gray surface of 8 per cent reflection-factor, would cause a brightness of only one tenth of that in the former case. This brightness might be too low in value to appear to vary under the 25-cycle electric energy. The matter of flicker is touched upon here chiefly to emphasize this phase of vision. However, it is of practical interest in lighting on low-frequency electric energy and in various special fields such as the motion-picture screen.

It is beyond the scope of this book to discuss this phase of vision in detail but it appears worth while to present the data in Fig. 35 in order to give the reader, who may be unfamiliar with the subject, an idea of the frequencies at which flicker vanishes. In this case the cycle of varying brightness is one-half bright and one-half dark and the change from one to the other is abrupt. It is produced by means of a rotating disk, with equal open and opaque spaces, placed between a light-source of small dimensions and the surface illuminated. The frequency of flicker (cycles per second) is increased until the flickering brightness of the illuminated surface disappears. Inasmuch as the brightness of the surface depends on both the intensity of illumination and the reflection-factor of the surface, curves are plotted of vanishing-flicker frequency for surfaces of different reflection-factors for the same range of illumination in foot-candles. It is seen that for surfaces in general the rise in this critical frequency is most rapid below five foot-candles. It should be particularly noted that this is a case of complete and abrupt change from bright to dark and that the period of bright and dark are equal. The author [36] has shown the effect of wave-form of the

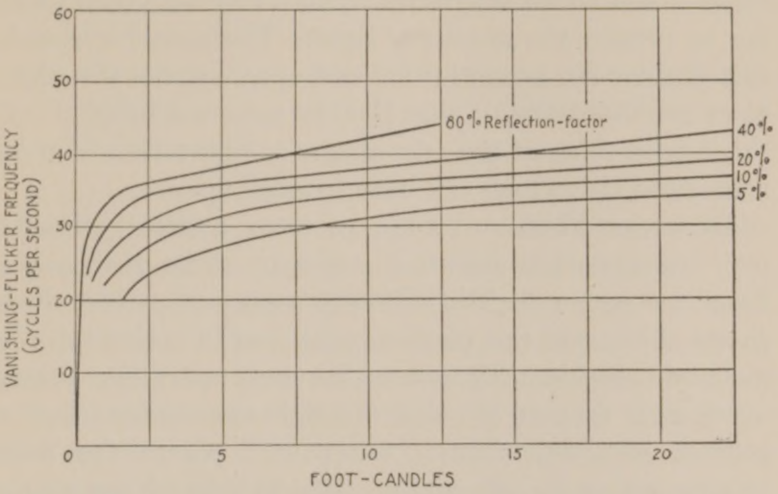


Fig. 35. The frequency at which flicker disappears for surfaces of various reflection-factors illuminated to various intensities as indicated by the horizontal scale. The flicker was caused by abrupt changes from bright to dark, the periods of bright and dark being equal.

cycle elsewhere, but the oniy cases where flicker is more persistent is when the period of darkness is much greater than the period of light.

External Factors in Vision

Although in previous chapters many of the fundamentals of vision have been presented, there are many other details of vision that have not been touched upon. In general, we see by virtue of our ability to distinguish differences in brightness and in color. The eyes and the visual processes involved are not the only factors in vision. There are external factors equally important, such as the direction, the diffusion, the quantity, the distribution, and the quality of light. Shadows play a part as well as high-lights. Backgrounds are sometimes very important. In other words, if we are to produce the best conditions for seeing, we must aid the visual sense by giving the best conditions to these external factors. If we had only the eyes to consider there would be little that we could do to aid vision excepting to furnish the necessary light. The data presented in this chapter are generally for two eyes but the test-objects were two-dimensional; that is, they were not in relief. For this reason some of the advantages of binocular vision over monocular vision have not been touched upon.

Binocular Vision. Two eyes have a great advantage over one eye when objects in relief are to be distinguished. Each eye sees a slightly different aspect of a three-dimensional object and this plays a great part in giving the effect of relief. Incidentally, one of the most marvelous features of vision is that we see objects out in space where they are instead of seeing them "internally" where the retinal images are or in our brain. This is one of the greatest examples of learning. The various muscular stresses such as those due to convergence of the eyes, we have learned to interpret in terms of external space. Two eyes greatly extend our interpretation of the external world.[42] Knowledge plays an important part and where our knowledge is supposedly accurate, but is actually erroneous, we misjudge or are confronted with illusions. In any thorough study of lighting conditions in relation to vision, the added advantages of binocular vision should be taken into consideration.

The principal modes by which we perceive the third dimension of space and of objects and other aspects of the external world are as follows:

a. Extent
b. Perspective
c. Elevation of objects
d. Variation of light and shade on objects

e. Variation of visor angle in proportion to distance
f. Muscular effort attending accommodation of the eyes
g. Muscular effort attending convergence of the axes of the eyes
h. Interference of near objects with those more distant
i. Stereoscopic vision
j. Clearness of brightness or color as affected by distance (of interest only outdoors for great distances)

Shadows. The area on an object which does not receive the dominant direct light we will term the *shadow.* The shadow of an object cast upon another surface we will term the *cast shadow.* These play very important parts in seeing objects.[6] Without them objects would be invisible when the background was of the same brightness and color. Sometimes it is the shadow cast by the object upon another surface that reveals the object to us. The size of the light-source or, to be exact, the solid angle subtended by the light-source determines the character of the shadow-edge. The sun causes a fairly sharp shadow; the sky a very indefinite one. So it is with artificial lighting equipment. Small sources of light cause sharp shadows. Larger diffusing glass units produce shadows with softer edges. Ceilings produce effects corresponding to the sky. The position of the light-source determines the position or direction of the shadow. The amount of scattered light from the ceiling and other areas determines the brightness of the shadow. If details are to be seen in shadows the latter should be luminous. In such cases the shadow should receive not less than 10 per cent as much light as an adjacent surface under full illumination. Of course, this cannot be adhered to strictly but it represents at least a limit of desirability. When details are not to be seen in the shadows, vision will usually be aided if the shadows are very dark. In general, multiple shadows are confusing to vision, so that it is desirable to have a predominant light-source.

Highlights. These are the complementaries of shadows and they are important much in the same way. The object is often distinguished by the contrast between highlight and shadow and the form is often distinguished by the character of the highlight or by the modulation between highlight and shadow. A cylindrical polished object has a linear highlight, a spherical one a small highlight, etc. Sometimes we distinguish an object only by its highlight. This is particularly true of small objects, such as fine wire.

Backgrounds. Inasmuch as contrast is essential to vision our control of background can be used to great advantage. We can make the background very much brighter or very much darker than the object we wish to see. The smaller the object the greater is the contrast necessary to see it. For opaque objects we can use illuminated backgrounds of as high brightness as necessary. This is a very satisfactory method of seeing in many cases, such as photographic negatives. However, it is often impracticable and is generally more trying on the eyes than the dark background. A fine polished wire can be seen best as a brilliant highlight on a dark background. The latter can be obtained practically black by providing a hole in a box lined with black velvet. Practically no light comes out of this hole, therefore it is nearly perfectly black. The highlight on the fine wire can be easily obtained by means of a local light-source well shaded from the worker's eyes. This kind of fine work requires local light-sources supplemented by general lighting. A few years ago there was a tendency to condemn localized light and to solve all lighting problems by general lighting. It was obvious at that time that those advocating such a procedure were not thoroughly familiar with the details of lighting and vision.

Color can be used in the background sometimes, but it should be a shade of a tint of a mid-spectrum hue, such as green, yellow-green, or yellow. In many places one will find operators working without plain backgrounds against which to see the work notwithstanding the installation of backgrounds would be simple, inexpensive, and effective.

In the use of bright backgrounds against which dark details are seen, it should be noted that irradiation — the spreading of the bright areas over the dark areas — tends to decrease the apparent size and therefore the visibility of the dark details. On the other hand the fine detail seen as a highlight is apparently enlarged and therefore more visible. An exaggerated case is a glowing filament of a lamp. It appears many times larger than it actually is. Even at a low voltage when it barely glows it appears much larger than it is. When the filament is "cold" it is scarcely visible.

An interesting experiment of the effect of background can be performed by stretching fine wires across strips of white, gray, black paper and black velvet. By experimenting with highlights on the wires, and by using dark and light wires, some interesting observations can be made.

Chapter IX

SPEED OF VISION

SEEING is a commonplace achievement in which we are seldom confronted with the element of time. Even more rarely are we conscious of time as a factor. However, work is an integral in which time is a vital factor, for the output of any worker or group of workers is directly influenced by the "speed" at which individual acts are accomplished. In general, any operation at which a worker is engaged involves visual discrimination, mental decision, and muscular activity. The relative importance of these may vary considerably with different operations, but vision in most cases plays an important part. The trained operator becomes almost an automaton, accomplishing the various visual, mental, and muscular acts almost unconsciously or at least in apparent abstraction.

Workers may differ in output for a given time because of the fundamental individual difference in alertness or speed of reaction. In all operations involving vision, and all do to some degree, the individual must see what it is necessary to see. He may do so quite unconsciously, nevertheless he must discriminate. For example, if he is inspecting material for flaws, he must see the flaws or overlook them. If they are present and he does not see them, he has not done his work well. If the lighting is inadequate or improper, his ability to see is reduced and he must look slowly and carefully and perhaps go over the same ground more than once. This consumes time and if the visual part of the entire operation is appreciable, the time consumed is appreciable. Of the time consumed in visual discrimination, a portion of it is lost unless the lighting is best for that particular problem of seeing. This would be very obvious if the visual act required a long time, like looking for a fine mark on an object. However, it is just as true in operations in which each individual visual act occupies only a short time. It should be obvious that lighting has a great influence on ease of seeing; therefore, we would expect lighting to play an important part in the output of most workers. As a matter of fact it does and to an extent unsuspected by most persons. One needs only to observe persons at work here and there to be convinced of the handicaps of improper and inadequate lighting. The eyes may be squinted, the head screwed around, the object turned over and what not before the visual act is completed when it could have been achieved under proper and adequate lighting in a straightforward manner with less strain on the operator and lower cost.

The speed of discrimination or speed of vision, as it is termed for the sake of brevity, involves all factors of light and lighting which influence our ability to see differences in brightness, color and fine detail. In the general case those factors influencing the discrimination of color also may be important. However, in actual practice after the quality of light is chosen, the chief factors of light and lighting are the intensity of illumination, the distribution of light and brightness, and the direction of light. Of these, the first is still of interest even after the others have been taken care of in *proper* lighting, for we have the possibility of increasing the intensity of illumination to a very high value before reaching a point where the advantage to vision ceases to increase correspondingly. This point is well proved in Chapter VIII. Some of these visual laws have been known for years. Furthermore, reaction-time has been studied for years and it has long been known that intensity of illumination and brightness are important factors in the time involved in the act of discrimination. However, for some reason (perhaps the previous relatively low efficiency of light production) the time element in seeing has not received much consideration until recently.

Tests in the industries are showing that production is increased when better lighting is substituted for poor lighting. Some of the data are presented in Chapter X. Valuable as these tests are, it is necessary to depend upon laboratory experiments to analyze the possibilities. Experiments in the industries should be continued, as doubtless they will be, but these are not subject to the control necessary to unravel the complexity of human activity which involves vision. Thus we need and welcome the data obtained in laboratory researches.

The effects of quality or spectral character of light have been discussed in other chapters; therefore, for the present, only the effect of intensity of illumination will be considered. Unless otherwise stated, all other factors are maintained constant in each of the researches described herewith.

The illuminant in all cases is the light from tungsten filament lamps which has a continuous spectrum as shown in Fig. 19. Its color is a yellowish white; that is, a very unsaturated yellow.

Inasmuch as most laboratory tests are made with black characters on a white background, it should be noted that this is a much better condition of visibility than the lower contrasts involved in most industrial operations. For this reason, it is well to perform laboratory tests with objects of reduced contrast, such as black on medium gray or dark gray. In general, it is found that visibility and speed of discrimination are of lower values under a certain intensity of illumination when the test-object is of low-contrast than when it is black and white.

Speed of Discrimination of Very Fine Detail

Although most of us seldom find it necessary to discriminate the finest detail that we can see under a given condition of lighting and surroundings, this so-called visual acuity is an important phase of vision from a scientific viewpoint at least. The data yielded by tests of visual acuity are also of significance in everyday work, but they are often overestimated. When applied to any particular eye they are usually a measure of the "factor of safety" of the eye in the discrimination of detail because most eyes are not required to do much discriminating of details at the threshold of visibility. In Chapter VIII it is seen that visual acuity increases as the intensity of illumination increases. The time required to discriminate or to recognize (that is, to see) a small object, decreases as the intensity of illumination increases. The speed of discrimination is the reciprocal of this time usually in seconds. The size of test-objects used in visual-acuity tests is given in terms of visual angle because such a specification involves both the actual size of the object and its distance from the eye. For objects very small in comparison with their distance from the eye, the visual angle is approximately proportional to size of the object divided by its distance.

In order to illustrate the effect of intensity of illumination on the speed of discrimination of fine details, the work of Ferree and Rand [49] will first be drawn upon. By speed of discrimination is meant the reciprocal of the time in seconds required for the observer to see the missing portion of the split ring. They used the international test-object consisting of a black ring on a white ground, a portion of the ring being missing. In other words, it is a black split ring on a white ground as shown in Fig. 36. The visual angle is that subtended by the dimension of the missing portion *a* of the black ring at the distance of the eye from it. This ring is rotated into various positions so that the observer must not only distinguish the missing portion, but, to make certain that he does, he is obliged to state in what position this missing segment is.

Ferree and Rand employed four visual angles, 1.15, 1.73, 2.49, and 3.45 minutes of arc, and illuminated the test-object with unaltered light from tungsten filament lamps. The visual angle of 2.49 minutes of arc is approximately equivalent to the visual angle subtended by the details of 10-point type at a distance of 13 inches. In order to give a further idea of small visual angles some data have been presented in Table XI. These data are plotted in Fig. 25.

Fig. 36. The international test-object for visual acuity. The dimension of the opening *a* determines the visual angle when distance from the eye is taken into account. The subject not only must see the discontinuity of the ring but must state in what position it is. Several sizes and positions are reproduced herewith so that the reader may compare them at a distance at which the smallest is not seen as a *split* ring.

The smallness of detail which can be distinguished by normal eyes depends largely upon retinal structure, but, for defective eyes, astigmatism and other errors of refraction may play a major part in lowering visual acuity. The limiting visual angle for normal eyes is about 40 seconds or 0.67 minutes of arc. That is, two objects separated by less than 0.67 minutes visual angle cannot be seen as being separated by most eyes that can be classed as normal.

In Fig. 37 are plotted the relation between intensity of illumination and the speed of discrimination of the international test-object (black split ring on white paper of 80 per cent reflection-factor) of the four different sizes or visual angles as obtained by Ferree and Rand. It is seen that over a range of intensity of illumination up to 12 foot-candles for the black-white test-object, the speed of discrimination increases and shows signs of continuing to increase far beyond this highest intensity of illumination.

If the test-object was truly black and the background was a dark gray of 8 per cent reflection-factor, the identical results shown in Fig. 37 would have been obtained under illumination intensities exactly ten times the values shown in the lower horizontal scale. For this reason the upper

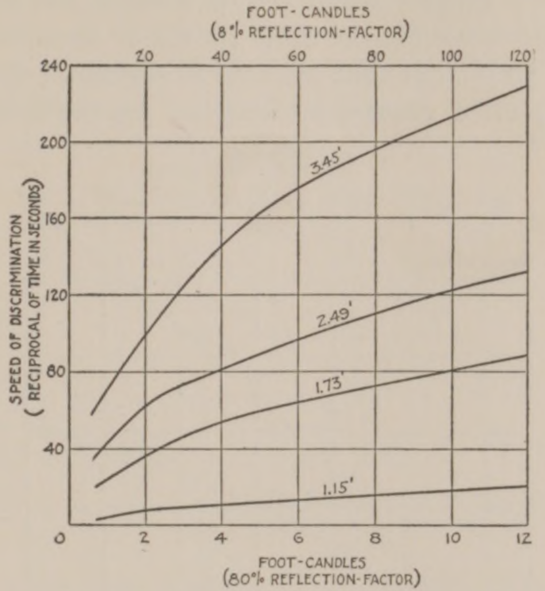


Fig. 37. Showing the speed of discrimination as affected by intensity of illumination (brightness of background) for black test-objects of four different sizes (visual angles 1.15, 1.73, 2.49 and 3.45 minutes. The lower scale represents the illumination of a colorless background of 80 per cent reflection-factor against which the test-object was viewed. If the background were a dark gray of 8 per cent reflection-factor, the foot-candles must be multiplied by 10. Thus the upper scale fits the data equally well assuming that the test-object was truly black on the background of 8 per cent reflection-factor.

scale is applied. If the upper and lower scales are reduced to brightness scales they will be identical. If any other reflection-factor of background is to be considered, the foot-candle scale can be constructed accordingly. It is only necessary to reduce it to the same brightnesses as the two scales given. Another point should be mentioned and that is, the fact that the so-called black of the test-object was not truly black. It reflected a slight amount of light — maybe as much as 2 or 3 per cent. Assuming it to be on the dark gray background of 8 per cent reflection-factor, it is seen that the contrast would be considerably less than true black on this same dark gray. However, this would require even greater intensities of illumination than those of the upper scale for the same speeds of discrimination.

In Fig. 38 the per cent increase in the speed of discrimination is plotted against foot-candles for the smallest and

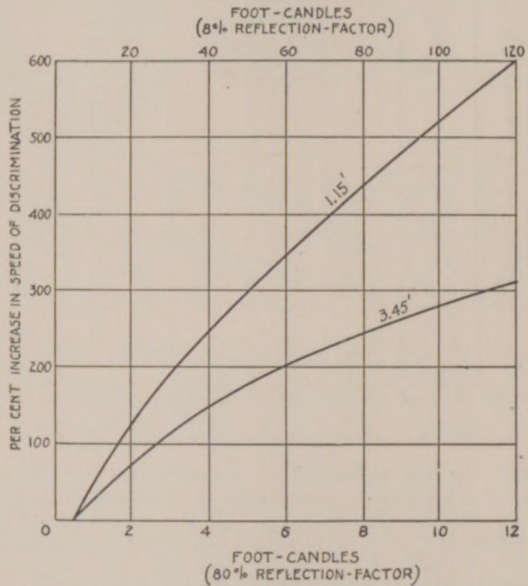


Fig. 38. Data in Fig. 37 for the smallest and largest test-objects are plotted in terms of per cent increase in speed of discrimination for the same range of foot-candles on the two backgrounds (so-called white and dark gray).

the largest test-objects (visual-angles) represented in Fig. 37. It is seen that the speed of discrimination increases more for the smallest test-object. The curves for the two intermediate test-objects if plotted from Fig. 37 on Fig. 38 would fall between those for the largest and smallest. It is seen that the per cent increase in speed of discrimination is greater for the smaller test-object.

In this investigation 13 observers were used. It is to be expected that the effect of increase of illumination becomes less as the visual angle or size of the test-object is increased; however, there is good reason for believing that there is a considerable effect for objects subtending much larger visual angles. Certainly for the lesser contrast (upper scale) speeds of discrimination, comparable with those of black-white contrasts of the greater values, require illumination intensities of 100 foot-candles or more.

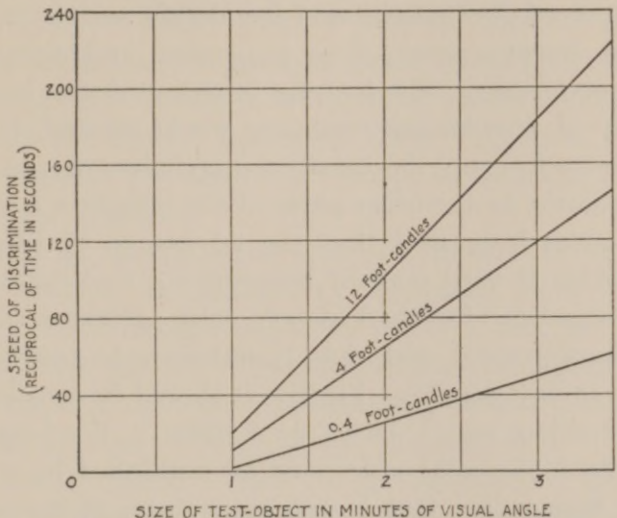


Fig. 39. Showing the relation between visual angle and speed of discrimination for three intensities of illumination on the black-white test-object. If the test-object were truly black and were seen against a background of about 8 per cent reflection-factor these foot-candle values would be ten times greater.

The relation between visual angle and speed of discrimination for three intensities of illumination on the black-white test-object is shown in Fig. 39. In plotting these data the author has taken the liberty of drawing straight lines because they " fit " the data fairly well and simplify the diagram somewhat. It is seen that the time required to recognize the test-object decreased (speed of discrimination increased) as the visual angle increased. Furthermore, the increase of discrimination as the visual angle increased was greater for a high intensity of illumination than for a low one.

In general, these data show that speed of vision (of seeing, of recognition, of discrimination) increases as the intensity of illumination increases. By extension it may be safely predicted that, other conditions being equal, a group of workers would turn out more work under a high intensity of illumination than under a relatively low one, when the work involved discrimination of fine details such as in weaving, fine machine work, close inspection, and many other factory operations. The increase in output due to increased intensity of illumination doubtless would depend, to a degree at least, upon the relative proportion of the visual discrimination to the other parts of the complete operation. In all cases it is seen that the advantage of increasing illumination is very marked between 0.4 foot-candles and 12 foot-candles (for black details seen against a so-called white background) and that it promises to continue far beyond 12 foot-candles. Finally, it should be recalled that this test-object was "black" on "white." For lesser contrasts the foot-candle scale must be multiplied by a factor greater than unity; that is, the percentages of increase for intensities in the region from 2 foot-candles to 10 foot-candles would be greater even than with the high-contrast test-object which was used. Much of our vision is concerned with lesser contrasts and the foot-candles required increase directly as the reflection-factor of the background decreases for black details seen against it. For other lesser contrasts, for example, light gray on white or dark gray on medium gray, the intensities required for equal visibility and speed of discrimination are much greater than for black on white. Therefore, the upper foot-candle scale has been introduced in Figs. 37, 38 and 39. (See Figs. 56 and 57.)

Dr. P. W. Cobb,[45] who for many years has contributed results of extensive researches carefully executed, has recently begun to report results of various experiments on the time required to recognize an object. Much of this work is particularly important in analyzing the various influences which aid or hamper vision. He used several test-objects. Some of them appeared to the observer out of a clear field; others were preceded and followed by "confusion patterns." In the former cases, the observer fixed his eyes on a point where the dot was to appear but the field was without pattern. In the latter cases, the observer fixed his eyes upon the point where the test-object was to appear, but before it appeared another pattern was presented for a short interval of time. This was followed immediately by the test-object and it in turn was followed by another pattern.

In Fig. 40 is shown the effect of illumination intensity on the speed of discrimination of a circular black dot on a so-called white background of 80 per cent reflection-factor. The black dot was 0.167 inches in diameter and was viewed at a distance of 19.7 feet. Its diameter, therefore, subtended an angle of 2.43 minutes at the subject's eyes. The dot was actually black; that is, its brightness was zero. The dot was preceded and followed by a blank field of the same brightness as the background upon which the dot was seen. In such experiments it is essential to *know* whether or not the observer really sees what he says he does. In these experiments the exposures were made in groups of ten consecutive ones. The dot was present five times and absent five times, the order of absence and presence being haphazard. The observers reported when the dot was present and when it was not. In each subsequent group of ten, the exposure was shortened until the results showed that the dot was no longer seen with certainty. It is seen in Fig. 40 that the speed of discrimination is still increasing at 130 foot-candles (on the white background) and that at illumination intensities below 10 foot-candles, which are those most prevalent indoors, the speed of seeing the black dot is far below its value at 50 foot-candles, for example. It is to be noted that the maximum speed has not been reached at 130 foot-candles on the white background

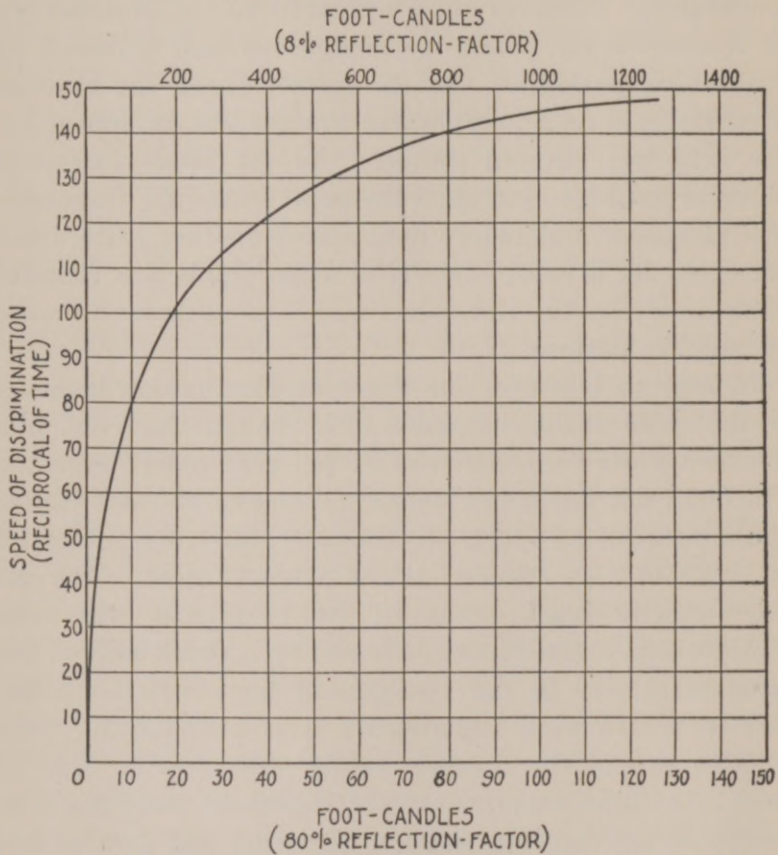


Fig. 40. Showing the speed of discrimination of a black dot (2.43 minutes visual angle) on a so-called white background (80 per cent reflection-factor for a range of illumination up to 150 foot-candles. The upper scale is for a truly black dot on a dark gray background of 8 per cent reflection-factor.

and there is no indication that it will be reached until much higher intensities are reached. This is in line with much of the data pertaining to visual laws which have been available for a long time. Furthermore, it is what would be expected from eyes and visual processes adapted for countless thousands of years to very high intensities outdoors.

Inasmuch as this test was for a black dot on a white background, it is of interest to inquire what would be the corresponding intensities for the same black dot when seen on a background of low reflection-factor. As has been done in the previous cases, a very dark gray background of 8 per cent reflection-factor is taken as representing a common extremely low contrast. The corresponding foot-candle scale is added at the top of Fig. 40. It is now seen that a point just above the bend of the curve corresponds to about 500 foot-candles for this low-contrast test-object; however, as Dr. Cobb has pointed out, the position of the knee of the curve depends upon the range of the scale plotted. This is discussed in Chapter XIII. Speed of discrimination is still increasing even at 1000 foot-candles. It is recognized in this case the dot was truly black, so that this transformation from lower to upper scale, in replacing the background of 80 per cent reflection-factor with one of 8 per cent reflection-factor, is strictly correct. Usually " black," reflecting some light as it does, results in a lower contrast than the low one represented by the upper scale. Hence, the foot-candle values in the upper scale should be even larger in most cases.

Speed of Reading

The choice of a test-object for a visual test is always a matter of serious consideration. It should be one easily described and reproduced; it should be such as to yield results that may be interpreted to some extent in terms of everyday visual operations; and it should be one that is sensitive enough to provide a measure of the influences under consideration. Reading is a very commonplace activity and reading matter can be accurately described and reproduced. Desirous of obtaining some measure of the effect of illumination intensity upon the speed of reading, the author and his colleagues chose reading matter in one of the initial investigations.[22]

Contrary to general opinion, ordinary reading is not solely a matter of visual acuity or the ability to see fine detail. Visual acuity is a measure of the finest detail that can be seen under a given set of conditions. The individual letters of a printed page are rarely so small as to be just visible under ordinary lighting conditions. In fact, they are many times larger than the smallest that we could see under the conditions. Furthermore, it is known that in reading, the eyes do not move at a uniform speed across the page. They jump from point to point, pausing in steady fixation usually from two to seven times across the ordinary four- or five-inch line. During these jumps the eyes cannot possibly see clearly any more than they could see rapidly moving print when they were fixed upon a stationary point. Clear vision not only takes place when the eyes are stationary, but, as shown in Fig. 28, visual acuity is marked only at the point of the retina intersected by the optical axis of the eye. In other words, ordinary reading involves recognition of groups of letters, and even of words, a great deal larger than the smallest which can possibly be seen under the average conditions of lighting. For this reason the results of visual acuity tests are not necessarily the same as those of reading and most visual acts, although there is bound to be a similarity.

A further reason for adopting the reading test was to develop a method of measuring the effect of illumination intensity on speed of vision without requiring a summary of data; in other words, to devise a "direct-reading" apparatus. A number of test-objects were used, such as lines of various kinds, letters and other characters, and different styles of reading matter. The contrast in the test-objects was chiefly that resulting from "black" ink on "white" paper, but later this contrast was reduced in the case of the most successful reading test-object (reading matter in Old English type) by decreasing the reflection-factor of the paper. The number of observers varied from 37 to 49 persons under middle age.

Eventually, after using various test-objects, the general plan adopted was to have an observer read aloud from a column of reading matter attached to a revolving drum *C*, Fig. 41, the speed of which he adjusted to correspond to his

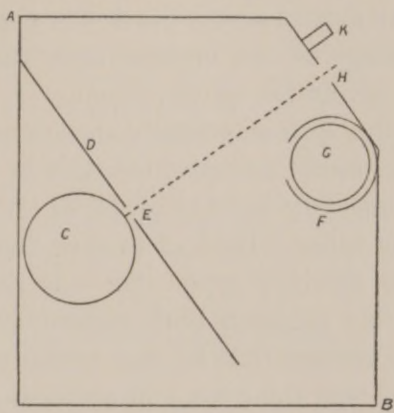


Fig. 41. Apparatus used for speed of reading tests. Old English print revolved on the drum *C* under the slit *E* which was viewed from *H* with the head resting on *K*. The light-source was *G* in the shield *F* and the intensity was controlled without change in quality. *D* was a screen of the same general brightness of the printed matter at all times.

highest rate of reading under a given intensity of illumination. A screen *D* with a horizontal slot *E* at the center concealed from view everything excepting three or four lines of the Old English reading matter. The screen was of the same general brightness as the white page at all times. When the speed of the drum and the observer's highest rate of reading did not agree, his reading would be intercepted by either one or the other edge of the slot. The speed of the drum, when properly adjusted by the reader for his maximum speed of reading under the particular illumination intensity, was read from the miles-per-hour scale of an automobile speedometer which was attached to the motor which drove the drum. The speed of the motor was controlled by means of a rheostat. The observer placed his forehead at *K* and looked through the slot *H*. The light-source was confined in a diffusing glass cylinder *G* and illuminated the reading matter through a slot in the opaque cylinder *F*. In order not to vary the color of the light, *G* was covered with tinfoil from which pointed " teeth " were cut. These teeth moved across the slot in *F* as *G* was turned and the percentage of the opaque area varied from zero to 100 for one revolution of the drum.

The Old English type was finally chosen because the rate of reading it was more uniform inasmuch as the reader was unable to recognize any word or group of letters much more readily than any other. He had to give strict attention to reading this less familiar type. He was required to read aloud because this required both mental and physical activity and made certain that he was actually reading every word. The type was clear-cut and uniform and was in the form of two narrow columns without paragraph indentions. It contained no uncommon words and the subject matter was such as would not require unusual thought or concentration on the part of the reader. Incidentally, such a test also introduces a condition not usually found in laboratory tests, but which is almost always found in practice. That is, the retina is pre-exposed all the time to various images so that the effect of after-images of various patterns is always present as it usually is. Other details will be found in the original paper.[22]

The results of this investigation are plotted in Fig. 42, for reading black print on white paper (Curve B) and black print on gray paper (Curve A). The reflection-factor of the white paper was 80 per cent and of the gray paper was about 23 per cent. On increasing the intensity of illumination from 0.4 foot-candles to 4 foot-candles, the speed of reading increased 54 per cent for the high-contrast test-object. On increasing the intensity of illumination from 4 foot-candles to 16 foot-candles the speed of the reading increased 15 per cent for the high-

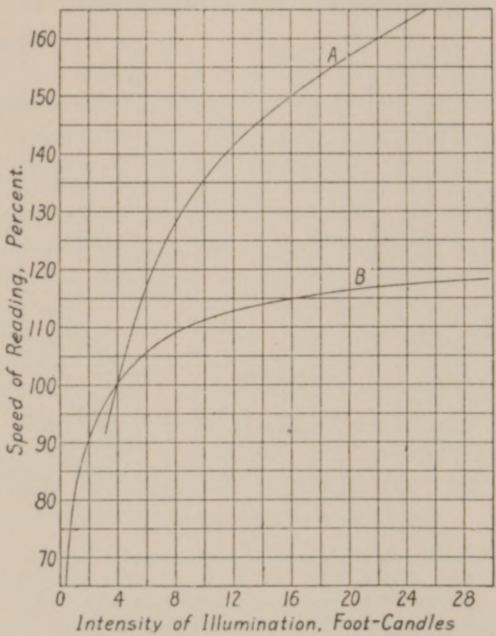


Fig. 42. Effect of intensity of illumination on the speed of reading. A is for a low-contrast test-object (black print on a background of 23 per cent reflection-factor). B is for the usual condition of black print on a white paper of 80 per cent reflection-factor.

contrast test-object and 50 per cent for the low-contrast test-object. It is seen that the influence of intensity of illumination is very marked in both cases but much more so for the low-contrast test-object. The latter contrast more nearly approaches the contrasts ordinarily encountered in vision than the black-white contrast does, with the exception, of course, of reading and some other work where white backgrounds are employed. It will be noted that the two curves are made equal at 4 foot-candles. Of course, the speed of reading A was actually much slower than B.

It is also of interest to plot these data in terms of the brightness of the background as in Fig. 43 instead of in terms of foot-candles as in Fig. 42. Now the results would be the same if the black ink was really black or non-reflecting. But ink is far from black and the results still

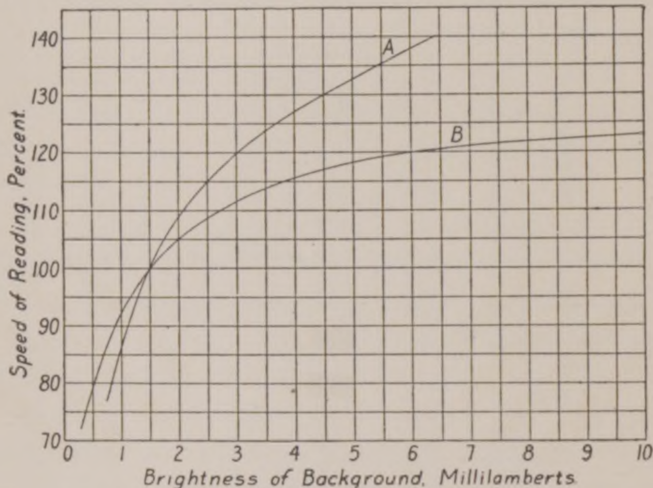


Fig. 43. Relation of brightness of background (the blank page) and speed of reading. (Data from Fig. 42.) *A* is for low contrast (black print on gray paper of 23 per cent reflection-factor) and B is for high contrast (black print on white paper of 80 per cent reflection-factor).

differ as shown in Fig. 43. This is of particular interest in indicating that the foot-candle scales (for surfaces of 8 per cent reflection-factor), which have been inserted on a number of illustrations in this and the preceding chapter, are above criticism. That is, the values should really be increased, as intimated several times, to allow for the effect of reflection of light by the so-called black test-objects in decreasing the contrast to a lower value than that due to a perfect black on a dark gray of 8 per cent reflection-factor. (See Figs. 56 and 57.)

It is seen in both Fig. 42 and Fig. 43 that the speed of reading shows signs of still increasing beyond the highest intensity of illumination (30 foot-candles) showing that the advantage of increasing illumination extends beyond this. This indication is very marked in the case of the low-contrast reading matter.

Speed of Discrimination as Affected by "Confusion-Patterns"

Let us again take up some of the more recent work of Dr. P. W. Cobb[45] in which he introduces the confusion field before and after the exposure of the actual test-object. His test-object consisted of two black bars as shown in *b*, Fig. 44. These could be rotated so as to present them in various

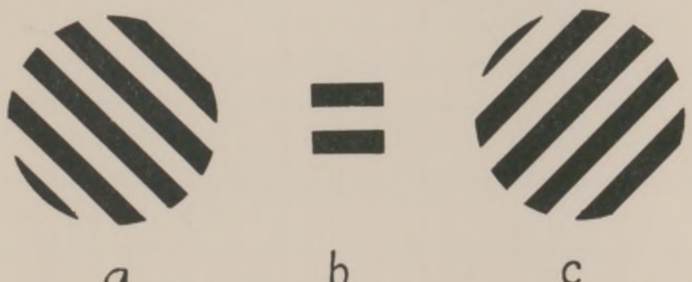


Fig. 44. The test-object *b* is preceded by *a* and followed by *c*. These confusion fields *a* and *c* have a marked influence upon the time required to distinguish *b*.

positions to the observer. The two other patterns, *a* and *c*, are confusion fields introduced respectively before and after the test-object *b* was presented. In Fig. 45 the curve A shows the relation of speed of discrimination of the test-object *b* preceded and followed by a blank field of the same brightness as the background of the test-object *b*. The curve B represents the relation found between speed of discrimination and intensity of illumination of the same test-object, but in this case the exposure of the test-object was preceded and followed by the confusion patterns *a* and *c* respectively, Fig. 44. The test-object consisted of two black bars, each 0.125 inches in width, and they were separated by a white interval of equal width. The length of the bars was three times the width of each bar so that the two black bars and the intervening white interval covered

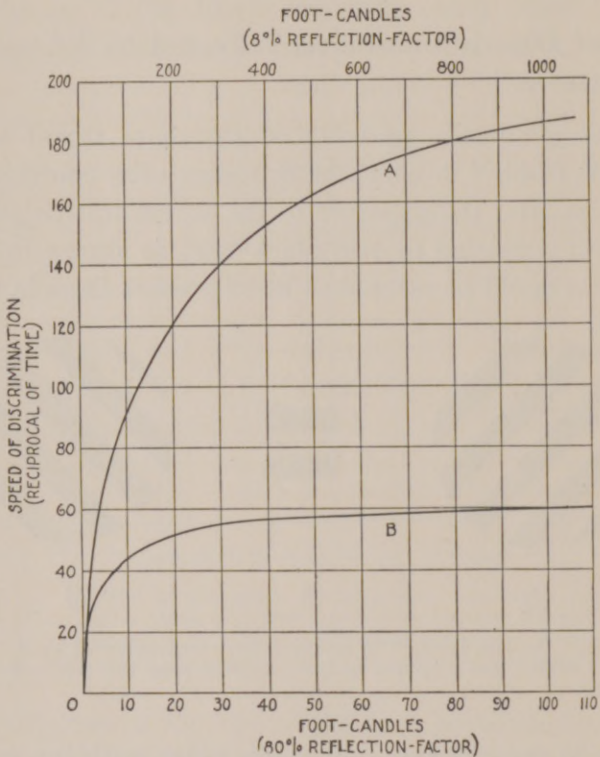


Fig. 45. Curve A is the relation of the speed of discrimination of the test-object *b*, in Fig. 44, to the intensity of illumination of the white background of 80 per cent reflection-factor. Curve B shows the results when the test-object *b* is preceded by *a* and followed by *c*, Fig. 44. The upper scale represents the relation between speed of discrimination and foot-candles if the test-object had been truly black on a dark gray background of 8 per cent reflection-factor.

a square area. In other words, this test-object could be produced by removing a middle one-third from a black square 0.375 inches on a side. The visual angle subtended by 0.125 inches at the distance of 19.7 feet employed in these experiments is 1.82 minutes of arc. The reflection-factor of the " black " bars was about 4 per cent and of the white background 80 per cent. Curves A and B represent the average results of four observers and a long series of careful tests with approved apparatus and methods. Subsequent tests with other observers gave similar results.

It is seen on comparing these two curves that the introduction of the confusion element, due to patterns *a* and *c*, Fig. 44, has materially decreased the speed of discrimination. It was to be expected that the variegated images continually falling in succession upon the retina in the course of everyday vision constitute a confusion to some degree at least, interfering with the seeing of any particular pattern of the series. These interfering after-images are not only visual but are also mental to some extent. It is known that after-images are more persistent as the brightness of the object increases, and Dr. Cobb's work indicates that this confusion is more effective at higher brightnesses than at relatively lower ones.

Dr. Cobb also worked with a larger test-object of the same form preceded and followed by confusion field correspondingly enlarged. In this case the test-object and confusion patterns were drawn to double the scale of the test-object used in connection with curves A and B. That is, the visual angle was that subtended by the distance (0.25 inch) between the black bars *a*, Fig. 44, at the distance of 19.7 feet. This visual angle was 3.63 minutes. For the larger test-object the speed of discrimination was greater than that of the smaller test-object for the same intensity of illumination. If plotted, the curve would be about 50 per cent higher than curve B above the " knee " of the latter. An idea of the angular size of these test-objects in terms of the same angular size of objects at a distance of 14 inches can be gained from Fig. 25. In all these experiments the results show the advantage of higher intensities of illumination and that the advantage is still apparent above 100 foot-candles on the white background and above 1000 foot-candles if the test-object had been a true black on a dark gray background of 8 per cent reflection-factor.

Simple Demonstrations

The increase in " speed of vision " with increase of illumination intensity can be demonstrated in various ways by anyone. An observer can be asked to read aloud a certain amount of printed matter under a low intensity of illumination and the time consumed can be recorded. He can then read the same amount of material under a much higher intensity. The time in the latter case will be found to be shorter than in the former case. It is better not to have the reader read the same material in the two cases.

Another simple way of demonstrating this is by exposing such a letter as *E* for different periods of time under different intensities of illumination. A slot may be cut in a white cardboard and a letter *E* pasted on another cardboard. This *E* is flashed by the slot at different speeds by means of different tensions of a spring or a rubber band. Even gravity may be employed by acting on a falling shutter or on a pendulum raised to different vertical heights.

For such rapid movements it is better to have the *E* stationary and to expose it by the passage of a slot in an opaque but movable cover. This is shown in Fig. 46. An " envelope " of stiff cardboard is made with a slot in the front as *a*, and a letter *E* on the back *c*, but in a position such that it shows in the slot when the slide *b* is removed. The slide *b* has a slot which passes the slot in the cover when the slide is as far in the slot as it will go. This is assembled by placing *b* in the slot and putting two rubber bands *R* around the assembly as shown. The exposure of the letter

E is less the further out the slide *b* is pulled against the rubber bands.

An improvement in some respects over the method employing a single letter is achieved by having a long slot several times wider at one end than the other as shown in *d,* Fig. 46. Several similar letters are exposed simultaneously

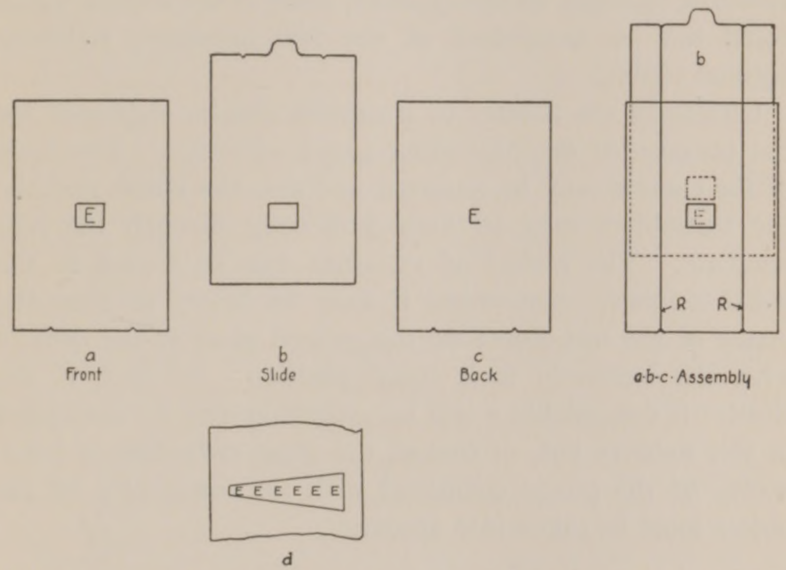


Fig. 46. A simple device for demonstrating the effect of intensity of illumination on the time required to distinguish an object. *a* is a slot in the front of an envelope and a letter E is on the back, *c*. The slide *b* is inserted and two rubber bands *R* are slipped over as shown in the assembly. By pulling the slide out against the bands different exposures of the E can be made. *d* shows a wedge-shaped slot in which several E's can be exposed for different periods simultaneously.

but for different periods of time. Thus a demonstration of the time element can be made without varying the intensity of illumination. At the proper intensity of illumination the letter at the widest part of the slot (longest exposure) will be clearly distinguished while the letter exposed the shortest time will not be distinguishable.

Mr. G. H. Stickney devised a simple demonstration by standing a cardboard cylinder on the turn-table of a modern phonograph. Letters of various size are pasted or printed on this cylinder. The speed of the turn-table can be varied and also the intensity of illumination. In the latter case the low intensity can be that contributed by the lighting of a room at a desirable point. A reflector containing a lighted lamp can be held in the hand and on suddenly directing the light on the cylinder, some of the letters, which could not be recognized at the low intensity, suddenly become visible.

Obviously the shutter of a camera can be employed for the purpose of demonstrating speed of vision. The back of the camera may be removed and also the lenses and the the test-object may be viewed directly through the lens aperture. The period of exposure can be varied in the usual manner. Sometimes it may be better to view the image of the test-object on the ground glass of the camera with the lenses in their usual position. In fact, if the shutter is dependable a real investigation may be conducted in this manner but, of course, the great reduction in luminosity of the image compared with the luminosity of the object must be taken into account.

Representing the result of indifference to lighting.

(*Above*) The average illumination intensity was 0.2 foot-candles. The inadequate illumination from bare lamps and improper reflectors results in lowered production, decreased safety, visual discomfort, and general depression of workmen.

(*Below*) The same factory after rehabilitating the lighting system. The average illumination intensity is now from 6 to 10 foot-candles.

CHAPTER X

LIGHTING AND PRODUCTION

ANY factor of our work environment which is essential to efficient human activity, is an important influence upon the output of a worker. This is true in home, office, factory, and in every place where vision is involved. How plainly we can see our work and our surroundings determines the certainty with which we act. How quickly we can distinguish things determines to a great extent the speed with which we perform the entire act. Seeing plainly and quickly makes for increased safety. A flood of light, properly controlled, is stimulative. It is not a powerful, forceful stimulant, but it is an enlivening factor. The surroundings are more cheerful and the worker's general attitude toward his work, his environment, and even toward life itself is bound to be influenced favorably. Certainly light and lighting are important in all these respects. The most effective lighting is that which makes it possible to see and to act with the greatest certainty, speed, safety and comfort. This will likely be attained when the important characteristics of daylight outdoors shall have been brought indoors. That is, light of the quality or spectral character of noon sunlight and illumination intensities of hundreds of foot-candles eventually may be found in specifications for the most effective lighting. There are many other factors such as diffusion, distribution of light, and brightnesses of surroundings which must be considered, but, in general, we may follow nature in this respect, in the absence of further knowledge.

It is interesting to note that increased production of workers due to better lighting is not obtained at the expense of the worker's energy. Good lighting does not *force* a worker to do more work in a given time. By increasing the ease or certainty of seeing it makes work easier and acts more certain. It eliminates the waste of time which is inevitable under improper and inadequate lighting. The worker is working just as hard (and with greater annoyance) under poor lighting as under good lighting but he is not accomplishing as much.

What May Be Expected from Improved Lighting

When we introduce the factor of cost we must modify, if necessary, our specification of the most effective lighting. There is no doubt that increased intensity of illumination and a general improvement in most lighting systems pay very large dividends. However, it is obvious that there is a point where the law of diminishing returns demands notice. Fortunately, great improvements in indoor lighting are still profitable rather than costly. That is, the value of the results of the improved lighting is generally far in excess of the increased cost of lighting. In many cases, great improvement in lighting can be achieved by replacing an ineffective and inefficient system with a modern installation without a comparable increase in cost of lighting. This is due to the fact that many present systems are wasteful of light and are not productive of the best conditions for seeing. The problem before the lighting expert is to determine exactly what proper lighting is and to apply it to the point of adequacy compatible with its cost and returns. In other words, the optimum conditions of lighting and the value of its results must be determined. Investigations so far indicate that we are far from the point where we must begin to consider the law of diminishing returns. All laws pertaining to vision, as shown in Chapters VIII and IX, show an increase in ability to see and to work with increase in illumination intensity, assuming other factors in lighting to be satisfactory. Tests of production under increasing intensities of illumination, indicate a tendency of production to continue to increase at still higher intensities than the maximum used in the investigations.

Some of the advantages of better lighting can not be accurately appraised in terms of dollars, but all will agree that they are worth something. The lighting expert has known what the principal advantages of improved lighting should be. As a consequence, in a survey of artificial lighting conditions in factories made a few years ago, manufacturers were asked to rank the various advantages as they saw them. Doubtless they did not possess exact records of the results of improvements in lighting, but their attitude in general is of interest. The percentage of manufacturers interviewed who included the various principal advantages known to the lighting expert were as follows:

	Percent
Increase in production	79
Decrease in spoilage	71
Decrease in accidents	60
Improvement in discipline	51
Improvement in hygienic conditions	41

This discussion is confined chiefly to manufacturing but it should be noted that the principles apply also to offices, stores, traffic, and in all places where there is human activity. The productiveness of better lighting in offices and in stores can be measured in terms of dollars as well as in factories.

In 1919, about 9,100,000 wage earners were working in manufacturing industries in the United States. Besides these there were about 1,447,000 salaried employes and about 269,000 proprietors and firm members. The total persons engaged was 10,812,736. Many of these were office-workers. With only one-tenth of the population of this country working in manufacturing industries, it is obvious that many millions are engaged in other activities and that a large percentage of these are in offices. Here good lighting also yields satisfactory dividends as the reading tests described in Chapter IX and other observations prove.

Effect of Improved Lighting on Production

Although analyses of visual processes, and the relation of lighting to them, are exceedingly important in learning how to use light, a final factor of great interest is the increased production, if any, attending an improvement in lighting. The effects of better lighting in increasing visibility and speed of vision are now well established beyond question. Much more work needs to be done before a complete science of lighting will be available. However, in the meantime investigations in factories have proceeded in parallel with laboratory researches. The actual results of improved lighting on production can be measured, although such an investigation, to be convincing, must be conducted in a more or less elaborate series in which all influential factors are either controlled or their influences determined.

Some interesting results were obtained by W. A. Durgin several years ago by determining the production of various departments in several factories before and after the rehabilitation of the lighting. His investigations were more of the nature of a reconnaissance, nevertheless, they were extremely valuable. A brief summary of a few tests made by W. A. Durgin on the influence of improved lighting on production in factories is presented herewith.

Case I. An increase in intensity of illumination from 4 foot-candles to 12 foot-candles resulted in increases in various departments as high as 27 per cent and as low as 8 per cent. The average was 15 per cent. The original lighting was much better than usually found in factories; still there was a marked increase in production when it was improved.

Case II. The original lighting was very unsatisfactory, the system (if it could be called such) consisting of bare lamps and dropcords. The intensity of illumination was increased 25 times with an increase in consumption of electrical energy of only 7 times. The result of the improved lighting was an increase in production in one department as much as 100 per cent. In no department was the increase in production less than 30 per cent. This was an extreme case.

Case III. The intensity of illumination was increased from 3 foot-candles to 12 foot-candles with an accompanying increase in consumption of electrical energy for lighting of only 3 times. The increase in cost of lighting was equivalent to 1.2 per cent of the payroll but the increase in production averaged 10 per cent.

Case IV. The intensity of illumination was increased 6 times but the consumption of electrical energy for lighting was only doubled. The increase in production averaged 10 per cent.

Durgin concluded that the average result of increasing the intensity of illumination to a reasonable value and of properly designing the lighting installation in factories, would be at least a 15 per cent increase in production at an actual cost of lighting equivalent to not more than a few per cent in the payroll. Many rehabilitations of artificial lighting have been achieved with great improvement of the lighting at a cost of about one per cent of the payroll of all the workers using the lighting.

An interesting case had been reported by John Magee in a department of a factory turning out piston-rings. The investigation of the influence of lighting on production extended over fifteen months. The original lighting system produced an average intensity of illumination of about 1.2 foot-candles. Three levels of illumination from the rehabilitated lighting system were used in the investigation, averaging about four months each. The average results during the tests at four different intensities of illumination are as follow:

Foot-candles	Per cent increase in production
1.2	0
6.5	13.0
9.0	17.9
14.0	25.8

The maximum increase in cost of lighting was about 48 per cent of the cost of the original lighting. This was equivalent to 2 per cent of the payroll. Savings represented by less spoilage and fewer accidents went a long way toward paying for the lighting.

There are so many influences on production that, to be entirely convincing, an investigation of the influence of lighting on production must be extended over a long period during which careful control and observation of various factors must be exercised. An investigation recently conducted by D. P. Hess and Ward Harrison [43] is particularly interesting because of the elaborateness of the tests which extended over a period of ten weeks. An inspection department of a factory was chosen and during the period the total number of inspectors varied from 38 to 48. The nature of the work consisted of inspecting material as it was turned out by automatic screw-machines and before heat-treating. The material consisted of various sizes of cups, cones, and threaded cones which are separate parts of a roller bearing. During the test-period over 7,000,000 pieces of material were inspected. The work is carried on in three stages. The first group of inspectors gauge the material for diameter and depth; the second inspect for defects such as chatter, tool marks, ingot breaks, thin ribs and bad chamfer; and the third group for imperfections in the thread on the inside of the cones, bad mill, bad chamfer and inadequate burnishing. Some of the work requires close visual inspection and in some of the gauging relatively little visual scrutiny is required. The inspectors were paid on an hourly basis. Relative humidity and temperature were maintained practically constant.

The original system of artificial lighting contributed an average illumination of 2 foot-candles, but the distribution of the light was uneven and caused bad shadows. Daylight entered through distant windows and overhead skylights.

During the first two weeks of the tests the original artificial lighting and daylighting were used in combination, the

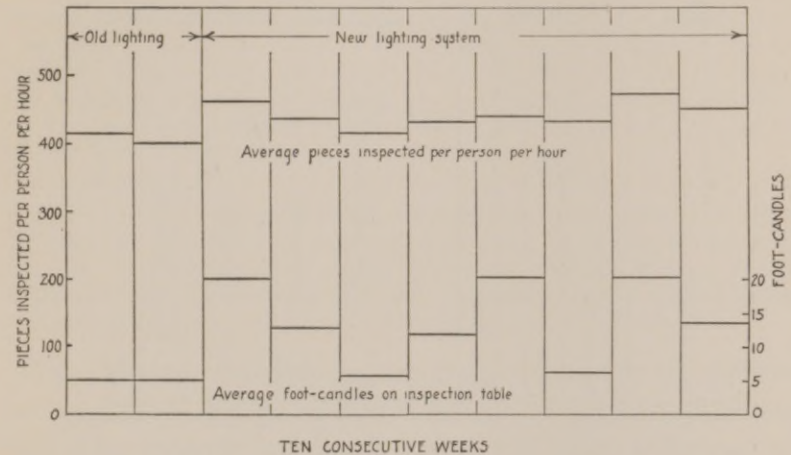


Fig. 47. Showing the average number of pieces of material inspected per person per hour for each of ten consecutive weeks; also the corresponding intensities of illumination for the various weeks. During the first two weeks the old lighting system (half daylight) was in operation. During the remaining eight weeks the new system of artificial lighting was operated.

average intensity of illumination being 5 foot-candles. Then the new lighting system went into operation and the skylights overhead were blackened. The new system consisted of glass-steel diffusers located on 8-foot by 10-foot centers and were hung 12 feet above the floor. The illumination intensity from the new system was maintained constant for the week; then it was changed to another value. The actual illumination intensities employed were 5 foot-candles for the first two weeks from the original lighting system, and 6, 13, and 20 foot-candles from the new system. The intensities from the latter system differed each week and in no progressive order. The production was reduced for each week to the average number of pieces inspected per person per hour. In Fig. 47 this average production is shown for each week along with the intensity of illumination. One will note at once that when the intensity was increased the production increased, and *vice versa*. This is very striking and convincing.

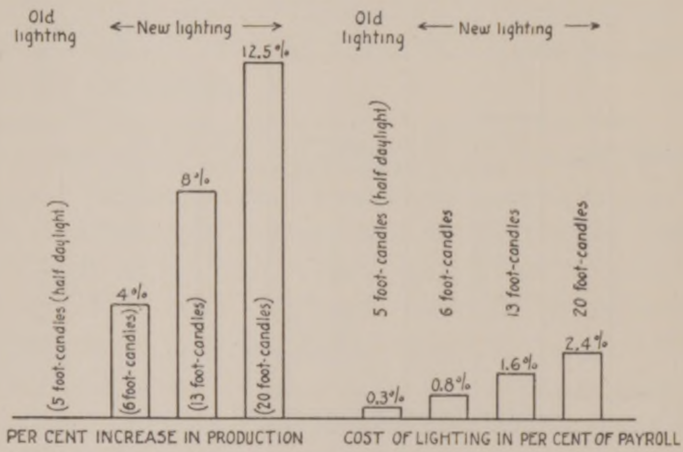


Fig. 48. A graphic illustration of the per cent increase in production and of the cost of lighting in terms of the payroll for the various intensities of illumination. The production increases are averaged from Fig. 47.

The average increase in production under various lightings as well as the cost of light in per cent of the payroll, are presented in Table XII and Fig. 48. These data show not only that production increases as the intensity of illumination increases (other factors being practically constant) but also the advantage of a well-designed lighting system over a poorly designed one. This is shown by the considerable increase in production for the new system with 6 foot-candles over that of the old system at 5 foot-candles. Reducing the former production to what it would very likely be at 5 foot-candles we find that about 3.4 per cent increase in production arises from the change-over from a system of poor design to one of good design, illumination intensity remaining constant.

TABLE XII

Showing the Relation of Intensity of Illumination to Factory Production.

	New Lighting System Foot-candles		
	6	13	20
Average production (pieces inspected per person per hour) *	424	440	458
Per cent increase in production	4.0	8.0	12.5
Cost of lighting in per cent of payroll	0.8	1.6	2.4
Per cent increase in production costing nothing	3.2	6.4	10.1
Ratio of increase in production to cost of lighting (per cent of payroll)	5	5	5.2

* Under the original system of poor artificial lighting and natural lighting giving an average illumination of 5 foot-candles the first two weeks test gave a production of 408 pieces inspected per person per hour. The cost of this poor artificial lighting (exclusive of the cost of natural light) was 0.3 per cent of the payroll.

In order to visualize the gradual increase in production for a modern system of lighting as the intensity of illumination is gradually increased, the data in Table XII and Fig. 48 are plotted in Fig. 49. It is interesting to note how the three sets of data (corresponding to the three illumination intensities respectively 6, 13, and 20 foot-candles) lie on straight lines. These straight lines if projected backward would pass close to zero although of course production would cease when there would still be some light but not enough to do the work. The more interesting speculation is that connected with projecting the straight-line relations forward. (See Figs. 62, 63, 65.) There is no indication at 20 foot-candles of a diminution of the rate of increase in production with increase in foot-candles. This would begin to be noticeable when the maximum speed of muscular activity or of movement was approached or when the maximum speed of vision (discrimination or recognition) was approached. It is difficult to state which would be the first to begin to retard the rate of increase in production with increasing illumination intensity. In fact, this depends upon the character of the work, for in different kinds of work these factors are differently involved. In work demanding rather fine

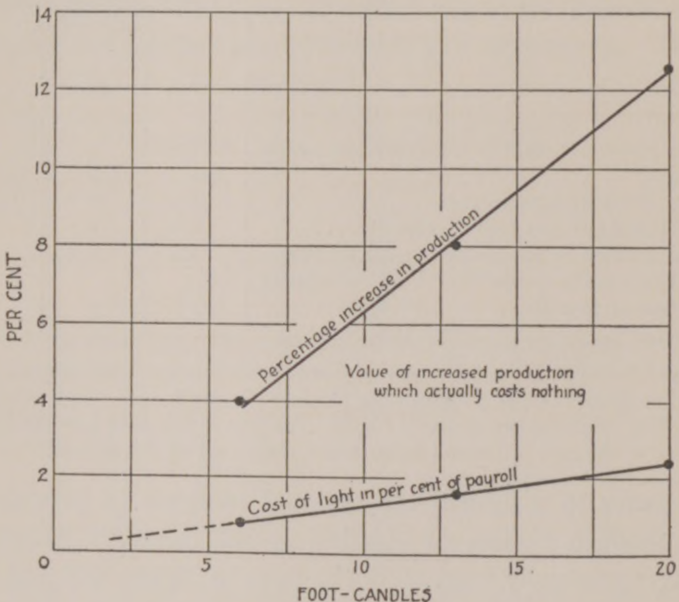


Fig. 49. Showing the relation of illumination intensity to the increase in production and to the cost of light in terms of the payroll.

visual discrimination, the maximum speed of vision is not approached until high intensities of illumination are reached and even if the maximum speed of movement has already been obtained, production will continue to increase until there is no increase in the ease or speed of visual discrimination.

In Chapter XI the results of cleaning glass areas of daylighting equipment in two cases, indicate that production was increased 5 per cent and 10 per cent respectively.

Laboratory tests of the speed of reading black print on white paper showed that the average speed of a large group of observers increased 15 per cent when the illumination intensity changed from 4 foot-candles to 16 foot-candles. The speed of reading black print on gray paper (23 per cent reflection-factor) increased 50 per cent over the same range of illumination. Although this test was performed in the laboratory, it is a real production-test for it applies directly to a large number of workers in offices, etc. and the results strengthen our conclusions in regard to the effect of illumination intensity on factory production. Strictly laboratory researches of visual laws discussed in Chapters VIII and IX, also indicate roughly what we might expect in any activity involving vision. From all these data it appears very conservative to conclude that the output of our factories could be increased a net 10 per cent by better lighting without cost. Where the lighting is particularly faulty this increase would be much greater. It should be understood that, up to very high intensities, ease and, therefore, speed of discrimination of finer details, at least continues to increase as the intensity of illumination increases. This increase at the very high intensities of illumination is more for low-contrasts than for high ones. This is discussed further in Chapters XIII and XIV.

It should be borne in mind that throughout this discussion the benefits of only increased production have been discussed. Decreased spoilage, increased safety, better discipline, and less eye-strain and consequent discomfort are all accompaniments of better lighting. All these have monetary value but it is difficult to appraise them. We shall let them represent good measure after we have appraised the value of increased production.

A Glimpse of Manufacturing Statistics

If we accept the proof that improved lighting can create value out of proportion to the cost of the lighting; that is, that it can create *net value,* it is of interest to show what the increased production means for all the manufacturers in the United States. Certainly the lighting of nearly every factory can be improved somewhat either in intensity or distribution of illumination. As pointed out in Chapter VII, only 9 per cent of the factories visited in an extensive survey had what was termed excellent lighting as judged by the low standard a few years ago. Standards have risen considerably during these few years and recent data indicate the desirability of much higher intensities, so that it appears safe to say that even those factories could have the lighting improved and paid for by the increased production.

In order to obtain a picture of our industrial economics some statistics have been condensed and rearranged from the Census of Manufactures for 1919, the last census available. In Table XIII a summary is given for the United States for the years 1904, 1911, 1914, 1919. It is seen that lighting in the industries affected over 9 million workers who turned out finished products valued at 62 billion dollars in 1919. In order to make it easier to compare various items, they are also given in per cent of the 1904 value in each case. The actual values are expressed in millions of dollars.

Most manufacturing is found in cities where, owing to smoke and congestion, natural lighting is generally less than in smaller places. On the other hand, electric service is likely to be better and higher standards of artificial lighting are more readily sold to factory management in the larger cities. Some statistics of manufactures for the year 1919 pertaining to cities of 10,000 population and over and also to cities of 100,000 and over are presented in Table XIV. These figures are percentages of the total for the United States for the year 1919.

TABLE XIII

Summary of Statistics of Manufactures for the United States.
Actual values expressed in Millions of Dollars;
Relative values in per cent of 1904 value.

	1904	1909	1914	1919
No. of establishments.......	216,180	268,491	275,791	290,105
Per cent................	100	124	127	134
No. of wage earners........	5,468,383	6,615,048	7,036,247	9,096,372
Per cent................	100	121	129	166
Capital:				
Millions of dollars.......	12,676	18,428	22,791	44,467
Per cent................	100	145	180	350
Wages:				
Millions of dollars.......	2,610	3,427	4,078	10,533
Per cent................	100	131	156	400
Cost of materials:				
Millions of dollars.......	8,500	12,143	14,368	37,376
Per cent................	100	143	169	440
Value of finished products:				
Millions of dollars.......	14,794	20,672	24,246	62,418
Per cent................	100	140	165	423
Value added by manufacture:				
Millions of dollars.......	6,294	8,529	9,878	25,042
Per cent................	100	136	157	405

TABLE XIV

Statistics of Manufactures for cities of 10,000 and over and for cities of 100,000 and over in percentage of the total for the United States for the year 1919.

	Cities 10,000 Population and Greater	Cities 100,000 Population and Greater
Number of factories..............	57.2 per cent	38.7 per cent
Number of wage-earners...........	70.2	41.7
Population......................	42.3	25.9
Value of finished products.........	72.6	45.7
Value added by manufacture......	74.1	46.3

From Table XIV it is seen that about three-fourths of the factory wage-earners and the manufactures are in cities of 10,000 inhabitants and greater, and at least one-half of the factories (measured by wage-earners and output) are located in large cities — in other words, within the reach of the larger and better organized central-stations, electrical contractors, etc.

Having had a glimpse of statistics of manufactures in Table XIII, it is interesting to see what even small increases in production amount to in the manufacturing industries alone. Taking the statistics of the Census Bureau for 1919, one per cent increase in production due to improvement in lighting above the additional cost of lighting is, for the year, equivalent approximately to

100,000 wage-earners
$100,000,000 wages
$250,000,000 value added by manufacture
$625,000,000 value of finished products

It seems to be fairly well established that reasonable increase in intensities of illumination and rehabilitation of lighting systems would on the average result in a net increase in production of at least 10 per cent. On this basis the *improvement* in factory lighting at the present time, would yield a stupendous result each year. It would do the work of one million wage-earners at a saving of one billion dollars in wages. This equivalent of a million wage-earners would increase the total value of finished products by 6 billion dollars. Without any additional cost, there would be an increase each year of over 2.5 billion dollars in the value of finished products added by manufacture at the present rate of manufacture. In other words, proper attention to lighting throughout the United States would create, on a basis of production in 1919, a net value of over 2.5 billion dollars exclusive of decreased spoilage, labor turnover, and accidents.

Thus *improvement* in lighting in 1919 could have been equivalent to 3 times the wage-earners employed in the manufacture of automobiles that year, and it could have increased (free of cost) the value added by manufacture to the value of finished products, an amount equivalent to the entire value of automobiles manufactured in 1919. In other words, if we had proper and adequate lighting throughout our factories, we would get the equivalent of our automobiles without cost. By doing the same for our offices and other work-places, we would likely get the equivalent of the necessary gasoline and oil to operate them.

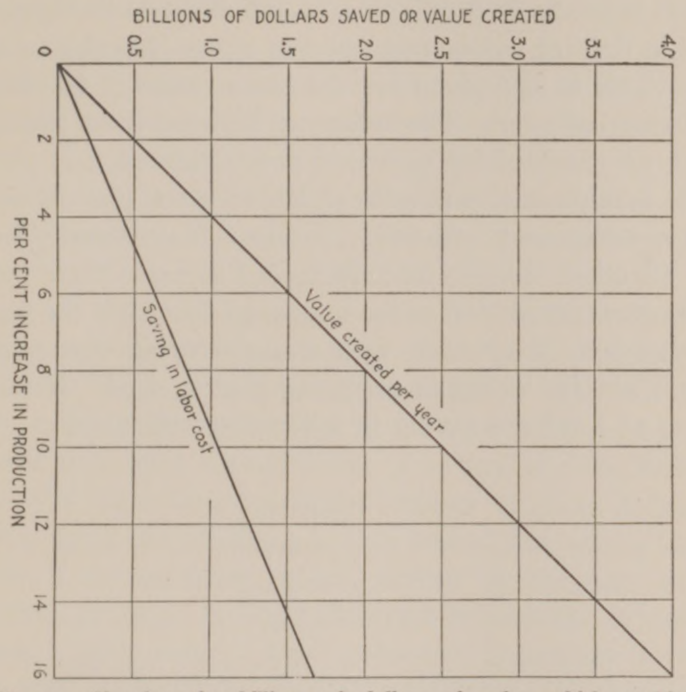


Fig. 50. Showing the billions of dollars of value which could be created without cost each year and also saving in labor cost for various increases in production due to improved lighting throughout the manufacturing industries of the United States. These values are based on the 1919 census of manufactures.

In computing the value in manufactured products which could be created by improvement in lighting, only the value added to finished products by manufacture has been considered. That is, the value of the materials has not been taken into account. This is not affected excepting by decrease of spoilage and we have no accurate figures in regard to the effect of improved lighting on that item. Spoilage is generally considered to be decreased about the same percentage that production is increased. In order to show the value which could be created by adequate and proper lighting each year at the 1919 rate of manufacture, Fig. 50 is presented. The created value is given in billions of dollars for various increases in production up to 16 per cent. If this increase in production is not desired, the improvement in lighting can be appraised in terms of saving in labor cost. This is also given for the same range of increase in production effected. The difference between these two items is the value added by increased production of that portion of the manufacturing process which does not include wages, such as equipment. However, it does not necessarily follow that all other links in manufacturing increase their output in the same proportion as the workman does; but the human element is so interwoven with manufacturing that perhaps we are not far wrong in assuming that it does. If we are wrong at least the saving in labor cost still holds.

Chapter XI

THE VALUE OF PROPER MAINTENANCE OF LIGHTING SYSTEMS

STRIKING evidence of a lack of appreciation of the value of adequate light is seen by the prevalence of dirty glass areas in factories. The daylight equipment in most factories represents an appreciable investment from which the maximum return is not obtained unless the glass is kept reasonably clean. Manufacturers who would not think of neglecting other essentials in profitable production will let the natural lighting diminish month after month by the accumulation of dirt. The loss from such neglect is not plainly visible but it is a loss none the less. With adequate artificial lighting the loss due to diminished daylight is greatly reduced because the cost of artificial light is a very small part of the total cost of production. However, manufacturers that are so unappreciative of the value of adequate light are not likely to be among those relatively few who have installed high-standard artificial lighting.

We wash the windows in our homes and offices through pride, if for no other reason, before the decrease in light becomes serious. In our factories this incentive is too often absent. As a result, " day " indoors is materially shortened but still worse is the loss of production, the decrease in cheerfulness, the lowering in discipline and in orderliness, and doubtless indirect losses such as increased labor turnover. The same results obtain from neglect of artificial lighting equipment. The accumulation of dirt on lamps, reflectors, ceiling and wall is costly. Improper lamps, burned out ones, voltage below normal, and old lamps decrease the output of light.

Effect of Cleaning Glass of Daylight Equipment

After the glass areas in a factory have been cleaned the management is usually convinced of many advantages such as increased production, less spoilage, a decrease in number of accidents, better discipline, fewer mistakes, and more cheerful condition. Usually the records are not adequate to reduce these items to monetary value and, indeed, some of them cannot be. However, it is generally conceded through experience and observation, that the benefits of cleaning glass areas greatly exceed the cost. Data supplied by the management of two different factories are presented herewith.

Case I. In the galvanizing department of a large manufacturing company the natural lighting had diminished markedly by the deposit on the windows. This deposit resisted various attempts at cleaning them in which sand, lye, acids, etc. were used. However, a cleaning compound was finally found which did the work. Brief statistics of the cost and of the value of cleaning are given herewith.

Costs of Cleaning

Cleaning compound	$30.00
Labor (11 days)	$66.00
Total for 6,000 sq. ft.	$96.00
Per square foot	$ 0.016

Value of Cleaning

Saving in artificial lighting per day	$ 0.60
Increase (5%) in labor efficiency	$13.75
Saving per day	$14.35
Saving per month	$358.75
Increase in profit on extra production	(not given)
Saving due to better inspection	(not given)

The saving in labor cost represented in an increase of 5% in labor efficiency in one week paid for the cleaning without taking into consideration the profit on the extra production, the value of better inspection (in this case errors of inspection were very costly) and other factors. The management stated that "one of the main reasons for cleaning the skylights was that it added greatly to the general appearance of the plant. This alone is worth the expense required."

Case II. In a warehouse of a very large manufacturing organization, 16,000 square feet of skylight were cleaned. Keeping this glass clean is a difficult matter in this plant because of the proximity to chemical industries; however, the management experimented until a cleaning compound was found that would do the work well and at a reasonable cost. Brief statistics of the cost and value of cleaning the glass are given herewith.

Costs of Cleaning

Cleaning compound	$250.00
Labor (448 hours)	$246.40
Total or 16,000 sq. ft.	$496.40
Per square foot	$ 0.031

Value of Cleaning per year

Saving in artificial lighting	$ 150.00
Increase (5%) in production	$7500.00
Gross annual saving	$7650.00
Net annual value	$7153.60
Reduction in errors	5%
Reduction in accidents	10%

The management of this warehouse state that "with better light the spirit and atmosphere of the plant changed. The workmen found the conditions far more pleasant and became even better satisfied with their jobs. Eye-strain was greatly reduced. On the whole the effect on the workmen was most gratifying." The cleaning of the glass areas paid for itself 28 times on the basis of cleaning once a year without considering the monetary value of a decrease of 5 per cent in errors in filling orders and a decrease of 10 per cent in accidents. Although no attempt was made to appraise the effect on labor turnover in this department employing 100 men, the management believes that "the more pleasant working conditions affect the labor turnover favorably."

There is no doubt that, where conditions are favorable, daylight will be continued to be used. It is an ideal illuminant, but owing to the difficulties of getting it indoors in sufficient quantity and of proper distribution, the design of daylighting equipment demands skill. That daylight indoors costs something is not at all to its discredit; however, this must be recognized if lighting is to receive just consideration. After daylighting equipment is installed at considerable cost it should be maintained or it does not pay dividends.

Absorption of Light by Dirty Glass of Daylight Equipment

In Chapter III it was shown that clean crystal glass transmits from 75 to 90 per cent of the incident light. In factory districts, or for that matter in any part of our cities, glass accumulates a film of dirt rapidly. Particularly in factory districts this is very difficult to clean if neglected for a long time. However, there are cleaning compounds to which any carbon scale or any dirt will yield. In Table XV are shown the transmission-factors of seven different glasses just as they were taken from skylights and windows and also after they were cleaned by means of a special cleaning compound. By cleaning, their transmission-factors were increased enormously, as seen by the last column. In one case the glass was so dirty as to be practically opaque. In the other cases the lighting had been reduced by the accumulation of dirt to an average of about one-sixth of the original value with clean glass. In terms of loss in production this means many millions of dollars in this country per year.

TABLE XV

Results of Cleaning Glasses in Factory Daylighting Equipment.

Type of glass	Transmission-factor (per cent)		Transmission Increased by Cleaning
	Before cleaning	After cleaning	
Plain clear	12	88	7.3 times
Plain clear	16	88	5.5
Fine ribbed	14	80	5.7
Fine ribbed	17	76	4.5
Fine ribbed	0.3	75	250.0
Wavy wire glass	13	80	6.1
Wavy wire glass	5	75	15.0

Measurements of intensities of illumination before and after cleaning the glass areas yield startling results. In many cases the increase is as much as 5 to 10 times and it is not uncommon to increase the illumination intensity in some parts of the interior from an average of one foot-candle with dirty glass to as high as 15 foot-candles.

Depreciation of Artificial Lighting

All equipment is exposed to dust and it is to be expected that artificial lighting equipment does not escape. The rate of depreciation in output of light due to accumulation of dust depends very much upon the location and type of lighting equipment. A direct-lighting system consisting of dense diffusing glass shades, opaque reflectors, or non-ventilated diffusing glass units will not depreciate in light output as rapidly as most other systems under similar conditions. It used to be thought necessary to ventilate lighting units. However, with modern tungsten lamps no ventilation is necessary if the enclosing glass is as large as it should be to provide a sufficiently low brightness.[38] Ventilating orifices suck in the dust along with the air and much of it remains deposited on the lamp and various parts of the equipment.

In from one to three months, depending upon the location and lighting equipment, a depreciation in light output from 10 to 50 per cent can readily take place from the accumulation of dirt alone. A regular schedule of maintenance is found to be the best method of insuring against great loss

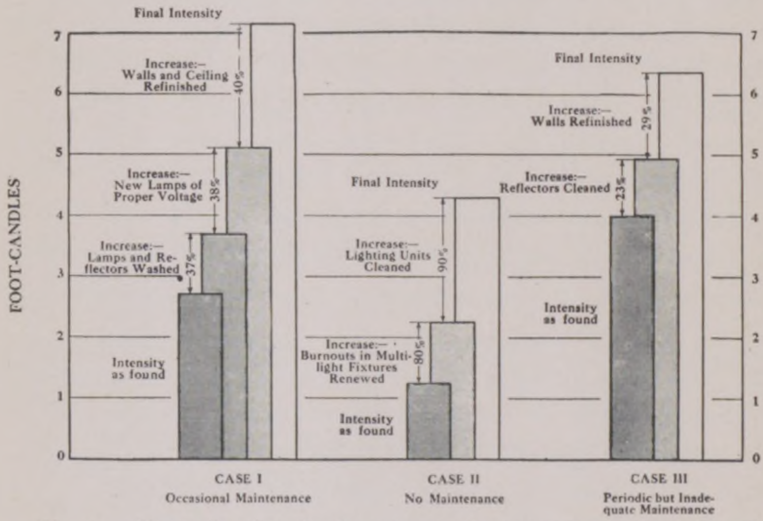


Fig. 51. Chart showing the importance of prompt renewal of burned-out lamps and systematic cleaning of the lighting equipment.

of light. Although the depreciation of artificial lighting equipment is not generally permitted to progress to the extreme that is common with daylight equipment, it becomes very marked in many cases. This is particularly costly owing to loss of production and to other factors when lighting intensities are initially quite low as is the case generally. The various factors and their influences upon light output and illumination intensities are well shown in Fig. 51 for three representative cases of semi-indirect and indirect lighting as determined by Ward Harrison.

Case I. This is one of occasional maintenance. The intensity of illumination after a long period of neglect was 2.7 foot-candles. The increase due to maintenance factors was as follows:

	Foot-candles	Per cent increase
Original intensity of illumination	2.7	—
Washing lamps and reflectors	3.7	37
New lamps of proper voltage	5.1	38
Refinishing ceiling and walls	7.1	40
Total increase in illumination	4.4	163

Case II. This was one in which lighting equipment was not maintained. The results of maintenance were as follows:

	Foot-candles	Per cent increase
Original intensity of illumination	1.2	—
Burned out lamps replaced	2.2	80
Lighting equipment cleaned	4.2	90
Total increase in illumination	3.0	260

Case III. This was one in which periodic but inadequate maintenance was carried out. The results of maintenance were as follows:

	Foot-candles	Per cent increase
Original intensity of illumination	4.0	—
Lighting equipment cleaned	4.9	23
Walls refinished	6.3	29
Total increase in illumination	2.3	58

In factories, direct-lighting systems are almost always specified, so that it may appear unfair to present maintenance data for semi-indirect and indirect systems. Ceilings and walls have much less effect on the illumination at the work for direct-lighting systems than for the others. The reader may drop this item out entirely if he desires, although in certain modern systems of factory lighting in which glass is a part of the equipment, the ceiling has an appreciable effect on the illumination at the work. In fact, a ceiling moderately illuminated adds greatly to visual comfort and increases the cheerfulness of the interior. Furthermore, the conditions in factories are generally such as to cause more rapid depreciation in the lighting than those in offices.

Anderson and Ketch [39] found lighting equipment exposed to oily sooty dust seven weeks depreciated more (from dirt alone) than when exposed to dry, fine dust for more than twice this period. Under these conditions they found depreciations for lighting equipment of the kind commonly used in factories varying from 11 per cent to 30 per cent due to accumulation of dust. Considering that in most factories lighting equipment is not regularly cleaned, that the periods between cleanings are generally quite long, that the reflection from ceilings has some influence, that the voltage is not always proper, and that burned-out, blackened, or improper lamps are allowed to remain in the sockets, the total average depreciation is likely to be much greater than the value found by Anderson and Ketch.

Cost of Depreciation in Lighting

In the three cases given in the foregoing, the increase in intensity of illumination due to proper maintenance was 58 per cent and 260 per cent respectively for the extreme cases. It is difficult to believe that something as important as a lighting installation will be permitted to depreciate so much through neglect, but the evidence is found on every hand. The chief trouble is that light is too commonplace. It is accepted as a matter of course and it receives little or no attention until the intensity of illumination becomes noticeably low. However, all this time there has been a loss of production, spoilage, wastage of time and perhaps accidents and lowering of discipline, all increasing unawares.

In Chapter X it was shown that doubling the intensity from 6 foot-candles to 12 foot-candles increased production 4 per cent. Halving an already inadequate intensity of illumination is likely to reduce production much more than 4 per cent.

It is startling to think that neglect of lighting equipment in the United States is costing us a billion dollars per year; however, on the basis of what we know of the influence of lighting on production this is just what is taking place if the depreciation is sufficient to cause a decrease in production of 4 per cent. Considering that we begin with inadequate lighting and that it does not need to depreciate 50 per cent to be responsible for such a decrease in production, this estimate of a billion dollar loss per year is not unreasonable. A large factor in manufacturing is daylighting and it is a fact of common observation that daylight equipment is generally permitted to depreciate very much.

The cost of cleaning direct-lighting equipment commonly used in factories is considered by A. L. Powell [40] to average between 3 cents and 5 cents each. Obviously, cleaning equipment too often would cost more than the saving due to the better lighting. It is best to design the installation to provide the desired intensity of illumination after reasonable depreciation; that is, to provide a factor of safety in the initial intensity. After a period of depreciation, when the gain due to cleaning offsets the cost of cleaning, is obviously the time to clean the lighting units. The length of this period will vary widely with conditions and will depend upon the factor of safety allowed initially. The cost of depreciation is by no means merely the cost of light lost. In fact, the decrease in production and the losses due to other factors which we have associated with better lighting are much greater than the cost of the light lost.

There is a depreciation in the output of light from a clean electric filament lamp (and mercury arcs as well) with hours of operation. This is not very serious during the normal life for which the lamp is designed but many lamps remain in service long after their normal life. Such lamps may cause considerable depreciation as seen in Fig. 51. A profitable schedule of cleaning can be determined without much difficulty in any given case. A foot-candle meter, which can now be purchased at a reasonable price, should be a part of the equipment of the larger factories and office buildings. In any case, the management will find that determinations of illumination in foot-candles are instructive and valuable. By means of data in other chapters it is easy to relate illumination intensities to production. By converting production into profits it is certain that the management of any factory, office, store, or any place where persons work for pay and are paid for profit, will see that lighting, adequate and proper, is the most satisfactory and profitable entry on the payroll.

CHAPTER XII

THE LIGHTING VALUE OF PAINT

OFTEN when we are trying to see something in deep shadow we hold our hand, a white envelope or something else so that it reflects light into the shadow. This is a minor use of the lighting value of surfaces of high reflection-factor. If the amount of light lost through neglect in painting surfaces or maintaining them of high reflection-factor could be computed, there is no doubt that the result would be staggering. This does not apply only to the use of paint but also to any surface covering; however, paint is the more practicable covering from the viewpoint of this book. The measurement of reflection-factor is now a comparatively simple matter in a properly equipped laboratory but accurate results can only be obtained under such conditions. Usually color-difference is involved and results obtained outside the laboratory are far from accurate. Furthermore, the reflection-factor of a surface depends upon the direction and distribution of the incident light in all cases excepting that of a perfectly diffusing surface. In general, walls and ceiling play a part in the distribution of light to the work-plane but the part they play not only depends upon their reflection-factors but also upon the character of the system of lighting. In factories and other places it has been found that machinery and other equipment when finished in a lighter color than heretofore, contribute an appreciable amount of light to the work-places. Furthermore, funereal finishes of walls, woodwork, and equipment are giving way to those which make the surroundings more cheerful.

Influence of Ceiling and Walls

In lighting a certain work-plane, such as a horizontal one 30 inches above the floor, the ratio of the amount of light reaching this plane to the total light emitted by the light-sources is termed the *utilization-factor*. Some of the light emitted by the light-sources is absorbed by the lighting equipment because a reflector does not reflect all the incident light and a diffusing glass does not transmit all the light. The losses in clean factory-lighting equipment of approved designs average about 30 per cent. The influence of the ceiling and walls obviously depends not only on their characteristics but also upon the character of the lighting system and upon the size of the room. In other words, they can influence the lighting only in so far as they have opportunity and this is a matter of the percentage of the total light which is incident upon them. For example, let us take a spherical room without windows or other openings and assume the ceiling, walls and floor painted uniformly. Also let us suppose a light-source to be hung in the center of this room and that the light-source be such that its direct light produces an illumination of one foot-candle on the walls. The light emitted toward the boundaries of the room is reflected many times and the illumination intensity of one foot-candle is augmented by this reflected light. This augmentation is zero if the walls, ceiling, and floor were perfectly black but becomes appreciable even for low reflection-factors. The results for a spherical room are easily computed, so they are given in Table XVI for the assumptions just made. In the table it is seen that when the surrounding walls are *perfectly black*, the illumination of the wall is just that of the direct light — one foot-candle. As the reflection-factor of the walls increases the illumination on the walls increases. When the reflection-factor is of about the best commercial white paint the illumination is doubled and as the reflection-factor increases from this point the illumination rapidly increases. It would be infinite if the walls were *perfectly white,* because no light would be lost at all by absorption and it would continue to be reflected and re-reflected.

TABLE XVI

Showing the Influence of the Reflection-Factor of the Walls of a Spherical Room upon the Illumination of the Walls. An Unshaded Light-Source Hangs in the Center of the Sphere of such Intensity that It Illuminates the Sphere with Uniform Direct Light to an Intensity of One Foot-Candle.

Material	Reflection-factor of Wall	Foot-candles on Wall
Perfect black	0 per cent	1.00
Ordinary black paint	4	1.04
Dark gray	10	1.11
Medium gray	50	2.00
Commercial white	80	5.00
White powder	90	10.00
Best white powder	98	50.00
Perfect white	100	Infinite

Although the foregoing is only a theoretical consideration it is interesting in illustrating the possibilities of reflecting light. In our interiors there are many objects which absorb light and even white walls and white ceiling are not over 80 per cent reflection-factor at best. It is impracticable to attempt to keep the floors highly reflecting and, furthermore, white surroundings are by no means the most desirable conditions from the viewpoint of eye-comfort and the best vision. Ceilings should be of high reflection-factor if the system of lighting is such as to emit much light directly to the ceiling. When considered from all angles it is questionable whether we should have walls directly in the field of view of greater reflection-factor than 50 per cent.

In the case of direct lighting with opaque white enamelled or silvered glass reflectors little light reaches the ceiling, so its reflection-factor from the viewpoint of artificial lighting is of little importance although it is of great importance in daylighting from windows. In the case of indirect lighting and so-called semi-indirect lighting a large percentage of the light is emitted upward to the ceiling and therefore the reflection-factor is important. Walls are important to the extent of the percentage of light that impinges upon them. Obviously in large rooms they are of much less importance than in small rooms. They are generally of much greater importance in natural lighting from windows than in artificial lighting.

In order to show the influence of the reflection-factors of ceiling and walls in artificial light, Table XVII is presented for three different types of lighting systems and for three sizes of rooms. The lighting equipment is assumed to be hung 10 feet above the horizontal work-plane upon which the relative values of illumination from a certain number of lamps are shown in the Table. These data were deduced from the excellent work of E. A. Anderson [41] on utilization factors. The numbers in parentheses following the words " ceiling " and " walls " are the reflection-factors respectively. The direct-lighting system is one in which approved white enamelled or silvered glass reflectors are used. The second system employs approved enclosed diffusing glass equipment. The indirect lighting system is one in which approved silvered glass reflectors or dense opal glass bowls are used.

The data in Table XVII will bear considerable study. In the large rooms the walls play an inappreciable part and it is interesting to note in item *a*, for example, the effect of the walls as the room size diminishes. This is conspicuous in all the items. The ceiling plays a small part in the case of direct lighting with opaque reflectors. This is seen by comparing item *b* with item *d* where the walls have the same

TABLE XVII

Showing Relative Foot-Candles on Work-Plane from a Given Number of Lamps Used in Three Different Lighting Systems for Various Reflection-Factors of Walls and Ceiling and for Three Sizes of Rooms.

Lighting System and Various Reflection-factors of Ceiling and Walls	Relative Foot-candles on Work-Plane		
	Small room (10 ft. by 30 ft.)	Intermediate room (20 ft. by 50 ft.)	Large room (100 ft by 100 ft)
Direct Lighting System:			
a. Ceiling (70) walls (50)...	50	90	100
b. Ceiling (70) walls (30)...	42	86	97
c. Ceiling (70) walls (10)...	35	81	94
d. Ceiling (30) walls (30)...	40	84	94
e. Ceiling (30) walls (10)...	35	81	91
Enclosed Diffusing Glass:			
f. Ceiling (70) walls (50)...	32	67	80
g. Ceiling (70) walls (30)...	25	59	74
h. Ceiling (70) walls (10)...	20	54	68
i. Ceiling (30) walls (30)...	20	49	58
j. Ceiling (30) walls (10)...	17	45	55
Indirect Lighting System:			
k. Ceiling (70) walls (50)...	23	52	65
l. Ceiling (70) walls (30)...	19	46	60
m. Ceiling (70) walls (10)...	16	42	55
n. Ceiling (30) walls (30)...	10	25	32
o. Ceiling (30) walls (10)...	9	23	29

reflection-factors but those of the ceiling are 70 and 30 per cent respectively.

Enclosed diffusing glass equipment emits a great deal of light upward to the ceiling and outward to the walls. This is quite evident by the generally lower values of relative illumination under this system than under the direct-lighting system. Both the ceiling and the walls influence the relative foot-candle values on the work-plane. By comparing *f*, *g* and *h*, the influence of the reflection-factor of the walls is seen. By comparing *g* and *i* or *h* and *j* the influence of the reflection-factor of the ceiling is seen. There are several outstanding features of Table XVII: (1) the appreciable influence of walls of small rooms or narrow rooms in which direct-lighting opaque reflectors are used: (2) the great influence of both walls and ceiling in all the rooms but particularly those of small and intermediate sizes in the case of systems of enclosing diffusing glass; (3) the very great influence of walls and particularly ceilings in the case of indirect-lighting systems. Surely Table XVII presents adequate proof of the lighting value of paint.

Reflecting Characteristics of Surfaces

Paints exhibit the various reflecting characteristics that surfaces do in general. These are shown in Fig. 52 where

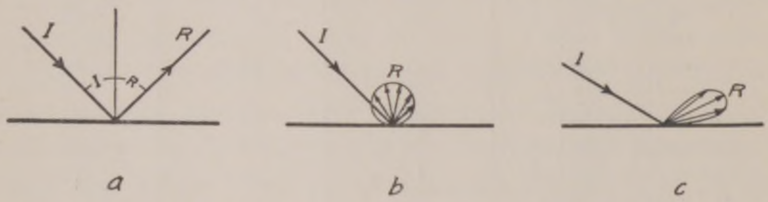


Fig. 52. Common reflection characteristics of surfaces: *a*, a regular or specular reflection: *b*, perfectly diffuse reflection: *c*, spread reflection.

I is the incident beam of light and *R* is the reflected light. Regular or specular reflection *a* is that of a perfect mirror where the angle of reflection *R* equals the angle of incidence *I*. This is approached by fairly polished metals and glossy varnished surfaces. A thick coating of glossy varnish on a jet black surface is a very good mirror. Such surfaces are undesirable from the viewpoint of lighting, because they reflect images of the light-sources, thereby causing glare and the attendant effects such as visual discomfort, eye-strain and reduced visibility. Glossy desk-tops, glossy walls and ceiling, and various polished surfaces are possible sources of glare.

Paints with dull finish approach perfect diffuse reflection *b* fairly closely although semi-matte finishes reflect not only diffusely but superposed on this is a sort of regular reflection which may be said to tend toward spread reflection *c*. A painted surface coated with glossy varnish or an enamelled surface may be represented by a combination of *a* and *b;* that is, by regular reflection superposed upon diffuse reflection. A good example of this is a thin sheet of glass laid upon a white blotting paper.

Metallic paints, such as aluminum paint, are excellent examples of spread reflection shown in *c*, Fig. 52.

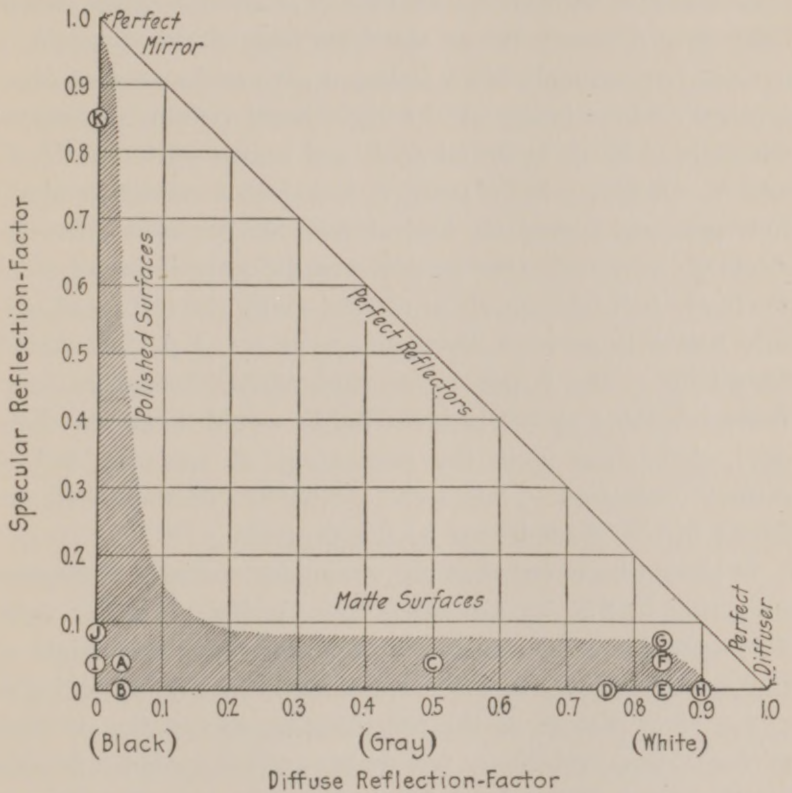


Fig. 53. Showing the amount of regular and of diffuse reflection of various surfaces which exhibit a combination of these two types of reflection. The regular reflection is determined for perpendicularly incident light.

- A Glossy black paint
- B Matte black paint
- C Glossy gray paint
- D White blotting paper
- E Best matte white paint
- F Best glossy white paint
- G Glazed white porcelain
- H Powdered zinc oxide
- I A surface of glass or water
- J Two surfaces of thin glass
- K Polished silver

So many surfaces show the characteristics of regular and diffuse reflection that it is interesting to plot them on a diagram such as Fig. 53. In this case the values of regular or specular reflection are for perpendicular incidence. The amount of light which a glossy varnished surface reflects is independent of the diffuse reflection of the coating beneath this transparent coating. This regularly reflected light amounts to about four per cent for glossy varnish for perpendicular incidence. In Fig. 53, surfaces which reflect light only diffusely lie on the base line of the diagram, a perfect (theoretical) black being at zero and a perfect (theoretical) white being at the right-hand corner. A matte commercial black is found at *B* and matte whites at *D, E,* and *H*. A glossy black paint is found at *A* reflecting about four per cent specularly and about four per cent diffusely. A glossy gray reflecting 50 per cent diffusely is found at *C*. Perfectly polished metals are found along the left-hand vertical line with average silver mirrors at *K*. A perfect mirror would lie at the upper corner and perfect reflectors (surfaces reflecting all the incident light) would lie on the diagonal, depending upon the percentage of specular and of diffuse reflection. Surfaces ordinarily encountered are found in the shaded area of the diagram.

It should be noted that the values for specular or regular reflection in Fig. 53 are for perpendicularly incident light. The specular reflection-factor increases with the angle of incidence as shown in Fig. 10. A study of Fig. 53 will give one a vivid picture of the reflecting characteristics of most surfaces, those relatively few which exhibit spread reflection (such as metallic paints) being the only exception from a practical viewpoint.

Reflection-Factors

The measurement of reflection-factor of a surface is a difficult matter if high accuracy is desired because, in general, the total incident light and the total reflected light must be measured by some integrating method. In the special case of a colorless surface which perfectly diffuses light, it is possible to measure its brightness with that of a standard diffusing surface of known reflection-factor receiving the same illumination. A block of pure magnesium carbonate is a satisfactory standard for this purpose. Its reflection-factor is found to be as great as 98 per cent, this value being safe for a clean surface of pure material.

High-grade commercial white paints have reflection-factors between 75 and 80 per cent, although many white paints reflect only 70 to 75 per cent. Occasionally a white paint will be found to have a reflection-factor above 80 per cent but seldom is a value of 85 per cent found in paints. Commercial white paints differ much more in reflection-factor than is commonly suspected by those who merely casually examine them. Other things being equal, an 80 per cent white has an appreciable advantage over a 70 per cent white paint from a lighting standpoint where the systems of lighting are such as to emit considerable light to the painted areas.

The reflection-factor of paints changes appreciably even when kept in a clean dark place. White paints generally decrease about 10 per cent in reflection-factor in a year or more. Most paints lose in reflecting value although some colored ones may fade and thereby increase slightly. This change is of little interest in general practice in factories, offices, etc. because deterioration due to dirt is very much more rapid. From a practical viewpoint hiding power, specific gravity, cost, and character of the surface are important factors.

The measurement of reflection-factors of colored surfaces is a very difficult matter because there are the additional difficulties of color-photometry. It would serve no useful purpose to present a table of reflection-factors of surfaces in general because of the impossibility of identifying these various surfaces. Even dry powdered pigments used in the manufacture of paints are by no means constant in reflection-factor. The product of one factory may vary from time to time and may be quite different from the same pigment produced by another factory. Nevertheless, there is some value to such data and, therefore, in Table XVIII is presented the reflection-factors of dry powdered pigments. They give a fair idea of the reflection-factors of colored media and also show that the reflection-factor of a colored surface depends upon the spectral character of the illuminant. Reds, browns and yellows reflect less sunlight and skylight than the yellowish artificial lights. Conversely the greens and blues reflect less yellowish artificial light than white sunlight or bluish skylight. The illuminants are those commonly met in lighting practice. For the sake of accurate specification the lumens per watt and the filament absolute temperatures (in degrees Kelvin) are also given herewith. The tungsten gas-filled lamp operated at about 15 lumens per watt and the filament temperature was 2780 degrees Kelvin. The tungsten vacuum lamp operated at 8 lumens per watt and its filament temperature was 2375 degrees Kelvin. The flame-tint light is that corresponding to the light from a candle flame. For the sake of specification it is that light which would be produced by a tungsten filament operating at a low wattage so that its temperature was 2000 degrees Kelvin.

Obviously the best manner of presenting data pertaining to reflection-factors is to accompany the data with the actual specimens. This is done in the color-chart which is found herewith. This chart first appeared in the excellent bulletin by E. A. Anderson.[41] The measurements of reflection-factors of the present chart were made by A. H. Taylor in the most approved manner by means of the Taylor reflectometer. Inevitably there is some slight variation intro-

Reflection Factors

The proportion of light reflected by walls and ceilings of various colors, that is, their Reflection Factors, have an important bearing on both the natural and the artificial lighting. The proportion reflected will depend somewhat upon the color of the incident light. The figures here given show what proportion of

# of Colored Surfaces

the light of Mazda lamps these painted surfaces reflect. Reflection Factors are of special usefulness in determining the Coefficient of Utilization (ratio of light delivered at the work to total light of lamps) applicable to an interior. The Reflection Factor of any colored surface can be approximated by comparing it with these samples.

No. 17
Buff Stone and Pale Azure
37%

No. 18
Buff
60%

No. 19
Buff Stone
47%

No. 20
Tan
28%

No. 21
Cocoanut Brown
16%

No. 22
Satin Green
63%

No. 23
Bright Sage and Ivory Tan
43%

No. 24
Bright Sage
38%

No. 25
Forest Green
16%

No. 26
Olive Green
21%

No. 27
Pale Azure and White
52%

No. 28
Pale Azure
39%

No. 29
Sky Blue
36%

No. 30
Shell Pink
51%

No. 31
Pink
50%

No. 32
Cardinal Red
16%

TABLE XVIII

Reflection-Factors (in per cent) of Common Dry Powdered Pigments.

	Blue Sky	Noon Sun	Tungsten (Daylight) Lamp	Tungsten (Gas-filled) Lamp	Tungsten (Vacuum) Lamp	Flame-tint Light
American Vermilion	11.7	13.7	14.8	16.9	17.7	20.1
Venetian Red	9.5	10.6	11.3	12.5	13.1	14.2
Tuscan Red	10.1	10.7	11.1	11.8	12.	12.8
Indian Red	9.2	9.9	10.3	11.	11.2	12.
Burnt Sienna	9.3	10.6	11.2	12.2	12.7	13.5
Raw Sienna	30.3	32.6	34.	35.7	36.6	38.
Golden Ochre	54.8	58.1	60.	62.3	63.4	65.2
Chrome Yellow Ochre	28.9	33.	35.2	38.7	40.4	43.5
Yellow Ochre	46.	48.8	50.5	52.5	53.4	55.
Chrome Yellow (Medium)	49.6	54.5	57.7	61.3	63.	66.
Chrome Yellow (Light)	70.	76.5	78.8	81.1	82.	83.9
Chrome Green (Light)	19.	19.4	18.5	17.8	17.5	17.3
Chrome Green (Medium)	14.2	13.6	13.2	12.5	12.	11.6
Cobalt Blue	18.3	16.2	15.2	14.1	13.	12.9
Ultramarine Blue	9.5	7.4	6.9	6.1	5.7	5.2

duced in the preparation of the specimens but the reflection-factors as given are generally within one or two per cent of the standard specimens. The Sherwin-Williams Co. prepared the painted papers and the names of the paints are those used by that company. The chart was furnished by the National Lamp Works of the General Electric Co.

Light diffusely reflected by a colored surface is tinted to some degree.[19] When the ceiling receives a large percentage of direct light from the lighting equipment, a conspicuous tint is given to the light reaching work-places if the ceiling is appreciably colored. This influence of colored surroundings is sometimes used to advantage but it is sometimes annoying as in coloring of daylight by adjacent colored walls.

Colors for Walls and Ceiling

For work-places, such as factories and offices, there are very definite color-schemes that cannot be surpassed in general satisfactoriness. For factories white ceilings and upper walls are best, in general, because they deteriorate rapidly enough. For the lower walls grayish green, olive green or dark buff is satisfactory. A lighter tint of the color used on the lower walls may be used on certain structural work or equipment, thereby giving the impression of a real decorative scheme. Workers have just as much right to look about them at pleasant surroundings. It is a growing practice to paint different pipe-lines identifying colors. It seems that it would be quite sufficient to paint only the valves or elbows instead of trying to outdo the futurists. Black is often used for radiators and pipe-lines but there seems to be little justification for this depressing absorbing paint in most cases. The author avoids the use of pure white wherever possible. It is too often harsh, cold, uninviting. It is greatly tempered in this respect by a slight cream tint. It would be much better if the too prevalent white of hospitals, bathrooms and other interiors were tempered to ivory.

In offices the ceiling which perhaps meets with most general satisfaction is a good white that has been tinted very slightly yellowish; in other words a cream tint. It seems that for visual comfort the reflection-factor of the walls should not exceed 50 per cent. A safe range is between 35 and 50 per cent. Buff or buff stone in which the color is very much subdued by gray is generally very satisfactory. A medium grayish green is another satisfactory color which the author would rank second to the buff or buff stone. In rooms with high ceilings it is well to carry the ceiling color down the walls making an appropriate frieze of this ceiling paint.

The matter of exposure is sometimes important. The buff or warm colors should be used in rooms of northern exposure in preference to the gray green. However, for southern exposure buff is still satisfactory, although many prefer the cooler color, such as gray green. The general superiority of the buff over the gray green is, in the author's opinion, enough to recommend its use when in doubt.

There is also a psychological phase of color in factories. In the dull cold winter months the warmer color such as buff may have some advantages but undoubtedly the gray green or cooler colors are decidedly advantageous for summer months. Obviously we cannot have both, and therefore it appears best to decide on the green for all year round. In the factory generally the worker should have no difficulty in keeping warm. In fact, perspiration is associated with work. For this reason the cooler colors seem to be generally more desirable than the buffs.

Painted Machinery

Throughout the entire industrial age manufacturers have persisted in painting machine tools and much other equipment either black or a very dark color closely akin to it. This not only contributed to the cheerlessness of poorly illuminated and ill-kept factories, but even in the modern factory where the lighting is fairly well done and orderliness reigns, dark machine tools have a depressing effect. They could be painted somewhat lighter in color without showing grease, finger-marks, etc. Entirely aside from this we have the lighting value of paint in such places to consider. All machine tools and equipment should not be painted white. Such a condition would be insufferable. However, if they were painted a very subdued color of a reflection-factor of 20 to 25 per cent, much light would be saved by reflection. But there is still an important phase of the use of paint and that is on surfaces near the work. The face-plate of a lathe, certain areas of the milling machine, the face of a press and many other areas near the tool or seat of operations can be painted a washable white or light gray. By reflection much light can be thrown upon the work and particularly in the shadows. On every hand we find such opportunities for using the lighting value of paint. No simple rules can be given. Each case is one involving lighting and vision. Sometimes these painted areas would be excellent aids to vision as backgrounds. In other cases the advantages of light reflection might be offset by the desirability of a dark background. All these factors should be considered but it is certain that there are many applications, small and large, of the lighting value of paints.

Glare from a light-source or from the reflected image generally is due partially at least to an excessive brightness-contrast. The high-light on a painted surface — the reflected image of a bright light-source — is more glaring when the surface is of low reflection-factor than when it is of a high reflection-factor. The brightness of the specularly reflected image is a matter of surface reflection and is not affected by the diffuse reflection. This accounts for the conspicuous high-lights on glossy dark surfaces and the much less noticeable high-lights on glossy light surfaces. This is an advantage of light colored surfaces.

Reflection of Invisible Radiation

Although the reflection characteristics of paint and other media for ultraviolet and infra-red radiations are of no direct importance in lighting, they are of special interest occasionally. It has been known for years that zinc oxide photographed darker than other white pigments. This is because it absorbs ultraviolet radiation shorter than about 366 mμ in wavelength. Pfund has confirmed this and has shown that titanox, lithopone and sublimated white lead reflect only slightly radiations of shorter wavelength than 320 mμ. Magnesium oxide reflects practically all ultraviolet radiations at least as short as 250 mμ in wavelength.

In the infra-red region paints also differ in reflecting characteristics although there has been little systematic investigating in this region. From the viewpoint of painting exteriors in hot climates at least this is important. In general, white exteriors which reflect much of the solar radiation are better than the darker ones which absorb much of the incident energy. It is easy to investigate this total absorption of energy by painting the exteriors of enclosures which are of the same shape and construction. By subjecting them to the same exposure of radiation and noting the temperature rise, the relative absorption can be ascertained. Even if metal strips are painted different colors and placed in the sunlight on snow, different rates of sinking into the snow will be noted. This gives a qualitative comparison at least.

Chapter XIII

THE MOST EFFECTIVE INTENSITY OF ILLUMINATION

IN other chapters the influences of lighting on vision and on human activity have been discussed at some length but no attempt was made to consider what is the most effective lighting. In the present chapter data of other chapters and additional data are used in an attempt to establish more or less definitely the illumination intensity which appears to be most generally suitable for the most effective vision and the most efficient work. In these discussions the matter of proper lighting will be subordinated to that of adequate lighting, for it is assumed that the lighting system will be free from glare. That this is possible even at very high illumination intensities is demonstrated outdoors in the daytime. In fact, glare and lowered visibility are less easily eliminated at low levels of illumination than at high ones. In other chapters there is plenty of testimony in favor of much higher intensities of illumination than are commonly encountered indoors. We also know by experience that it is not comfortable to read black print on white paper in the direct sunlight at noon, although we can discriminate details on surfaces of lower reflection-factors without discomfort. Therefore, we know that the most generally desirable level of brightness lies somewhere between that due to an illumination of our surroundings of a few foot-candles and the 10,000 foot-candles at noon on a day in midsummer.

Foot-candles, Reflection-Factors and Brightness

The lighting specialist and others interested directly in lighting think and act largely in terms of foot-candles while those interested more particularly in vision should specify brightness. This is quite as it should be. The lighting specialist is not interested in any particular surface of a certain reflection-factor but in all surfaces of the whole range of reflection-factors. Those who are concerned directly with vision naturally must deal first with the stimulus which is the brightness regardless of foot-candles and of reflection-factors. Nevertheless, the data must be transformable into both states. Particularly, those interested in lighting must visualize the brightnesses involved if they are to profit by much of the data pertaining to vision.

Anyone, if he stops to think, realizes that illumination intensity is cause and brightness is effect. The link between the two is the diffuse reflection-factor of the surface illuminated. It is customary to omit the word "diffuse" because specular reflection applies only to polished or glossy surfaces and the brightness due to it is dependent upon the brightness of the light-source and not upon intensity of illumination. This point is brought out in Chapter XII in connection with Figs. 52 and 53.

Owing to the fact that both brightness and illumination intensity are of interest in lighting and vision and that those interested more directly in lighting must be concerned primarily with foot-candles, the author devised the plan of presenting much of the data in the previous chapters in terms of foot-candles and diffuse reflection-factors. From the viewpoint of practice, so-called white is well represented by 80 per cent reflection-factor. By using this for the lower scale in many of the illustrations in Chapters VIII and IX, the data are readily visualizable. For convenience the upper scale in many of these illustrations represents foot-candles on a dark gray surface of 8 per cent reflection-factor. It is seen that these scales actually represent brightnesses, but the foot-candle unit still remains of primary importance. This proves to be a very practicable plan for the purpose of this book. It would be much simpler to use a brightness unit but the data would not be so easily visualized.

In Fig. 54 is shown the complete relation between brightness, reflection-factor, and intensity of illumination. On the left-hand scale are found the foot-candles required in illuminating surfaces of various diffuse reflection-factors (lower scale) to produce a brightness of one millilambert. If it is

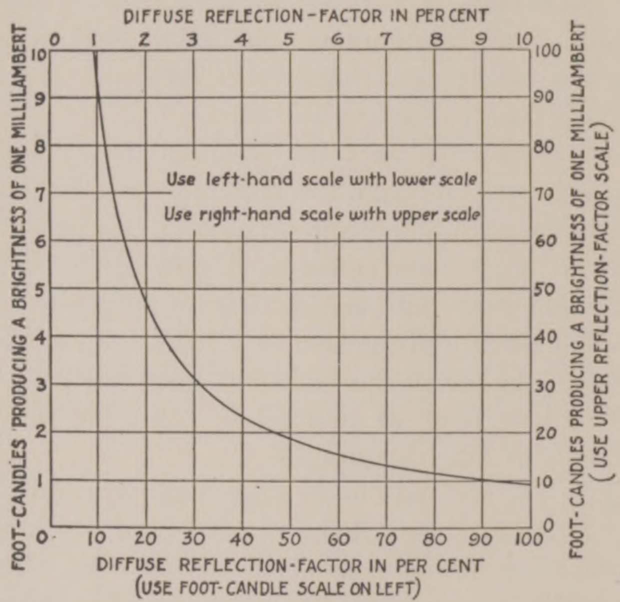


Fig. 54. Showing the illumination intensities in foot-candles for surfaces of various diffuse reflection-factors necessary to produce a brightness of one millilambert. The left-hand scale should be used with the lower scale for all values of reflection-factor greater than 10 per cent. For smaller values the upper and right-hand scales should be used.

desired to know the intensity of illumination for a surface of 20 per cent reflection-factor to produce a brightness of one millilambert, the curve directly above this value on the lower scale is seen to correspond to 4.64 foot-candles. For 80 per cent reflection-factor it is one-fourth this value or 1.16 foot-candles. For 10 per cent reflection-factor it is eight times the latter value or 9.28 foot-candles. For the sake of convenience the upper scale is for the range between zero and 10 per cent reflection-factor. The same curve applies to this range if the right-hand scale is used with the upper scale. For example, a brightness of one millilambert requires an illumination intensity of 46.4 foot-candles if the reflection-factor is only 2 per cent. It is obvious that from this diagram any other brightness can be considered by multiplying the results by its value in millilamberts. Furthermore, transformations can be made readily for brightnesses in terms of the other units presented in Chapter VIII.

Fig. 54 vividly presents the very large range in foot-candles necessary to make ordinary surfaces, which differ widely in reflection-factor, appear equally bright. This has been so often overlooked in investigations and in presenting the results of them that it is emphasized here. For example, our so-called whites are generally used as backgrounds for visual experiments and the foot-candle scale is used in presenting the data without emphasizing that the foot-candle values apply to this background of particularly high reflection-factor. As pointed out in a previous paragraph and in various illustrations in Chapters VIII and IX, the foot-candle values must be increased in proportion to the decrease in reflection-factor. Everyday visual work, particularly in industries and partially in every activity, is often concerned not only with backgrounds of much lower reflection-factor than so-called white, but the detail viewed against this background usually has a reflection-factor much greater than that of the so-called black. Furthermore, we are often obliged to see in shadow; that is, to discriminate details and differences in brightness and in color, on areas not receiving full illumination. Taking these facts into consideration, it is seen that the scale of intensities of illumination (foot-candles) relating to data obtained with black on white in full illumination should be multiplied by a large

" factor of safety " to make the data applicable to average visual activities. There are other phases which also tend to increase this " factor of safety."

The relation between brightness, reflection-factor, and illumination may be expressed as follows:

$$B = CIR$$

where B = Brightness
C = A Constant
I = Illumination Intensity
R = Reflection-Factor (diffuse)

If I is expressed in foot-candles we have,
Brightness in millilamberts = 1.076 IR
Brightness in candles per sq. in. = 0.00221 IR
For example, a surface diffusely reflecting 80 per cent of the incident light (0.8 reflection-factor) illuminated to an intensity of 50 foot-candles would have a brightness of, —
$1.076 \times 50 \times 0.8$ millilamberts = 43.04 ml.
or $0.00221 \times 50 \times 0.8$ candles per sq. in. = 0.0884 candles per sq. inch.

Plotting Data Pertaining to Visual Functions

In order to properly interpret data pertaining to visual functions it is necessary to recognize certain general characteristics of visual laws. Doubtless it has been noted that there is a general similarity among the curves expressing relations between brightness (illumination intensity multiplied by reflection-factor) and visual acts such as acuity, sensitivity to brightness-difference, speed of discrimination, etc. Some of the illustrations which verify this are Figs. 23, 26, 27, 40, 42, and 45. These and many other visual laws may be represented approximately by $y = \log x$. From a scientific viewpoint it is more convenient and often more instructive to plot the data, yielded by investigations pertaining to vision, on a logarithmic scale. This has been avoided purposely in preceding chapters because the logarithmic scales are confusing to those who are not used to thinking in terms of them. The logarithmic scale has an advantage in making it possible to plot a great range of brightnesses or illumination intensities in a small space and

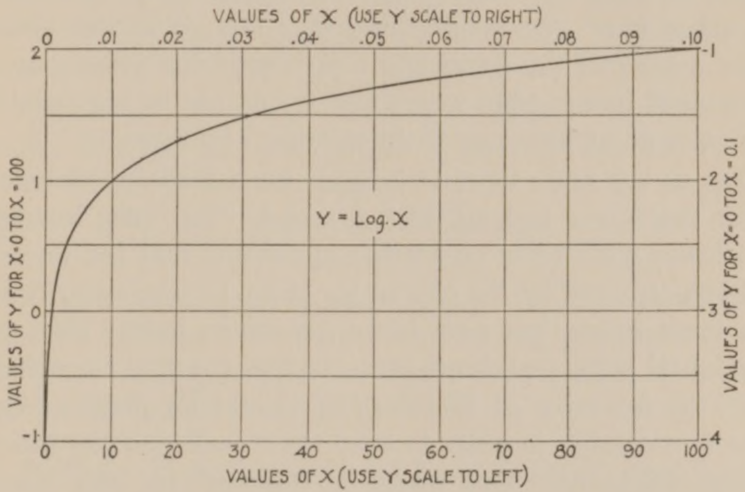


Fig. 55. The equation of the curve is $y = \log x$ and y is represented by the vertical scale on the left for corresponding values of x on the lower scale for a certain range of values (from $x = 0$ to $x = 100$). The identical diagram serves to represent another range of values ($x = 0$ to $x = 0.1$) as seen by applying the scale to the right and the upper scale.

this is often desirable with visual data because of the extensive range of sensitivity of the visual sense. This scheme was adopted in Figs. 22 and 30 because it was desirable to show the results over a great range. However, in most of the illustrations the regular scale sufficed to present the data in the range in which we are particularly interested.

In Fig. 55, $y = \log x$ is plotted for two ranges of values and the same curve fits both of them. The left-hand scale for y values applies to the lower scale of x values between $x = 0$ and $x = 100$. The right-hand scale for y values applies to the upper scale of x values between $x = 0$ and $x = 0.1$. Now supposing we had plotted the curve only for the range represented by the left-hand and lower scales. If this were an actual visual function (as it could be) and the lower scale represented foot-candles (for a specific background), we might conclude that the intensity of illumination should be greater than about 20 foot-candles in order to have the visual sense operating fairly efficiently. In other words, we might think that this value was above the "knee" of the curve and represented the beginning of a range of foot-candles where gain would not be appreciable for even great increases in illumination intensity.

Let us lay aside these two scales for a moment and consider the upper and right-hand scales. (In fact, imagine the lower scale replaced by the upper one and the one on the left replaced by the one on the right.) The same curve fits these scales, but now, if we assume as before that the horizontal scale represents foot-candles, we might conclude that the intensity of illumination should be greater than 0.02 foot-candles in order to have the visual sense operating fairly efficiently. This could be repeated for an infinite number of ranges of values with a different conclusion each time. Thus it is seen to be misleading to draw general conclusions too freely from the form of a curve plotted for a single range of values. This mistake is often being made.

With the foregoing limitations in mind, we find the form of the curve, and even the specific values applying to the region just above the "knee" of the curve, of considerable value. The form of the curve shows that the gain in y is less for a given increase in x as the value of x increases. Looking at it in any way, we find that when x is of a certain value it requires a greater increase in it to accomplish a certain increase in y than when x is of a lower value. If this curve represents a visual function such as sensitivity to brightness-difference we may state that an increase in sensitivity results from an increase in brightness (or illumination), but the rate of increase gradually lessens as the brightness increases. If the *x* values cover the entire range in which we are primarily interested, then further conclusions can be drawn with safety.

In the relation of artificial lighting with production in various activities we are interested chiefly in the region from one to a thousand foot-candles. In fact, from the viewpoint of the intensities of illumination in general use indoors and including the relatively few of the higher intensity installations and even the highest intensities that might possibly be considered for general lighting at the present time, a range as high as 100 foot-candles would be ample. The data represented in Figs. 23, 24, 26, 27, 35, 37, 38, 40, 42, 43, 45 and others apply to the range of foot-candles of interest to us at present in the consideration of effective lighting. For this reason we may use these curves for drawing conclusions as to the desirability of certain foot-candle values.

A Résumé of Data Bearing Upon Illumination Intensity and Vision

In previous chapters we have seen that vision improves with increase of brightness or of illumination intensity. Now let us review these data with a view of establishing the minimum or perhaps a range of illumination intensity for the best vision. It should be borne in mind that these data were obtained in laboratory researches where there was little or no distraction, where the subject could be at ease, and the conditions in general were of the best. In all these researches excepting those actually involving "speed of vision," the subject had all the time necessary to arrive at a judgment. In other words, he did not feel hurried. Actual work conditions are quite different from the ideal conditions of the laboratory; therefore, it appears reasonable that a " factor of safety " should be allowed for work conditions. This is discussed later.

The following is a summary of data bearing upon intensity of illumination for best vision as determined for various acts and test-objects. An attempt is made to estimate conservatively the minimum illumination intensity that is permissible if the eye is to function reasonably near its best efficiency. In those cases where the range of illumination intensity extends to sufficiently high values the best range of illumination intensities is also indicated. In order to get a fairly complete view the values are given in terms of brightness in millilamberts and also in foot-candles for surfaces of 80 per cent and 8 per cent reflection-factors respectively. White light or the unsaturated yellowish light from ordinary light-sources and neutral or colorless surfaces are implied.

The summary in Table XIX pertains chiefly to data already presented in Chapters VIII and IX. In only a few cases is it possible to give the value of brightness or illumination intensity where the best vision is attained. In only a few cases is it possible to give even the approximate range of more efficient vision. This is due to the fact that data are not available throughout a sufficient range. Therefore, in most cases only the approximate lower limit of the best range of brightnesses or illumination intensities is available. It should be understood that visual efficiency continues to increase above this lower limit, but that in the judgment of the author these are the lower limits for good vision even in the ideal conditions of the laboratory. In some cases visual efficiency is still very rapidly increasing at the highest brightness represented by the available data.

Near the bottom of Table XIX certain values are taken from data by Nutting.[44] What he terms *discrimination-factor* is the brightness of a field divided by the just noticeable brightness-difference in a portion of the field.

TABLE XIX

Data pertaining to the range of brightness for efficient vision. These are taken chiefly from the various illustrations indicated.

	Milli-lamberts (a)	Foot-candles	
		80% R (b)	8% R (c)
Fig. 23. Best region for sensitivity to brightness difference *is above*	9	10	100
Fig. 26. Best region for discrimination of fine "black" details on a bright background *is above*	9	10	100
Fig. 37. Best region for rapid discrimination of "black" international test-object on a brighter background *is above*	10	12	120
Fig. 40. Best region for rapid discrimination of a small "black" dot on brighter background *is above*	87	100	1000
Fig. 42. Best region for rapid reading of "black" print on a brighter background *is above*	17	20	200
Fig. 45. Best region for discrimination of "black" bars on a brighter background *is above*	90	100	1000
Fig. 45. Best region for discrimination of "black" bars on a brighter background (preceded and followed by confusion patterns) *is above*	35	40	400
Fig. 57. Ditto but lower contrast *is above*	180	200	2000
Fig. 22. Minimum brightness-difference is discerned at	300	350	3500
Nutting's data. Instantaneous threshold is a minimum percentage of adaptation-field brightness at about	300	350	3500
Fig. 22. Best region for discerning brightness-difference	9–2600	10–3000	100–30000
Nutting's data. Best range for instantaneous threshold	100–1000	115–1150	1150–11500
Nutting's data. Best range of discrimination factor	10–100	12–115	115–1150

This represents the ability to discriminate relatively large details (not the finest at least) when there is no appreciable color-difference; that is, the discrimination is due to perception of brightness-difference in a field of brightness. For example, if we have a large field of a certain brightness, we shall be able to distinguish a spot slightly darker or brighter. The brightness-difference necessary to see the spot depends upon the brightness of the background. Nutting's discrimination-factor which he computed for a large range of brightnesses is a maximum for a range from 10 to 100 millilamberts. This range of brightnesses is produced by 12 to 115 foot-candles on a surface of 80 per cent reflection-factor and by 115 to 1150 foot-candles on one of 8 per cent reflection-factor.

The data on instantaneous threshold were taken from Nutting's publication [44] of work by Blanchard, Reeves and himself. They exposed the eyes to a field of a certain brightness, 60 cm. square and viewed at a distance of 35 cm. This field brightness was suddenly extinguished leaving a small square (0.3 cm on a side) in the center of the large field. The brightness of the small square was adjusted until it was just discernible immediately after the brightness of the large field was extinguished. This procedure was carried out over a very great range of field brightnesses (0.000001 ml. to 10,000 ml.) and the instantaneous threshold (least brightness of small square that was discernible at the instant the brightness of the large field was extinguished) was determined throughout the entire range of brightnesses of the large field. For the range of field brightnesses from 100 to 1000 ml., the instantaneous threshold brightness was of the order of magnitude of 0.2 per cent of the field brightness. This percentage rapidly increased as the field brightness decreased below or increased above this range. This is of interest in every-day vision because vision is being directed from one surface to another of different brightness. Speed of discrimination will in general be best for those ranges of brightnesses (levels of illumination) at which the eye can instantaneously discern the smallest fraction of the brightness to which it was just previously adapted. It is seen that this best range of brightness corresponds to a range of 115 to 1150 foot-candles on a surface of 80 per cent reflection-factor or of 1150 to 11500 foot-candles on one of 8 per cent reflection-factor.

These data on instantaneous threshold are so important that they are reproduced for a portion of the range of brightnesses in Table XX. The instantaneous threshold brightness has also been computed in per cent of the field brightness. Values of discrimination-factor, as defined by Nutting, and of minimum perceptible brightness-difference, have also been included in this table. The values in parentheses are doubtless computed or estimated.

TABLE XX

Visual Sensitometric Data.

Field Brightness * Millilamberts	Instantaneous Threshold Brightness	Brightness of Instantaneous Threshold in Per Cent of Field Brightness	Minimum Perceptible Brightness Difference	Discrimination Factor B/dB
0.000001	0.00000093	93.0	(1.00)	1.0
0.00001	0.0000042	42.0	(0.66)	1.5
0.0001	0.000019	19.0	0.395	2.5
0.001	0.000087	8.7	0.204	4.5
0.01	0.00039	3.9	0.078	12.8
0.1	0.00175	1.75	0.037	27.0
1.0	0.0082	0.82	0.021	48.2
10.0	0.036	0.36	0.018	57.5
100.0	0.191	0.19	0.017	58.1
1000.0	2.14	0.21	0.024	41.7
10000.0	(232.0)	(2.32)	(0.048)	(20.9)

* To transform these brightnesses into foot-candles on surfaces of 80 per cent and 8 per cent reflection-factor multiply millilambert values by 1.16 and 11.6 respectively.

The Best Illumination Intensity Regardless of Cost

Although in some aspects of lighting and vision we do not have adequate data available, in general there are enough data to warrant some conclusions. At least we may establish the best range of illumination intensities for general visual activity. These limits are not clearly defined but we do have sufficient data upon which to base a lower limit. The upper one we may safely conclude is so high as to be quite beyond hope of realization in artificial lighting at the present time. Even though it might be proved to be economically profitable to provide illumination intensities of several hundred or a thousand foot-candles of artificial light, the inertia of the user of light would not likely be overcome very easily. From the viewpoint of lighting practice the value of better lighting is of primary interest. We know that present conditions of artificial lighting can be greatly improved *at a profit* because of the increased safety, production, and cheerfulness. A question naturally arises as to where the law of diminishing returns may establish a dead line. This is discussed later. For the present let us consider the matter of illumination intensity quite aside from cost.

In Table XIX we have seen a summary of the influence of illumination intensity upon vision and the illumination intensities of moment in the judgment of the author have been recorded. Of course, for any specific kind of work we could determine the important elements of vision that are involved and to what extent they play a part in the entire human activity. We shall find that brightness discrimination is always essential. Sometimes visual acuity or the discrimination of the finest detail is involved. Nearly always fairly small details must be discriminated. In nearly all cases color-discrimination is involved but usually in a secondary, though helpful, manner. Relatively few areas are actually colorless and often there is a helpful color-difference superposed upon brightness-difference. Colored backgrounds and colored light can be helpful or harmful in special cases. However, for the present it is best not to include a consideration of color. Quality of light has been discussed in previous chapters, therefore it is not considered here. White light or the so-called white (yellowish) light of ordinary continuous spectrum illuminants was employed in obtaining the data under discussion. This is the kind of light that will be generally employed unless we find that we can safely improve upon Nature in this respect.

Early in this chapter, it was pointed out that many visual functions are approximately logarithmic in character and therefore care must be exercised in drawing conclusions from the curves of plotted data. The form of these curves is similar to many efficiency curves of devices such as electric motors. If the range of values is that in which we are ordinarily interested it is of interest to draw such conclusions as are summarized in Table XIX bearing in mind the limitations. Column *a* gives the lower brightness at which vision begins to operate fairly efficiently. Inasmuch as it is desirable to think in terms of foot-candles let us consider column *b*. Here it is seen that 10 foot-candles (on a surface of 80 per cent reflection-factor) is the lower limit of illumination intensity which the data indicate as desirable according to the judgment of the author. It should be noted that vision becomes better or more efficient for a great range of foot-candles above this "lower limit." This is indicated in all the illustrations mentioned in Table XIX and by the data in Table XX. The highest value of this lower limit is uncertain because most of the data available do not extend far enough. However, the highest value (that the available data yield) of what seems a conservative lower limit is about 100 foot-candles for 80 per cent reflection-factor or 1000 foot-candles for 8 per cent reflection-factor.

Where the data are extensive enough we find the best range to be from 10 to 3000 foot-candles (for 80% R) or 100 to 30,000 foot-candles (for 8% R). These data also yield the value for the most efficient vision as determined by the minimum perceptible brightness-difference and the instantaneous threshold. It seem to be about 350 foot-candles (for 80% R) or 3500 foot-candles (for 8% R).

TABLE XXI

Summary of Values in Table XIX

	Foot-candles	
	80% R	8% R
Lower limit of desirable intensities	10 to 100	100 to 1000
Range of desirable intensities	10 to 3000	100 to 30000
Illumination intensity for best vision	about 350	about 3500

Low Contrast Requires More Light

In several chapters it has been pointed out that much of our laboratory work has been done with test-objects of high contrasts such as " black " details on ordinary " white " backgrounds. Conclusions drawn from these data underestimate the importance of higher intensities of illumination. For this reason in many of the illustrations, particularly in Chapters VIII and IX, two scales of brightness have been supplied. These two scales are for foot-candles on surfaces of 80 and 8 per cent reflection-factor respectively. The foot-candle values on the 8 per cent reflecting surface are 10 times those on the 80 per cent scale for *equal brightness* of background. The former scale in all these cases shows the great importance of higher intensities because most of the brightnesses or backgrounds which we encounter in general vision lie somewhere between the two extremes.

The only data available for speed of vision for lower contrasts than the usual black-white is that of speed of reading in Figs. 42 and 43 and that obtained by Cobb, Figs. 56 and 57. These show the relatively greater importance of higher intensities of illumination for low contrast than for high contrast. However, the actual contrasts between the type and background in the reading tests were not measured. Furthermore, the curves in these two illustrations

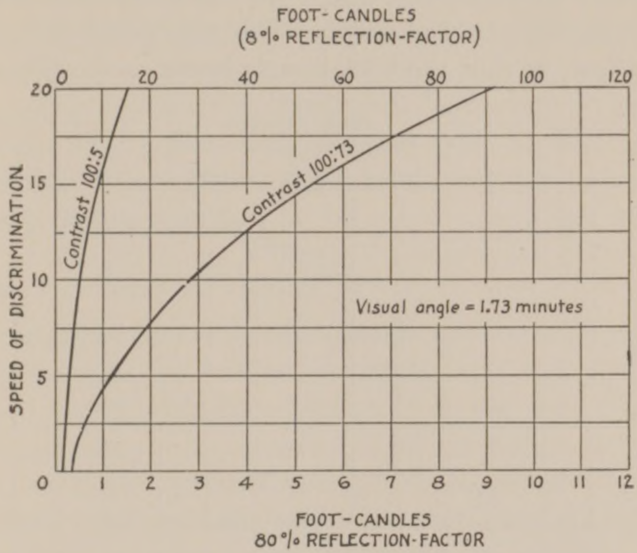


Fig. 56. Showing the influence of intensity of illumination (or brightness of background) on the speed of discrimination of a test-object consisting of bars 3 mm. wide separated by intervals of the same width and viewed at 19.7 feet. The test-object was similar to *b*, Fig. 44, and it was preceded and followed by confusion patterns similar to *a* and *b* (Fig. 44) respectively. The high contrast (100:5) consisted of the usual "black" on "white." The low contrast (100:73) consisted of light gray bars on "white." The data are the averages of 21 observers.

are made equal at one point so that they cannot be compared one with the other from a viewpoint of absolute values.

Recently Dr. P. W. Cobb has completed some experiments with 21 persons for the test-object illustrated in Fig. 44, but for two extremely different contrasts. In one case the contrast between the white background and the black bars in *b*, Fig. 44, was 100 to 5. In the case of low contrast, the contrast between the background and the bars was 100 to 73. The test-object *b* was preceded and followed by "confusion patterns" *a* and *c* respectively. The data are plotted in Figs. 56 and 57. The data represented by the two curves in Fig. 56 were obtained with the bars of the test-object *b*, Fig. 44, 3 mm. in width separated by white intervals of equal width. The test-object was viewed at 19.7 feet, so that the visual angle between the black bars

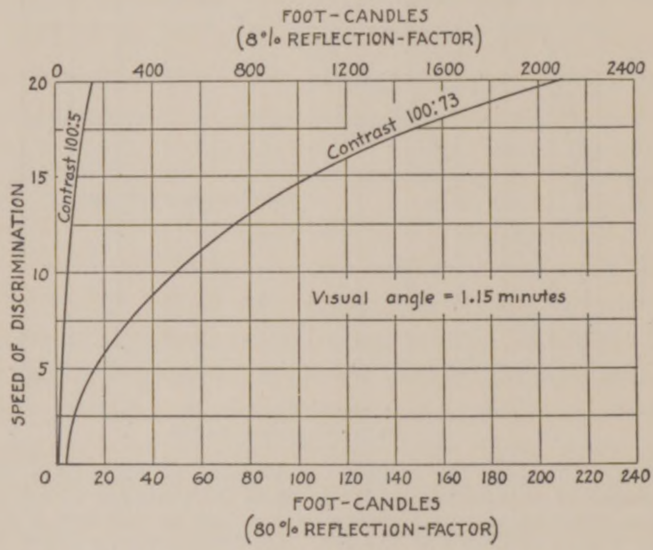


Fig. 57. Data from an investigation similar to that whose results are plotted in Fig. 56. Same observers, apparatus, etc., except that the bars of test-object, (and intervals between) were 2 mm. wide. Note the relatively high intensities of illumination required to attain the same speeds of discrimination as in Fig. 56.

was 1.73 minutes. The test-object used in obtaining the data presented in Fig. 57 had bars and intervals 2 mm. in width. Viewed at 19.7 feet the visual angle between the bars was 1.15 minutes.

It is seen that the speed of discrimination for the high-contrast test-objects increased very rapidly with brightness of the background (foot-candles on a surface of 80 per cent reflection-factor). For equal speeds of discrimination the low-contrast test-objects required very much higher intensities of illumination than the high-contrast ones. Furthermore, it is noted that the foot-candle scale for Fig. 57 covers 20 times the range of that for Fig. 56. In other words, a decrease in size of test-object from 1.73 minutes to 1.15 minutes requires about 20 times the illumination intensity (background brightness) for equal speeds of discrimination of the two low-contrast test-objects. If the background had a reflection-factor of 8 per cent instead of 80 per cent the upper foot-candle scales would apply in Figs. 56 and 57. It will be noted that in the latter case the foot-candles are very high values.

Average Reflection-Factor

Throughout these chapters brightness and illumination intensity have been related by expressing the brightness in terms of foot-candles on a surface of 80 per cent reflection-factor and also on a surface of 8 per cent reflection-factor. These represent extremes fairly well because the former is a so-called white and the latter is a very dark gray. If we were confronted all the time with surfaces of this very dark gray and were obliged to discriminate brightness-differences and details darker than the surface, we would need at least ten times more light than if the surfaces were so-called white. If we should choose 3000 foot-candles as the best intensity of illumination for the very dark gray surroundings, we would find this intensity too great for white surfaces. On the other hand, if the illumination intensity is barely sufficient for efficient discrimination of dark details on so-called white surfaces, certainly the intensity is insufficient for surfaces of low reflection-factor and also for those in shadow.

There is quite a range of illumination intensities, near the region of best vision, throughout which vision is fairly efficient. Taking this and other factors into consideration we may conclude that it would be fair to base our illumination intensity on an average reflection-factor of 40 per cent.

On consulting Table XIX it will be seen that a conservative and safe estimate of the good average brightness for efficient vision is 350 foot-candles on a surface of 80 per cent reflection-factor. Taking into account this average reflection-factor of 40 per cent, we conclude that 700 foot-candles is approximately the best for work in which vision plays an appreciable part, provided the work receives full illumination and the conditions are as generally satisfactory as in the laboratory.

If we wish to provide for best vision in shadows receiving *only* 10 per cent of the full illumination, the value of the illumination intensity outside the shadows would be 7000 foot-candles. In Tables XIX and XXI it is seen that this is about twice the upper limit of desirable range for so-called white surfaces and is just at the upper limit which the data indicate as the desirable range for average reflection-factor of 40 per cent. Therefore it is not desirable to provide fully for the best vision in shadows. Thus we arrive at a point where judgment alone is available and the matter may be considered as being involved in the factor of safety.

Factor of Safety in Lighting

Certainly it is not unreasonable to apply a factor of safety in lighting. If we could determine the best illumination intensity, what would be a reasonable factor of safety? Laboratory conditions are ideal compared with work conditions. The complication of movement of arms and body, the changing adaptation of the eyes to different brightnesses as we look from one surface to another, and various distractions tend to reduce the efficacy of vision. It seems necessary to take these matters into account. Factors of safety in structural design have no necessary relation to factors of safety in lighting and vision but it is of interest to recall that the former are often from 5 to 10. That is, it is not uncommon after making computations based on reliable physical data, to provide for strengths from 5 to 10 times that actually necessary for the purpose.

We have a somewhat different situation in vision. Although vision becomes better or more efficient as the level of brightness (or illumination) increases, a level is finally reached beyond which ability to discriminate fine details and brightness-differences diminishes. Therefore, we must be careful not to provide for the best vision for backgrounds of low reflection-factor, for low-contrasts, and for details in shadow, at too great sacrifice of vision in the case of backgrounds of high reflection-factor which receive full illumination. In Table XIX and XXI it is seen that the best range of intensity for so-called white surfaces extends to about 3000 foot-candles. Even beyond this there is a range where vision is quite satisfactory; however, it is well to bear this value in mind. It would be 6000 foot-candles for 40 per cent reflection-factor.

In the preceding section it was concluded that 700 foot-candles represents a fair average value for the best vision when an average reflection-factor of 40 per cent is assumed. In a shadow receiving 10 per cent of full illumination, this value would be increased to 7000 foot-candles. This leaves no room for increase by means of a factor of safety which would take care of the difference between vision in the laboratory and that under actual work conditions. As a matter of fact, if we should provide for best vision in shadows for average surfaces, we would find it necessary now to use a factor of safety less than unity in order to have efficient vision for so-called white backgrounds. Therefore, if we ignore vision in shadows we could have a factor of safety of about 4 because the upper limit of brightness for the best range of vision is 3000 foot-candles for a surface of 80 per cent reflection-factor and the best illumination intensity is about 700 foot-candles on a 40 per cent reflecting surface. Considering everything, this factor of safety may be too high because it is giving too much importance to vision in shadows. However, the advantage of being able to see well in shadows is experienced every day outdoors.

The desirable value of factor of safety depends upon the illumination intensity which is actually under consideration. If we are dealing with one of 10 foot-candles and were considering illumination intensity only from the basis of good vision, we could easily justify a factor of safety of 10 or even 30.

This discussion is not introduced for the purpose of establishing a fixed value of factor of safety but only for the purpose of suggesting the desirability of such a factor. Certainly under the prevailing intensities of illumination, factor of safety should receive consideration and at least it should be of a magnitude considerably larger than unity.

To summarize again we may conclude that the following illumination intensities would be about the best as based on laboratory conditions. Certainly work conditions would not demand lower intensities.

For reading black print on white background and not necessary to see in shadows, 350 foot-candles.

For discriminating very dark details on backgrounds of 20 per cent reflection-factor, 1400 foot-candles.

For general work assuming an average reflection-factor of 40 per cent and seeing in shadows not necessary, 700 foot-candles.

For general work as in the preceding case but where seeing in shadows is important at least 1000 foot-candles.

The maximum upper limit of the desirable range of intensities is not far from 3000 foot-candles.

Chapter XIV

THE MOST ECONOMIC INTENSITY OF ILLUMINATION

IF light did not cost anything, the most economic intensity of illumination would be that at which vision in general would be best. As seen in Chapter XIII, that intensity is in the neighborhood of 350 foot-candles for discriminating black details on white backgrounds, such as in reading. It would be somewhere between this and 3000 foot-candles for general work. The best intensity for average work conditions demanding the best vision is in the neighborhood of 700 to 1000 foot-candles. The average intensity of illumination indoors is less than one per cent of this latter value in artificial lighting and is not much more than one per cent of this value in congested commercial and industrial districts in natural lighting indoors.

In discussing the illumination intensities for best vision for various specific and average purposes, cost of lighting was purposely ignored. It is interesting to establish, approximately at least, the ideal intensities for work. In practice it is to be expected that cost may be a limiting factor in striving to attain the ideal. If history repeats itself, the cost of artificial lighting will continue to decrease. If in the present century the cost of light decreases as much as it did during the past one, in the year 2000 light will cost only one thousandth of what it did in 1800. But we need not look that far ahead, because the cost of artificial light is low enough now to justify much better lighting than even the best installations supply today. Furthermore, the cost of light will continue to decrease.

Cost of Artificial Lighting

The cost of lighting varies somewhat with location and, of course, from year to year. For this reason cost data are included here with some misgiving. Without such data certain discussions cannot be presented, so it appears desirable to present some data of this sort. E. W. Commery has very carefully computed the many items and checked his results with various contractors and others. These data are presented in condensed form in Table XXII and in several graphic charts. They apply to Cleveland in the winter of 1923–1924. The lighting system consists of porcelain-enamelled (RLM dome) steel reflectors and bowl-enamelled tungsten gas-filled lamps spaced uniformly on 10-foot centers. The illumination intensity is uniform throughout the room which is 100 ft. by 200 ft., a representative unit of factory construction. The illumination intensities are not initial ones from clean lighting equipment and new lamps but are " average in service." That is, an average depreciation of 25 per cent in lighting is taken into account. The size of the lamp used is given in each case. The " materials " include everything with the exception of lamps; the latter are treated as a separate item. The installation costs are separated from the operating costs per year. The computations are based on 2500 hours' operation per year. Interest, taxes, etc. are assumed to be 10 per cent and depreciation 12.5 per cent. The number of outlets remains constant for the entire range of illumination intensities. Electric energy being such a large item in operating cost at the present time and its cost being so variable, operating costs are given for 1 cent, 3 cents, and 5 cents per kw-hr. All items of cost in the table are given in dollars.

TABLE XXII

Costs of installation and of operation per year (2500 hours) of a lighting system for a factory 100 ft. by 200 ft. for various intensities of uniform illumination. Porcelain enamel (RLM) steel reflectors and bowl-enamelled lamps are uniformly spaced on 10-foot centers. First-class wiring in conduits with adequate control of circuits. The foot-candles are average in service, allowance being made for an average depreciation of 25 per cent in initial light when equipment is clean and lamps are new. Materials include everything except the gas-filled tungsten lamps. These are in a separate item. Costs computed for Cleveland in 1924. Costs given in dollars.

Foot-candles	1.9	3.8	5.5	9.2	13	21	39	61	85	128
Watts per lamp	50	75	100	150	200	300	500	750	1000	1500
INSTALLATION COSTS:										
Materials	$807	$819	$936	$1058	$1093	$1499	$1766	$2104	$2814	$2814
Labor	269	273	312	353	364	500	589	701	938	938
Contractor	285	290	300	374	750	1030	1214	1445	1932	1932
Total Installation	1361	1382	1579	1785	1843	2529	2980	3549	4746	4746
Cost per outlet	6.80	6.90	7.90	8.90	9.20	12.65	14.90	17.75	23.80	23.80
OPERATION COSTS PER YEAR:										
Interest Taxes (10%)	$136	$138	$158	$179	$184	$253	$298	$355	$475	$475
Depreciation (12½%)	170	173	197	223	230	316	372	444	592	592
Lamp Renewals	181	221	261	321	425	657	930	1442	1520	1920
Maintenance	300	300	300	300	300	300	300	300	300	300
Energy at 1¢ per kw-hr	250	375	500	750	1000	1500	2500	3750	5000	7500
Total Annual operating cost with electric energy at 1¢ per kw-hr	1037	1207	1416	1773	2139	3026	4400	6291	7887	10787
3¢ per kw-hr	1537	1657	2416	3273	4139	6026	9400	10791	17887	25787
5¢ per kw-hr	2037	2707	3416	4773	6139	9026	14400	21291	27887	40787

In Fig. 58 the total annual operating cost in dollars is presented for the lighting installation for different intensities of illumination delivered on the work-plane. Inasmuch as electric energy is such an important factor in operating cost, the total cost is given for three different rates, namely, 1 cent, 3 cents, and 5 cents. It is seen that up to 130 foot-candles the curves are practically straight lines.

In Fig. 59 it is seen that the total of fixed charges, such as interest and depreciation, is small, being for the most part less than 25 per cent of the cost of electric energy, or

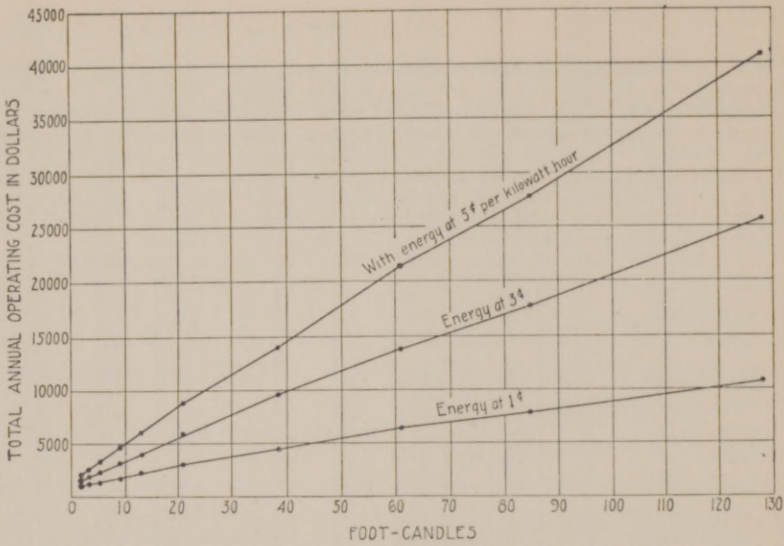


Fig. 58. Cost of operation per year (2500 hours) of a lighting system yielding a uniform illumination on the work-plane for various intensities. The room is 100 ft. x 200 ft. RLM dome porcelain-enamelled reflectors, containing bowl-enamelled tungsten lamps, are spaced uniformly on 10-foot centers.

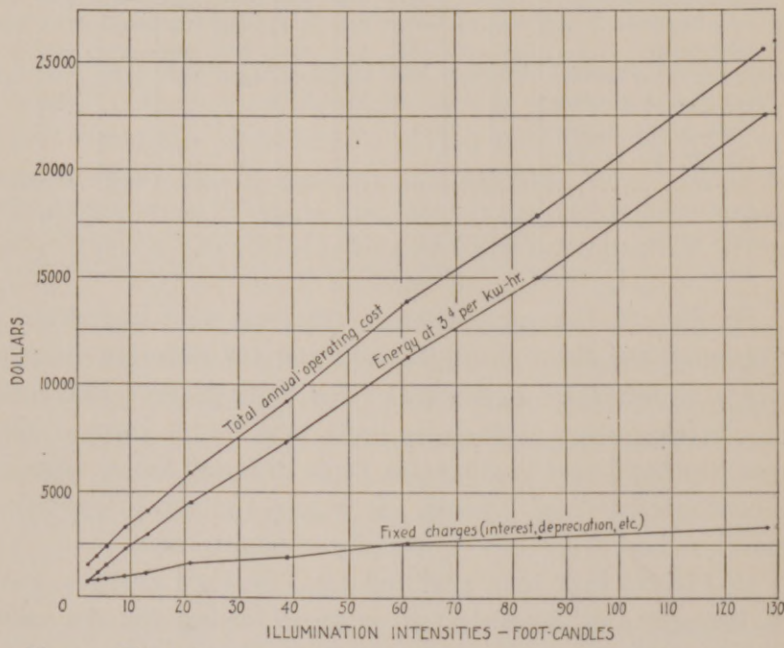


Fig. 59. Fixed charges, cost of electric energy at 3 cents per kilowatt hour, and total annual cost of operation for various uniform intensities of illumination on the work-plane.

about 20 per cent of the total annual operating cost based on 2500 hours' operation per year. It will be recalled that this is for a factory 100 feet by 200 feet.

In Fig. 60 costs of lamp renewals, depreciation, and interest and insurance per year are presented. It should be noted that the scale of dollars to the left is very much dif-

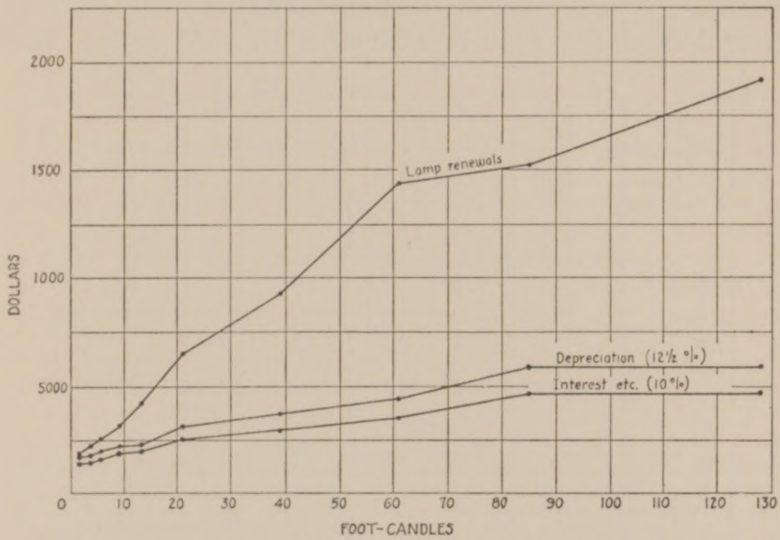


Fig. 60. Lamp renewals, depreciation, interest and insurance for various uniform intensities of illumination on the work-plane.

ferent from those of Figs. 58 and 59. The items represented in Fig. 60 are very small parts of the total as will be seen in Table XXII.

In Fig. 61 the operating cost has been reduced to cents per foot-candle per square foot per year. Here again, owing to the relatively great importance and variability of the rate for electric energy, the data are presented for three different rates, namely 1 cent, 3 cents, and 5 cents per kw-hr.

Increased Production Can Purchase More Light

As shown in Chapter X, an increase in production results from an increase in illumination intensity as far as any investigations have extended; that is, to 20 or 25 foot-candles. Laboratory experiments, such as those discussed in Chapter IX, indicate that speed of vision continues to increase even beyond the limit to which the investigations have been extended, that is, beyond the region of 100 foot-candles for a surface or background of 80 per cent reflection-factor or to the region of 1000 foot-candles for a surface or background of 8 per cent reflection-factor. Of course, work

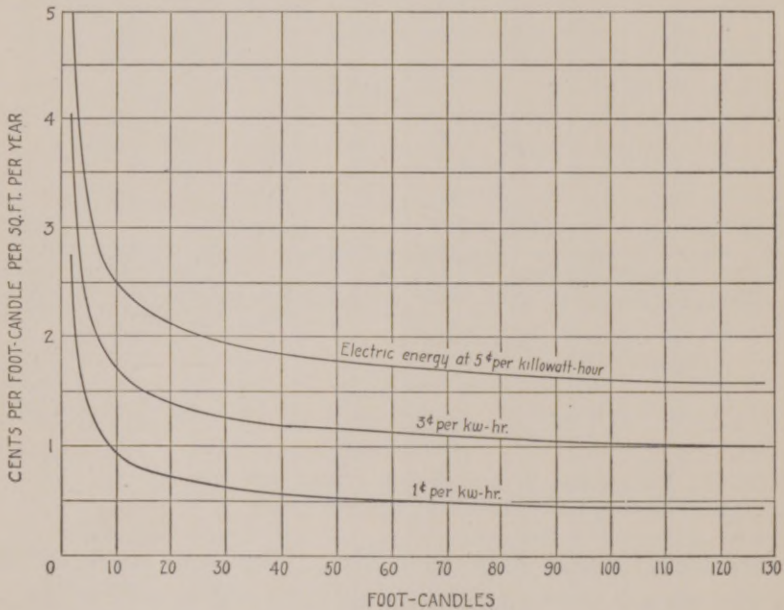


Fig. 61. The operating costs of the lighting reduced to cents per foot-candle per square foot per year. Electric energy being such a large part of the total, the results are given for three rates, namely 1 cent, 3 cents, and 5 cents per kw. hr.

does not generally involve vision alone, but as long as vision is a part of the operation and it can be increased in speed, there will be an increase in production. It is reasonable to expect that illumination intensity will affect production in proportion to the ratio of the visual part to whole operation. It is also reasonable to expect that the character of the visual part of the work will also have something to do with the effect of illumination intensity on production.

In Fig. 49 we saw a gain in production of 12.5 per cent with a cost of lighting equivalent to only 2.4 per cent of the payroll when the intensity of illumination was 20 foot-candles. That is, the production under the new lighting system when it delivered 20 foot-candles to the work-plane,

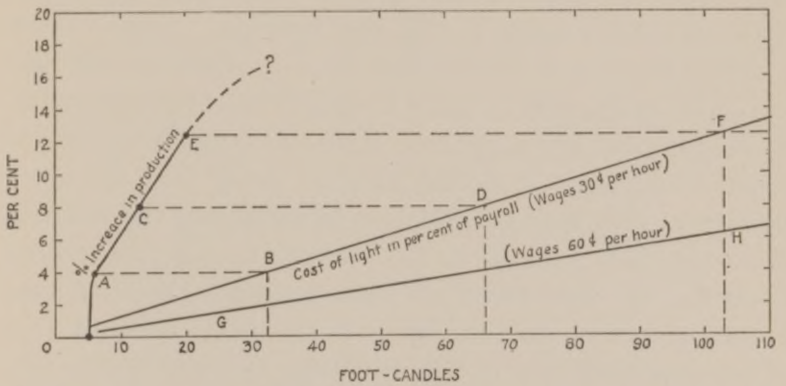


Fig. 62. Illustrating how much light can be purchased for actual increases in production. Data represented by *A*, *C*, and *E* are same as in Fig. 48. The Line *BD* extended both ways represents cost of light in terms of payroll (average wage 30 cents per hour). The line *GH* represents cost of light in terms of a doubled payroll (average wage 60 cents per hour). In this case, the production under the old lighting is taken as a basis. By projecting horizontally from *E* for example, the point *F* indicates the foot-candles (103) of the new lighting that could be purchased by the increase in production.

was 12.5 greater than the production under the old lighting system. The cost of lighting increases approximately uniformly with increase in intensity of illumination as seen in Fig. 58. With this in mind let us look at the results of Fig. 49 plotted on a different scale as in Fig. 62. The points *A*, *C*, and *E* represent the increases in production under the new lighting system for 6, 13, and 20 foot-candles respectively. The actual production under the original lighting (which was about 5 foot-candles of artificial and natural light mixed and poorly distributed) is taken as a basis. The increase-in-production curve *ACE* continues upward beyond *E*. Where it goes will be discussed later. The interesting point at the moment is how much light the increase in production can purchase. The line *BDF* represents the cost of light in per cent of the payroll for the actual wage-scale of 30 cents per hour. If a horizontal line is extended to the right from the point *E*, it intersects the line *BDF* at *F*. This means that the increased production under 20 foot-candles, if spent for light, would purchase 103 foot-candles of the new lighting. This is rather startling because it means that we can afford in this case, in many others, and perhaps in nearly all cases, intensities of illumination much greater than any actually in use for general lighting. It should also be noted that there will also be an increase in production in increasing the intensity of illumination from the 20 foot-candles to 103 foot-candles. Certainly all data point to such a result. By the same process it is seen that the line *CD* intersects *BDF* at *D* or at 66 foot-candles. In other words, the increase in production under 13 foot-candles can purchase 66 foot-candles of the new lighting. Likewise the increase in production *A* at 6 foot-candles would purchase 33 foot-candles of the new lighting.

Now suppose the given number of workers received an average wage of 60 cents per hour instead of 30 cents. The cost of light in terms of this doubled payroll is only one-half (*GH*) as much as in the actual case (*BF*). Projecting the line *EF* until it meets *GH*, we would find that the intersection would be at 206 foot-candles. In other words, with the higher-priced workers the increase in production under 20 foot-candles would purchase 206 foot-candles of the new lighting.

Now let us reconsider the data in Figs. 49 and 62 by eliminating the old system of lighting. This makes it possible to see the results of increasing the intensity of illumination for a proper system of lighting without there being any other variable such as a change from an old system to a new one. This is done in Fig. 63. Now the production under 6 foot-candles from the new system of lighting is taken as a basis and the percentages of increase in production are computed. At 13 foot-candles the increase was 3.8 per cent and at 20 foot-candles it was 8

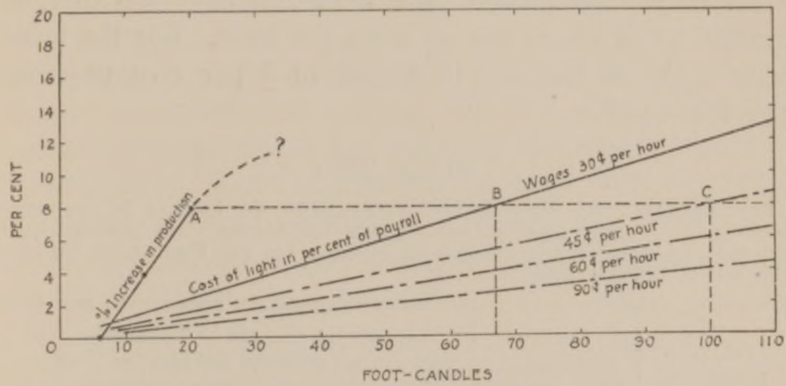


Fig. 63. Similar to Fig. 62 excepting that the production under 6 foot-candles from the new lighting system (Fig. 48) is taken as a basis. This eliminates the matter of different systems of lighting. The cost of light in terms of the payroll is represented for several wage scales, 30 cents per hour being the actual one at the factory where Hess and Harrison obtained the data.

per cent. Projecting the increase at 20 foot-candles *A* across horizontally it meets at *B* the line representing the cost of light in per cent of the payroll. This point *B* is at 67 foot-candles when wages averaged 30 cents per hour. Thus it is seen that the increase in production (with the same lighting system) under 20 foot-candles as compared with that under 6 foot-candles will purchase 67 foot-candles of the new lighting. What further increase in production would result in passing from 20 to 67 foot-candles is discussed later. Certainly it would be appreciable. The same process can be applied to any other increase of production.

It is also interesting to see where the line *AB* would cut the lines representing the cost of light in terms of the payroll for other average wages per hour. For example, if the average wage were 45 cents per hour the line *AB* cuts this line at *C*. A summary of the results from Fig. 63 is presented in Table XXIII. It is seen that as the payroll increases the amount of light that even a small increase in production can purchase is very great. For example, an increase in production of 2 per cent pays for 17 foot-candles when wages are 30 cents per hour and pays for 50 foot-candles when wages are 90 cents per hour, For the latter wage scale an increase in output of 8 per cent pays for 200 foot-candles.

TABLE XXIII

Showing how much light can be purchased by the increase in production resulting from a given increase in intensity of illumination. The lighting system and the number of workers remaining constant but the illumination intensity and wage-scale being changed.

Per Cent Increase in Production	Actual Foot-candles	Foot-candles that can be Purchased by the Increase in Production if Wages Per Hour are:			
		30 cents	45 cents	60 cents	90 cents
0	6.0				
2	9.4	17	25	33	50
4	13.0	33	50	67	100
6	16.6	50	75	100	150
8	20.0	67	100	133	200

It simplifies matters to adhere to one set of data in presenting these various analyses, although it is recognized that there may be criticism to the effect that the data obtained by Hess and Harrison [43] are stressed too much. Besides the excuse of simplicity in treatment, their data are the best available from factories at present and are quite complete and convincing. The investigation was carefully conducted over a period of ten weeks in an approved manner. Furthermore, their data are strongly supported by much laboratory data, some of it, such as reading, being actual production data. Various factory tests also yield similar results. In fact, there is a gratifying consistency among all these results indicating that, if the illumination intensity were increased in offices and factories to 20 foot-candles, there would be an increase in production from 10 to 15 per cent at a cost of lighting amounting to one to three per cent of the payroll. If this is true, an illumination intensity of 100 foot-candles is certainly practicable at the present time.

In Chapter XIII it was shown that intensities from 350 to 1000 foot-candles are ideal. Are such intensities practicable at the present time considering the cost of lighting? Unfortunately we do not have production data extending far enough to state positively. Certainly we have seen that 100 foot-candles are not to be considered far from practicable at least.

Form of Curves Representing Increase in Production

As has been pointed out before, many visual functions, including those of speed of discrimination, have similar forms. These are satisfied fairly well by logarithmic equations. This would have been clear if the author had adopted the simple expedient of plotting much of the data presented, on logarithmic scales. This was purposely avoided because logarithmic scales are confusing to those unused to them and, furthermore, in most cases the range of brightness or of illumination in which we are chiefly interested can be taken care of by the usual scale. It would simplify and aid greatly the consideration of the economics of lighting, if equations relating illumination intensity and increase in production were available. To obtain these it is now necessary to perform actual tests for a given operation. Obviously, it involves a large amount of work and expense to carry this out even to 40 or 50 foot-candles. Laboratory work can be done very much simpler and under better control, so it is likely that laboratories must continue to supply the data that encourage progressive men to increase illumination intensities much beyond those that have been used. Furthermore, there is an unwarranted attitude against laboratory work. Too often do we hear the so-called "practical" man speak of laboratory results as having little bearing upon practice. As a matter of fact they have a great deal of bearing and, furthermore, they are very dependable data in most cases and pertinent to activities in the office or factory. The fault lies largely in lack of interpretation of such data in terms of practice.

The author has given considerable study to the forms of various curves relating vision and speed of vision to illumination intensity, and has found that certain simple logarithmic equations represent most of these curves very well. L. L. Holladay has kindly gone over much of the data and checked the results. Of course, it is possible to develop equations that exactly fit the results. By plotting the data logarithmically, extrapolation beyond the range of available data can be done without great risk of appreciable error if the extrapolation is not carried too far. This is because a range from 20 to 200 foot-candles is logarithmically equal to a range from 2 to 20 foot-candles.

In Fig. 64 are presented the simplest logarithmic equations that satisfy certain representative data pertaining to speed of reading or of discrimination of various test-objects. The full lines represent the respective equations and the circles represent some of the original data to illustrate how closely even the relatively simple equations represent the actual results of speed of discrimination. On the right of each curve is found the number of the Figure in which the original data are plotted. The horizontal scale is that of foot-candles on a surface of 80 per cent reflection-factor and each curve has its own scale as indicated. The vertical scale is that of speed of vision, each curve having its own scale. It is seen that the agreement between the plotted equation and the actual data is quite close. For various details the reader should refer to the original illustrations in Chapter IX.

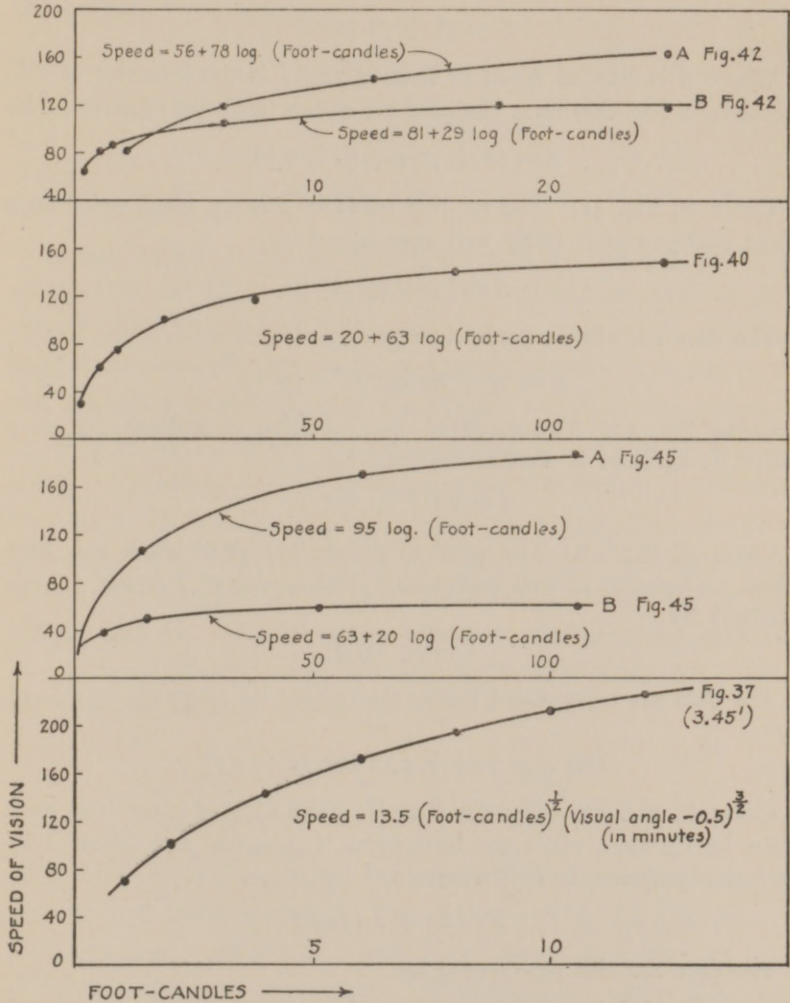


Fig. 64. The simplest equations which fairly well represent the data presented in certain illustrations in Chapter IX have been determined. They are represented by the curves. To show how well they represent the actual data, some of the latter are indicated by the circles.

A Brief Summary of Fig. 64.

Curve *A*, Fig. 42. The relative speed of reading black print on the gray background is fairly well represented by

$$S = 56 + 78 \log I$$

Where S is relative speed of reading and I is the intensity of illumination in foot-candles. The data are almost perfectly represented by

$$S = 66 + 71 \log (I - 0.8)$$

Curve *B*, Fig. 42. The relative speed of reading black print on a white background is fairly well represented by

$$S = 81 + 29 \log I$$

The data are almost perfectly represented by

$$S = 84 + 24 \log (I - 0.23)$$

Curve Fig. 40. The speed of discrimination of a black dot on a white background is well represented by

$$S = 20 + 63 \log I$$

Curve *A*, Fig. 45. The speed of discrimination of black bars in a white background is well represented (for values of I above 5 foot-candles) by

$$S = 95 \log I$$

The data are represented better throughout its range up to $I = 50$ by

$$\text{Log } S = 1.57 + 0.38 \log (I - 0.5)$$

Curve *B*, Fig. 45. The speed of discrimination of black bars on a white background, when the test-object is preceded and followed by confusion patterns, is well represented by

$$S = 63 + 20 \log I$$

The data are also represented by

$$\text{Log } S = 1.43 + 0.21 \log (I - 0.5)$$

Curve Fig. 37. The data on speed of discrimination of a split ring (international test-object) for four visual angles (1.25, 1.73, 2.49, and 3.45 minutes) is fairly well represented by

$$\text{Log } S = 1.13 + 1.5 \log (V - 0.5) + 0.5 \log I$$

Where V is the visual angle in minutes of the missing portion of the ring. This equation for a test-object of 3.45 minutes visual angle is the one plotted in Fig. 64.

Simple equations approximately representing the data are as follows for the four visual angles:

$$\text{For } 1.15 \text{ minutes, } S = 2.7 + 14.2 \log I$$
$$\text{For } 1.73 \text{ minutes, } S = 12.5 + 79 \log I$$
$$\text{For } 2.49 \text{ minutes, } S = 42 + 77 \log I$$
$$\text{For } 3.45 \text{ minutes, } S = 59 + 150 \log I$$

Many other examples besides those in Fig. 64 could be presented to illustrate that speed of vision and various visual functions are fairly well represented by logarithmic equations. This aids us in visualizing what is likely to be the effect on production if we should increase the intensity of illumination far beyond those actually used in production tests. Certainly our explorations in this realm in advance of actual tests are not solely speculative because we have the support of these various relationships. For this reason let us return again to the production tests presented in Figs. 48, 62 and 63. The relation between actual production and intensity of illumination is fairly represented by the following two equations,

$$P = 371.0 + 65 \log I$$
$$\text{Log } P = 2.577 + .064 \log I$$

where P is the average number of pieces inspected per person per hour and I is the intensity of illumination in foot-candles. However, the per cent *increase* in production interests us most. Considering only the new lighting installation, and taking the production at 6 foot-candles as a basis, the increase in production G is related to the intensity of illumination I as shown in the equation

$$G = 15.17 \log I - 11.8$$

This curve is plotted in Fig. 65, the portion *AD* and beyond is that for which there are no test data. It has already been pointed out why we may have some confidence in extrapolating. The logarithmic plot yields a straight line and we can extrapolate to somewhat higher values of foot-candles with considerable confidence that the results are going to be roughly approximate at least. Most of the available data on visual functions support this procedure.

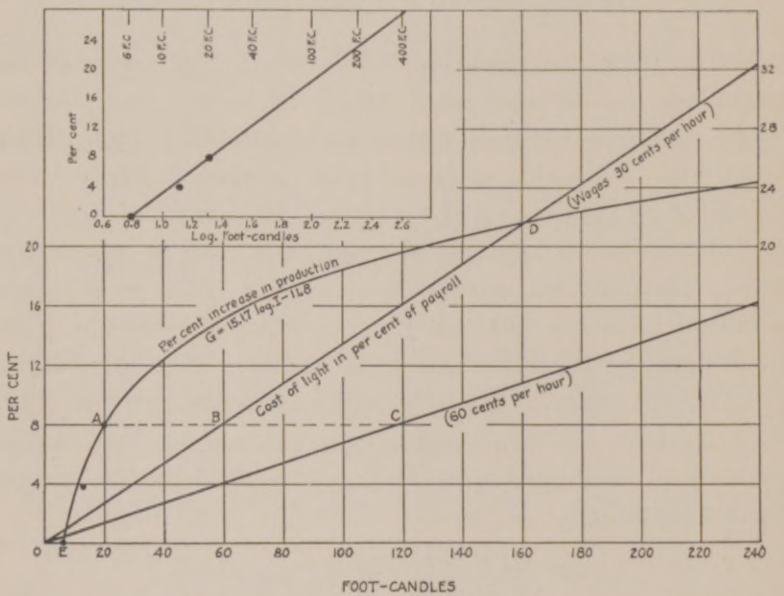


Fig. 65. An equation was determined for the data on increase in production Fig. 48 and is represented by the curve *EAD*. The cost of light in per cent of payroll (average wage 30 cents per hour) is represented by *BD* extended both ways. *EAD* intersects *BD* at 160 foot-candles. The cost of light in per cent of payroll if average wage were 60 cents per hour is also represented.

In the upper part of Fig. 65 is shown the method of obtaining the logarithmic equation which fits the data fairly well. The left-hand scale is per cent increase in production over that at 6 foot-candles. The logarithms of the foot-candles are plotted on the horizontal scale. Assuming that the relation between per cent increase in production and the logarithm of the foot-candles is linear, we draw a straight line which seems to fit the data represented by circles. This straight line is then extended. A few points on a scale of actual foot-candles are shown at the top. This illustrates the fact that, assuming the linear relation just mentioned, we can extrapolate from 20 to 200 foot-candles without extending the actual straight line unreasonably far. Of course, this does not prove that the logarithmic equation accurately represents the results which would be obtained in the region unexplored by actual test. However, it is presented for what it may be worth and to give a picture of what might be expected.

The relation between intensity of illumination and the cost of light in terms of the payroll (average wage 30 cents per hour) is represented by the line *BD* extended. Fig. 58 supports this straight-line relation. It will be noted that the curve *AD* representing *G*, the per cent increase in production, intersects *BD* at *D*. The latter point is at 160 foot-candles. In other words, if the equation fairly represents the relation between increase in production and foot-candles, at 160 foot-candles the increase in production (over the production at 6 foot-candles) equals the cost of lighting. Supposing this factory had a well-designed lighting system supplying 6 foot-candles to the work-plane. If the intensity of illumination were increased to 160 foot-candles (assuming accuracy of the equation relating *G* and *I*), this new lighting would be obtained at a net cost of nothing, production would have increased 22 per cent, and there would be the additional advantages of decreased spoilage and increased safety and general cheerfulness. If in this same factory the wage was 60 cents per hour the cost of light in per cent of the payroll would be represented by the straight line passing through the point *C*. This line extended would meet the curve *AD* extended in the neighborhood of 400 foot-candles.

In Fig. 63 and Table XXIII it is seen that the actual increase in production at 20 foot-candles would pay for 67 foot-candles for the group of persons involved at the actual average wage of 30 cents per hour. It would pay for 133 foot-candles if the wage scale were 60 cents per hour. These are facts directly arising from actual data. In Fig. 65 it is indicated that if the curve relating foot-candles and per cent increase in production is approximately correct, the increase in production over that at 6 foot-candles would pay for 160 foot-candles when the wage is 30 cents per hour and would pay for about 400 foot-candles if the wage were 90 cents per hour. No claim to accuracy in prediction is made, although for this test in an inspection department where vision is an important part of the operation, it seems that we can have confidence in at least a portion of the curve between *A* and *D*. Certainly vision in general would improve up to 350 foot-candles at least, and in many cases up to higher intensities. In fact, it has been indicated that we can expect improvement in vision up to 1000 foot-candles, at least, for general factory work.

It should be noted that the discussion of Fig. 65 pertains to increase in production due solely to increase in illumination intensity from a *well-designed* lighting installation. The increase in production in changing from a poorly designed installation to a well-designed one is usually considerable, quite aside from the increase due to increase in intensity of illumination.

Chapter XV

VISIBILITY AND SAFETY

IT has been amply proved in preceding chapters that adequate intensities of illumination are necessary for the best vision and therefore for efficient work. They also decrease spoilage, increase safety, decrease eye-fatigue, and tend to make work-places more cheerful. Illumination intensities may be adequate, but still the lighting may be improper. The light-sources may be glaring, polished surfaces may reflect bright images, shadows may be harsh, or the direction of light may not be satisfactory. All these may reduce the ability to see and may cause visual discomfort with all its complex ramifications. Improper lighting, with the exception of inadequate intensity, has not been discussed in preceding chapters. This relates more to the design and control of lighting which is beyond the scope of this book. Nevertheless, it appears desirable to touch upon some of these points, briefly at least, because adequate lighting loses much of its value if it is improper.

The efficiency of a lighting system is not measured solely by the efficiencies of the light-source and the lighting equipment, and the reflection-factors of ceiling, walls, etc. It is not merely a matter of cents per foot-candle per square foot per year. Efficiency of lighting finally involves efficiency of vision and also eye-comfort. In other words, efficiency in lighting is the ratio of satisfactoriness to cost.

It has been well proved that inadequate and improper lighting causes defective vision. In some industrial plants it has been found that as many as 50 per cent of the workers have defective vision. There is an increasing percentage having defective vision as the average age of a group increases. Much of this increase can be attributed to bad lighting. Adequate light properly shaded and diffused can do much to retard this increase in defective vision with age. Furthermore adequate lighting should not be based solely upon a consideration of perfectly normal eyes. A factor of safety should be allowed for that great percentage whose vision is defective.

Glare

This is a term which is used rather loosely. Perhaps it is best to confine it to a lighting condition which causes visual discomfort. Glare may be due to

a. *Excessive brightness* of a light-source or of its image reflected from polished or mirror-like surfaces. The brightness that is not glaring depends upon the adaptation of the eye, the background against which it is seen, and somewhat upon its size or visual angle. For general lighting conditions indoors the maximum brightness should not exceed 20 candles per square inch and it is best to keep it as far below this value as possible. This can be done by properly diffusing the light.

b. Perhaps our most common source of glare is *excessive contrast*. Outdoors at night a flaming match may be glaring amid the very dark surroundings. The sky is not glaring out doors but a patch seen through a window amid the relatively dark surrounding walls is commonly somewhat trying on the eyes. If the backgrounds against or amid which lighting equipment is viewed are of fairly high reflection-factor, and if they receive an appreciable amount of light, glare will generally be eliminated if the lighting equipment is satisfactorily diffusing.

c. A bright area of small visual angle may not be glaring but a large area of the same brightness may be very glaring. In other words, *volume of light* incident directly on the eye is a factor in glare.

d. *Light sources too close to the line of direct vision* are more glaring than if they are further away from this line. They are also less glaring if they are in the extreme upper than if in the extreme lower part of the visual field.

e. The light-sources may be properly shaded from the eye but *mirrored or polished surfaces* may reflect an image toward the eyes. Therefore such surfaces should be avoided wherever possible, because they can reduce or even defeat the best efforts of the lighting specialist.

f. The *time of exposure* to glaring conditions has something to do with the effectiveness of the glare. A bright light-source for instance can be looked at for a moment without as much glare resulting as if it were looked at for a few seconds. On the other hand if the source is not too bright the retina can become adapted to it if looked at directly. This does not mean that no harm results. In fact, this adaptibility is unfortunate because it makes persons careless about glare.

These are the chief factors in glare. No attempt is made here to give limiting values.[46] Anyone with some feeling, some ability to observe, and some common sense can readily learn to sense conditions discomforting to vision.

It is convenient to divide glare into three classes.[47] *Veiling glare* obscures details by a veil of light spreading from a brilliant light-source near the line of vision, or more rarely by diffused light in smoky, foggy or dusty air.

Dazzle glare is uncomfortable, distracting, and reduces the ability to see. This is the most common type of glare. It can be due to light-source or lighting unit or to the images of these reflected from polished surfaces.

Blinding glare is due to an extreme brightness that greatly decreases for a time the ability of the retina to respond to light. Powerful after-images remain for some seconds or even a minute or two, depending upon the brightness of the glare source.

All these types of glare decrease the ability to see and therefore not only decrease the efficiency of a worker but increase the possibility of accident.

Brightness of Light-Sources and Lighting Equipment

An idea of the brightnesses encountered is obtained from the data in Table XXIV. The brightnesses of clouds and various skies are presented in Table III.

TABLE XXIV

	Approximate Brightness in Candles per Square Inch.
Noon sun	1,000,000
Crater of ordinary carbon arc	100,000
Tungsten filament vacuum lamp (8 l. p. w.)	1060
Tungsten filaments of gas-filled lamps	2400–5000
Tungsten filament of gas-filled 50-watt lamp	2630
Tungsten filament of gas-filled 500-watt lamp	4500
Diffusing bulb of 50-watt tungsten lamp	8
Enamelled portion of bowl-enamel tungsten lamp	10–15
Mercury vapor tube	15
Brightest sunlit cloud	20
Sky	0–4
Globes of good diffusing glass of various diameters and containing a 100-watt lamp	
Diameter 5 inches	4.5
" 6 "	3.1
" 7 "	2.3
" 8 "	1.8
" 10 "	1.1
" 14 "	0.6

Recommended globe sizes of good diffusing glass

Lamp size	Globe diameter	
50–75	8	2.5
75–100	10	2.5
100–150	12	3.0
150–200	14	3.5
200–300	16	4.0
300–500	18	5.0

Eye-Strain

This is the result of inadequate or of improper light. When light is inadequate the work must be held too close to the eyes. This results in a strain of the eye-muscles. Glaring light-sources tend to attract the attention and the eye-muscles must strain themselves to keep the eyes on the work. Glaring conditions cause one to " pucker his eye-brows " with a resulting strain. If the lighting is quite non-uniform there is a noticeable effect of the necessity for pupillary adjustment in looking from one brightness to another of a different magnitude. Eye-strain is not conspicuous under the high intensities of daylight, and under proper conditions eye-strain can be eliminated in artificial lighting.

Eye-Fatigue

Under proper and adequate lighting, the eyes are not fatigued any more than the body is under proper working conditions. Everyone with reasonably normal eyes is quite satisfied with the high intensities of daylight. Rarely is a day so bright in summer that the eyes are not comfortable, although we have become used to shading the eyes by means of hats even from much of the sky. Eye-fatigue is much less under high intensities of proper lighting than under low intensities of lighting which are otherwise proper. There is some indication that light approaching daylight quality (white) is more desirable for long periods of serious work than yellowish or less natural light. Certainly eye-fatigue is more noticeable after long periods of reading or close work under a low intensity of illumination than under an adequate one. Eye-fatigue is perceptible when the surroundings are quite dark as compared with the work. Of course, the eyes are rested by looking from the bright work-surface to some area less bright but this is a different matter.

Visibility

A reduction in ability to see is one of the results of glare. Therefore, improper lighting conditions decrease the efficiency of the workman. Glaring light-sources or their reflected images reduce visibility very greatly if they are near the line of direct vision. Light is scattered in the eye and there are certain diffusion effects in the retina or somewhere in the visual processes that reduce the ability to see. If a light-source is very bright, the after-image may be blinding for a long time. (See Fig. 34.) Visibility gradually decreases when the eyes are subjected to improper lighting conditions.

Visibility of black details on a background of small area is best when the immediate surroundings are about as bright as the background of the test-objects.

Safety and Accidents

Improper and inadequate lighting is responsible for about 20 per cent of all traffic and industrial accidents.[17] R. E. Simpson [48] has stated that each year there are more accidents in this country due to inadequate and improper lighting than the yearly rate of casualties that this country suffered during the recent World War. According to statistics a few years ago an average of more than 100,000 men were continually incapacitated for work owing to accidents due to inadequate or improper lighting. This number of men could mine over 100 million tons of coal per year and only 10,000 tons of it would be necessary to supply them with adequate and proper lighting. According to Simpson, industrial accidents cost this country at the present time about two billion dollars annually. Twenty per cent of this loss could be eliminated by providing good lighting. This saving would pay the present artificial lighting bill for the entire country. Lighting will some day be a compulsory safeguard just as railings and other safety devices are today.

Traffic

The moving of traffic safely and rapidly is very largely a matter of good lighting. In walking or in driving we depend upon vision and it must be quick and certain. We have traffic in factories, in office buildings, on the streets and everywhere that there is human activity. Automobile accidents, according to Crum, cost this country about one billion dollars per year and it is fairly certain that nearly 20 per cent are due to inadequate or improper street-lighting. Crimes are found to be reduced on streets after they have been adequately lighted.

But there is another aspect that has been generally overlooked and that is the bearing of adequate and proper lighting upon the rate of movement of traffic. This does not mean the use of light-signals, for that is quite another matter. For example, signs or other signals may direct a person downstairs but the speed at which the stairs will be descended (other things being equal) will depend in some manner upon the intensity of illumination, the position of the light-source, freedom from glare, etc. Certainly a person proceeds cautiously, even falteringly, in the dark. On increasing the amount of light, when is the point reached beyond which no increase in natural speed is noticeable? Certainly this point is not at the low intensities found on our streets and even in hallways, subways, etc. In order to get the greatest natural movement of traffic, the lighting must inspire a feeling of complete safety. The amount of light must be adequate. Shadow is necessary to reveal obstacles and steps if they are not revealed by painted contrast. Visibility should not be impaired by glaring light-sources in the field of view. The general stimulating effect of adequate light and bright surroundings should also be a factor in the movement of traffic.

Visualizing these obvious requirements in direct comparison with conditions as we find them in streets, in corridors, on stairways, in subways, and even in stores, certainly is convincing that here is a field for research and possible accomplishment. Street-lighting is almost everywhere inadequate, but it involves problems and economic considerations which separate it from many of the other highways of traffic. There is little excuse for the inadequate lighting in corridors and on stairways where traffic is heavy; still these are usually less adequately illuminated than the other portions of the building. In our subways, on our elevated platforms and in our railway stations where the movement of traffic is a vital factor in the carrying capacity of cars (at least during the rush hours), adequate and proper lighting would be effective. There are also many stores in which the movement of traffic is a vital factor on sales. Here the lighting is usually much better than in the other places mentioned, but is it the best? Is it such that it inspires complete safety, provides the best visibility, and stimulates the greatest activity? These three goals must be achieved by lighting before the highest natural speed of the traffic is attained. Everywhere we look in our congested cities we see opportunities for light to hasten the footstep by inspiring confidence and stimulating activity.

Traffic Signals

The application of electric light in controlling and directing traffic is growing rapidly and with this growth there is an increasing need for standardization. It is not surprising that self-luminous signals are finding favor for several reasons. Such signals can operate at any time during night as well as day. They can be as powerful as desired, inasmuch as this is a function of the intensity of the light-source associated with them, admitting other things being equal.

In the control of traffic, vision and its more common defects must be considered. Form and color are the chief fundamentals of a signal. These can be satisfactorily incorporated in a self-luminous signal. Form alone is of very doubtful value because a signal should be recognizable at a reasonable distance. Quite an appreciable number of persons have vision so defective that they cannot accurately distinguish form at a distance. However, this difficulty is not found in the recognition of certain colors. There is a tradition to the effect that about four per cent of the people are color-blind but this statement is as misleading as it is indefinite.

Only two signals are fundamentally necessary for *STOP* and *GO* respectively. Red and blue-green are quite suitable and it is exceedingly difficult to find a person who cannot distinguish these two colors as being different. Persons experienced in color-vision believe that perhaps no more than one in a hundred thousand persons would have difficulty in distinguishing these two colors as being different. However, it is likely that a thousand times more persons have eye-defects so serious as to make form unrecognizable at a reasonable distance. Furthermore, fog, rain, smoke and dust often obliterate form when under the same conditions a powerful self-luminous color-signal would still be seen as a spot of colored light. Even the selective transmission of fog, smoke, etc. cannot alter a blue-green light sufficiently at a reasonable distance to cause it to be confused with red.

In practice a third color has been found desirable as an " interval " color; that is, as a signal to clear up matters before the next signal is flashed. Yellow is found satisfactory for this, for it offers no difficulties from the color-vision viewpoint.

After utilizing color, the most powerful and practical aspect of light for traffic signals, it may be well to take advantage of form. With colored signals this may be largely a matter of position. For example, we may have a horizontal line of red lights and a vertical line of blue-green lights. Certainly many things can be done, but the crying need is to standardize upon one of the best and to adopt it generally.

In signals, attention-value is important and the two colors red and blue-green seem to meet the requirements of appropriateness and distinctiveness. Intensity, of course, is another factor upon which attention-value depends, but the mistake is often made of depending upon photometric measurements or candle-power for determining this phase of attention-value. Here we encounter something akin to glare and certainly glare finally must be measured by the eye. Let us take as an example the so-called " stop-light " commonly used on automobiles. Let us assume two lenses equal in diameter and of the same candle-power toward the eye. If one of these is a ground glass and the other is covered with indentations of appreciable size, the latter will be found to be of greater attention-value, even when all other factors such as color, size, and candle-power are equal respectively for the two signals. Of course, this is not true when the two signals are so far away as to appear as points of light. The explanation lies in an unexplored realm of physiological optics, but an analogy throws some light upon the matter. For example, if we wish to awaken someone by throwing something against the window pane, a handful of sand is not as effective as an equal weight of coarser pebbles. In fact, one large stone equivalent in weight to the handful of sand would likely break the glass while the handful of sand would be harmless in this respect. So it is with light. A certain intensity of light from a ground glass is not as glaring or as powerful in gaining attention as the same intensity from a glass of equal area but consisting of larger bundles of light-rays such as emitted by a glass consisting of proper indentations of appreciable size.

These are important factors in traffic signals which must be understood in all their variety of influences on vision if the best choice of signals is to be made. It is to be hoped that our greatly increasing traffic will result in a special study and proper application of light. When this is done self-luminous colored signals having lenses or beams of proper optical design will be found best and this should be universally standardized.

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