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Criteria for Recommending Lighting Levels

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U.S. Department of Commerce
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

FOREWORD

This is one of a series of reports documenting National Bureau of Standards (NBS) research and analysis efforts in developing energy and cost data. The data supports the Building Energy Conservation Criteria Program sponsored by the Office of Buildings and Community Systems, U.S. Department of Energy (DoE). The work described in this report was supported by DoE/NBS Task Order No. A008-BCS under Interagency Agreement No. EA-77-A-01-6010. The work was originally sponsored by DoE's Architectural and Engineering Systems Branch and is now sponsored by the Technology and Consumer Products Branch.

This report discusses the various experimental procedures used in the past and/or currently being used. Recommendations are made as to the most valid and defensible methodology to serve as the basis for recommending levels of illumination. This report discusses the results of a number of the experimental procedures and methodologies, and provides basic groundwork for additional experiments and analysis, which will form a practical basis for recommending energy-conserving design illumination levels that conform to real-world office activities.

ABSTRACT

The effect of lighting on behavior ranges from allowing simple detection of objects to creating moods and impressions. Lighting standards and recommendations for general applications should be based on the visibility (seeing) requirements where differences between individuals are minimal. Furthermore, lighting criteria or standards must evaluate the seeing process under stimulus conditions approximating those encountered in the real space. It is recommended that conspicuity, defined as: "how well the detail stands out from the background", or ease of seeing be the metric for visibility. Subjective visual response criteria cannot be universally applied where significant differences in interpretations and evaluations between individuals and/or groups of individuals occur. Instead they should be treated as design options to be applied when they are important aspects of the intended function of the space. In discussing the above issues, the paper identifies the major categories of variables included in the perception of the visual environment and organizes them logically with respect to their relationship in developing lighting criteria and standards. This analysis includes a breakdown of the visual processes into sensory and perceptual components.

Key words: Conspicuity; contrast; illumination; lighting; lighting levels; suprathreshold visibility; vision.

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1.0 INTRODUCTION

Serious disagreements exist among researchers and lighting practitioners concerning the amount of illumination required to perform specific visual tasks. But, a general consensus exists among these groups that the determination of required illuminance levels is a necessary criterion for any lighting design, where visual task performance is an integral part of the activities to be performed in a given space.

Standards and guidelines are often said to be an unnecessary constraint to design freedom, in that they restrict the options available to the designer. This potential conflict between standards and design freedom is more apparent than real--since they have very different objectives. Standards are meant to be universally applicable, while design decisions are typically supposed to be responsive to special classes of activities and/or users. Design decisions can, therefore, lead to different lighting recommendations, even when visual tasks are similar. For example, in fast food outlets where the desire from the customers' point of view is to have fast service and the owners' desire is for the customer to eat fast and leave, high illumination levels are more conducive to obtaining this desired end. But, in restaurants where an intimate atmosphere is a desirable goal, light levels are kept low to be more conducive to a leisurely dining environment. The light levels may not be the optimum for reading the menu, but most of us will not be bothered or even be aware of this low light level for reading purposes. This same light level in an office will be intolerable.

In this paper, the "standard" and "design" approaches will deal with considerations of the following questions:

(1) Standards and Criteria -- How much light is needed to see? This question deals with physiological mechanisms directly involved in visual sensations, generally evaluated psychophysically, with the performance criterion being: how well we can see. This information would have universal application -- i.e., it is similar for most users within a class. The Snellen Eye Chart Test used to assess the capacity of the eye to see details is an example of a procedure developed for this purpose. In this test, you are said to have 20/20 vision, when your ability to recognize letters at 20 feet is the same as that for the average population. If not you are presumed to have some weakness in your visual sensory mechanism.

(2) Design -- How much light is needed to obtain a productive, comfortable and pleasant environment? This question deals with moods, feelings, impressions and other subjective factors that influence job performance as well as how much light we need to see. Consequently, considerable differences in responses can be expected among individuals.

The basic differences between these two formulations of lighting requirements will be discussed in detail, after the introduction of some necessary background material.

Several approaches have been advocated to determine the amount of light needed to perform visual tasks. They differ from one another primarily with respect to the type of behavior (response) being measured.

1. One research method is based on judgments of acceptability and/or comfort. That is -- the lighting level which results in maximum satisfaction and/or comfort (e.g., in response to questionnaires or verbal scales) is thought to be the proper basis for lighting standards and guidelines.

2. An alternative rationale is one which starts with the premise that since the purpose of lighting (e.g., in commercial buildings) is to achieve productivity of some kind, i.e., work performance, productivity measurements under actual or simulated working conditions provide the only valid basis for lighting standards.

3. Finally, there are researchers who argue that the only way of achieving an objective basis for recommending lighting standards is by conducting controlled laboratory studies designed to assess the functional capacity of the visual sensory system.

In the following pages, we will discuss these different viewpoints and recommend, that for consistency and general applicability, physiological and psychophysical laboratory studies designed to investigate how well the eye "sees" are the most appropriate and defensible basis for determining lighting levels standards and guidelines.

Lighting level is only one of many variables which influence people's response to the visual environment. Upon reflection, this point seems to be an obvious one. Yet many members of the lighting community seem to equate two very different views of lighting: <u>The quality of the visual environment and the amount of light needed to perform visual tasks</u>. For example, let us say lighting levels were changed in an office and that these changes were accompanied by significant differences in the amount of production errors. Several explanations of this result may be postulated: Among those confined to lighting are (1) changes in task visibility and/or (2) a preference for the new lighting levels over the levels used earlier. The first explanation assumes the criterion to be the amount of light needed to perform visual tasks, while the second one is based upon qualitative factors as well. The blurring of the distinction between these two basically different approaches to determining lighting requirements has significantly contributed to the problems that exist today with respect to recommended lighting standards and guidelines.

One goal of this paper is to identify the major categories of variables included in the perception of the visual environment, and to organize them logically to facilitate the development of lighting criteria and standards. We will do this by exploring the relationship between visual quality, "How good is the visual environment?," and the lighting levels needed for visual task performance, "How much light do we need to perform visual tasks?"

There are many ways to present a paradigm to outline the components needed to assess the visual environment. Diagram 1 elucidates the points to be emphasized in this paper. In the interior lighting design of office spaces, user acceptability and work performance are key considerations. Lighting plays a dominant role in enabling us to see in order to perform visual tasks, of course, but also significantly influences our perception of the visual environment. This perceived environment, i.e., the worker's reaction to, or evaluation of, the visual environment, also affects work performance and user satisfaction. But these are not the only factors to be considered when examining the visual environment. When evaluating lighting variables by testing user satisfaction or work productivity, non-visual contributions (in some cases unidentified) importantly influence the outcome attributed to the lighting variable being investigated. The role of these factors in user acceptance and work performance will be discussed next.

2.0 USER ACCEPTANCE

A good environment is one which is acceptable to the user. By acceptable we do *not* mean preferred, rather the basis for acceptance is that the design is not rejected by the user. The visual environment may be satisfactory or acceptable, but not necessarily the preferred or ideal condition. The design of an environment which is ideal for all users of a space is difficult, if not impossible, to achieve. For example, a user may prefer a blue room but may find an existing cream colored room acceptable, or may prefer X lux of illumination, but find 0.5 X lux or 2.0 X lux acceptable.

A common method for assessing acceptability is a questionnaire using a 5 or 7 point scale, directly asking the occupant: "About how satisfied are you with the lighting aspects of your office?", the choices being; "very satisfied," "somewhat satisfied," "indifferent," "somewhat," or "very dissatisfied." Assessments of this type are very broad and can be influenced by any one (or a combination) of many variables. *A specific question may follow the general one, for example; "About how satisfied are you with the light levels in this room?" Again, we are only interested in testing the acceptability of the space*. We are still faced with the problem of what criterion the observer was using in his evaluation of light level. Studies of this type indicate large differences in preferred light levels among observers. We can make the questionnaire highly specific, and hope that we are assessing a basic quality, that will be similar for different observers.

NBS conducted a study that attempted to identify preferred light levels, using a questionnaire in conjunction with a visual task. Subjects were asked to choose a level of task visibility, in this case based on perceived contrast, that they felt would be good enough to work under for a sustained period of time, two hours. The stimuli were five-bar grating patterns. (See figure 15). More specifically, NBS wanted to determine what visibility level will be acceptable to most workers, e.g., 90 percent of the workers. Keeping the background luminance constant, observers were asked to choose that contrast level which they felt would be "just acceptable" for sustained work (reading for two hours) and also the "definitely acceptable" level for the same task. The contrast range between these two levels were defined as acceptable levels. In figure 1 the bars represent the arithmetic mean plus 1.28 standard deviations. The bars represent 90 percent of the population, that is, a one-tailed test that includes 1.28 standard deviation. We are only interested in one direction of the distribution, that portion of the just and definitely acceptable distribution contributing to the overlap between the two. Therefore, 10 percent of the values for the high end of the "just acceptable" category, and 10 percent of the low end for the "definitely acceptable" category, have been dropped. A region where the just and definitely acceptable bars did not overlap would represent contrast values that are acceptable for all observers, neither too good (over-design) nor too poor (low visibility) task for 90 percent of the sampled population. None of the pairs of bars show such a non-overlap region.

These results indicate that there are large differences among observers' estimates of "goodness of task visibility" required for sustained visual work. What is considered "definitely acceptable" by some observers is said to be less than "just acceptable" by others. Furthermore, subjective estimates of acceptability are affected by other variables in addition to the variable being expressly evaluated. For example, expressions of satisfaction may be to room decor, wall color, etc.

3.0 WORK PERFORMANCE

When we consider why lighting criteria and standards are needed for buildings, the most obvious reason is "to enable visual tasks (activities) to be performed." A logical follow-up question is: "How can lighting be used to improve productivity (task performance)?" Finally, in seeking answers to these questions, why not take the most straightforward approach available--conduct systematic research under actual work conditions? For tasks of a routine nature the index of merit for work performance is productivity, which is generally measured by number of errors, accuracy, speed, latency or quantity and quality of output.

A direct attack on this problem, one under "realistic" conditions, was undertaken at the Hawthorne Works of the Western Electric Company in 1929. A series of studies, extending several years, was conducted to clarify the relationship between lighting levels and the performance of a variety of jobs.[2] The Hawthorne studies were the earliest and perhaps the most comprehensive studies in the discipline of "industrial psychology." The findings and insights which resulted from the Hawthorne studies[3] point to many difficulties encountered in field research activities.

The first study at the Hawthorne Plant was conducted in three selected departments. The work consisted of (1) inspection of small parts, (2) assembling relays, and (3) winding coils, respectively. Four lighting conditions were used, ranging from 3 to 44 footcandles. For control purposes, the same tasks were performed under uniform existing lighting conditions. The findings of the study were very ambiguous. In the first department, production varied without any relationship to lighting level. In the second and third departments, production increased but the increase could not be attibuted to increased lighting levels. Follow-up studies were conducted, but they further confused the issue. Constant lighting levels in one department resulted in as much increased productivity as an increase in lighting levels did. Finally, under severely reduced lightng levels (3 footcandles) workers maintained their usual productivity. It became evident to the researchers at this point that they were unable to find a simple casual relationship between lighting levels and productivity in their field studies. (A second study, to be discussed later, performed at Hawthorne provided insights as to what had happened in the first study.)

Productivity studies conducted in laboratories are more sophisticated in the use of control groups or using the individual worker as his own control. For example, laboratory simulations of real-world productivity, using pay-off matrices can minimize the influence of psychological variables.[4] But in spite of these attempts to control extraneous variables, the nature of the methodology utilized in productivity studies cannot test the independent variable with a specificity that limits the outcome as being the direct function of the single manipulated variable. Productivity studies intended to study lighting variables may be confounded by contributions from the non-visual as well as the visual sensory process (see diagram 1). These non-visual contributions to user acceptance and work performance will now be discussed.

For purposes of this paper, which is concerned with the methodology and data base on how levels of illumination affect seeing, a visual and non-visual dichotomy will be a useful categorization. As in most efforts to describe human behavior, there will be grey areas, that is, phenomena that do not fall neatly into either category or may fall into both categories. We shall see that even the visual processes must be separated into contributions from the sensory and perceptual levels, when the objective is to develop criteria for levels of illumination and visibility.

4.0 NON-VISUAL

Other Sense Modalities. The acceptability of an architectural space from the standpoints of aesthetics and visual task performance can be affected by non-visual environmental conditions. For example, the auditory and thermal attributes of a space can have a beneficial or detrimental effect on visual responses of the occupants.

Interaction--Visual and Other Sensory Areas -- Most sensory research has been designed to examine one parameter at a time. This is true for all sense modalities -- visual, auditory, thermal, etc. However, with the advent of increased interest in man-machine interactions, where realistic problems in complex environments were being studied (e.g., aircraft cockpit design), it became evident that the interactions of many factors must be studied, if researchers were to achieve viable solutions to practical problems. Consequently, a research literature does exist which focuses on interactive effects of characteristics of one environmental feature directly affecting one sense (e.g., noise) on the sensory response or task performance where another sensory modality is of primary importance (e.g., visual perception). A limited number of such studies will now be described.

Lofberg et al.[5] studied the combined effects of temperature and lighting level on the performance of school children working on two tasks -- addition and the detection of Landolt ring gaps. Three different lighting levels (60, 250, 1000 lux) and two temperatures (22°C, 26°C) were used in the study. The authors report, that under a neutral temperature, visual performance was better at high illuminances, but under higher temperatures a decrement in visual task performance was observed for the higher illuminances, i.e., they found a significant interaction between the thermal and visual sense modalities.

Shigehisa and Gunn[6] investigated the interaction of lighting level and noise levels while adult subjects were watching television in a simulated living room. Noise levels were varied between 84 and 92 dBA, and three light levels were used (3, 22, and 129 lux). They found that significant interactions occurred between light and noise levels. Annoyance was lowest under dim (3 lux), highest for medium (22 lux) and in-between for the highest level (129 lux).

Fanger et al.[7] conducted a study which included the visual, auditory and thermal sense modalities. They investigated the effects of both color and noise on thermal comfort sensations. Each of 18 subjects was exposed to two types of colored light ("extreme red" and "extreme blue") and two levels of white noise (40 dBA and 85 dBA) in all four possible combinations. Subjects were permitted to adjust ambient temperature to their satisfaction. The authors summarize their findings as follows: "The subjects preferred a slightly lower (0.4°C lower) ambient temperature under blue light than under red light." (Noise had no effect on thermal comfort.)

The studies discussed above have well defined physical correlates that can be investigated and/or controlled in studies of visual performance, space usefulness and acceptability, provided the investigator is aware of these effects. The studies described above constitute a small sample of many investigations, which explored the effects of systematic changes in one sensory area, on responses which were predominantly based on another sensory response. However, we must also consider other non-visual contributions to visual performance which are difficult to control or in some cases not considered because their importance was unknown. These are the psychological factors -- attitudes, motivations, emotions, etc., present in any real world context or simulated real world environments (see diagram 1).

Psychological factors which may influence work performance include variables associated with differences among individuals such as learning experiences and motivation. In general, these variables influence the attitudes that the worker brings to the job. The Hawthorne studies conducted as a followup to the experiment described earlier, provide what is now considered to be a "classical" example of the importance of attitudinal variables in a study intended to deal with the effects of lighting conditions on productivity.

The main purpose of the second Hawthorne study, which took five years to complete, was to exercise greater control over the many variables that could have influences performance in the first study. One means of achieving the desired control was to separate the group being studied from the normal work environment. The selection of the work task to be examined was also governed by the desire for experimental control. The task chosen was a simple and repetitive one -- the assembly of small relays, which requires no machinery and which permits an accurate measure of productivity. The researchers examined environmental conditions (e.g., light level), work schedule, changes in supervision and the use of incentive plans as methods to increase production.

The authors found that none of these factors could be said to have a cause-effect relationship on productivity -- which as in the first Hawthorne study showed a continuous increase over time under most conditions. They concluded that the productivity increases were due to increased motivation and a more positive attitude toward the job. The changes in work performance were due not to perceived changes in the working environment, but changes in the worker's attitude toward the job. Differences of opinion exists as to the specific attitude change that caused increased motivation, but there is general agreement in the main findings that the productivity changes were due not to the environmental variable manipulated (light levels) but to psychological changes resulting from participation in the study.[3] So profound was this discovery that the term "Hawthorne Effect' is still used to caution behavioral researchers about the pitfalls about finding simple cause/effect relationships in field studies.

Non-visual components of the environment can play an important role in the appearance and acceptability of the visual environment, thus affecting worker performance and user acceptability. In short, these variables can act as contaminating, uncontrolled stimuli in studies of the visual environment. Yet, they do not make direct contributions to visibility per se, i.e., "how well we see". These non-visual factors (e.g., motivation and mood) are generally products of past experience, that is, learned behavior which can differ from individual to individual. These variables may play a role in determining "how well we think we see," but responses of this type should not serve as the basis for an objective criterion for recommending levels of illumination. Any investigation attempting to quantify 'goodness of seeing' as a function of levels of illumination at the acceptability and/or productivity levels can be confounded by contributions from these non-visual components.

In summary, because of the difficulty in controlling the contributions of non-visual variables, the writer feels the use of acceptability and productivity studies as the empirical basis for quantifying recommended levels of illumination is questionable. Rather studies involving direct assessments of the visual process are suggested as the most valid basis for recommending levels of illumination. On the other hand, although non-visual variables do not directly affect "how well we see," they must be considered in lighting design, since user acceptability and worker productivity are the final criteria in the assessment of the usefulness of a building.

5.0 VISUAL PROCESS

The visual process is defined as including the basic physiological processes (e.g., retinal receptors) up to evaluative responses of the visual environment (e.g., this space appears dynamic). That is, the response is directly traceable to inputs obtained from the visual system. Following the lead of Jay,[8] we can define the continuum in terms of <u>information</u> processing, i.e., "anytime we ask a human observer to respond to any externally applied stimuli, some level of information processing occurs." Information processing (interpreting) contributes little to simple visual responses. Neural responses occurring between the externally applied stimuli and the subject's response can be obtained. This may not be practical and furthermore is not necessary, but we must realize that different degrees of information processing occurs when the dependent variable (measured output) is directly linked to responses from the observer. When we confine ourselves to simple overt responses from the human observer, as in psychophysical experiments, the level of information processing is minimal and increases as observers are asked to consciously (or unconsciously) evaluate or interpret a given visual environment, e.g., "Are you satisfied with the lighting in this space?".

This visual process continuum is a large and complex one, with probably no definitive point at which it can be divided into distinct categories. We shall adopt the distinction suggested by Bartley[9] and divide the continuum representing the visual processes into two categories: "The first is the behavior that follows closely upon stimulation, a behavior that is immediately available for responses to the stimulus impingement upon it. The second category includes all activity that succeeds the first...". We shall label the first category the <u>sensory process</u> and the second the <u>perceptual process</u>. An experiment by Leibowitz et al.[10] described below is an operational example of the distinction made above.

Leibowitz et al limited information processing by controlling the presentation duration of the stimuli. The stimuli were tilted circular targets presented at two different exposure durations, 0.01 and 1.0 seconds. They found that for the longer exposure the predominant response was "a circle," whereas with the shorter duration the observers reported seeing ellipses. These findings were explained as follows although this may not be the only explanation: for the shorter duration the responses followed the law of retinal image, the tilted circle forms an ellipse on the retina. For the one-second exposure the responses followed the law of shape constancy, that is, although the retinal image was an ellipse, the opportunity to have more than a single glance at the target permitted information processing to occur, i.e., a circular plate on the horizontal plane appears elliptical. In the longer duration case interpretation or judgement could take place, but for the shorter duration, the time to make eye movements was limited. The longer duration permitted the subject to make more than one glance. It allowed time for adequate information processing to occur, permitting a subject to reach a conclusion based on the relationship between sensory input and information acquired by past experience. In the short duration exposure, the response was closely related to the stimulus characteristics with limited interpretation, whereas the longer exposure involved a higher order of stimulus interpretation.[9]

The above is an example where the learning situation or experience is similar for most observers, therefore, difference in responses <u>between</u> individuals would be minimal. As we increase the level of information processing, consequently, increasing the diversity of past experience (information) on which the response is based, we find corresponding increases in the diversity of responses between individuals.

6.0 SENSORY PROCESS

The sensory processes are the elementary processes or sensations underlying perception. The sensations (e.g., brightness) are then interpreted or evaluated, leading to impressions of the environment (e.g., "This space is cheerful," or "This space is gloomy."). Sensations are generally investigated by psychophysical or physiological studies. These sensations may then be interpreted or evaluated (additional information processing) resulting in an occupant's evaluative response assessed by questionnaires; preference, similarity-dissimilarity, like-dislike scales, etc.

The sensory process differs from the perceptual process in that the response is largely determined by the visual sensory system and fairly predictable[9]. Another important distinction is that the sensory process is minimally influenced by past experience or learning, relative to the perceptual and psychological factors discussed earlier. That is, the level of information processing can be kept to a minimum in investigations of the sensory processes. This is not to say that the sensory process data are totally unaffected by past experience or attitudes. For example, the response of the observer may be influenced by the "set" of the observer. Visual cues are more readily detected when the observer is expecting them and conversely it may not be seen if one is distracted -- e.g., listening to a conversation. But these nonsensory contributions are relatively easy to control in laboratory investigations, e.g., a warning signal before the onset of the visual stimuli, for the example cited above.

7.0 PERCEPTUAL PROCESS

The perceptual process involves evaluative responses, impressions (what we see). But the role of impressions in work performance and user acceptance involves more than what we see. It may include higher orders of information processing like preference (what we like to see) or evaluative responses (what we think we see). As stated earlier, an important component in higher order impressions is learned behavior, which can lead to significant differences in responses between different individuals, activities and cultures because of differences in past experience.

Even with similar past experiences lighting level preferences may differ, depending on the activity or use of the space. A given lighting level may be called gloomy for one type of activity or space (office), but that same level may be described as intimate or relaxing for another (dining). Conversely, a lighting level said to be too bright for one activity (dining), may be judged to be satisfactory for another activity (office work).

There is universal agreement that consideration of perceptual factors, impressions, is necessary in a good lighting design. Recently, Lam[11], Jay[8] and Boyce[12] have discussed the role and importance of subjective impressions in lighting design. Flynn[12] has described and discussed research methodologies--factor analysis, multidimensional scaling and semantic differential techniques--that identify and scale these impressions in a systematic and objective way. Lighting can be manipulated to give the desired impressions for a given space and activity. But what role should impressions play in an objective basis for recommending levels of illumination for visual task performance?

Impressions of the visual environment are components that can affect work performance and user acceptance. Impressions also involve the concept of "what we see," and this involves higher orders of information processing or stimulus interpretation. However, if visual conditions are too poor, than the perceptual deficiency is due to the sensory process. For example, if the visual conditions are such that an observer mistakes an E for a B, this most probably was due to sensory process limitations, although most of us can think of instances where letter misidentification was due to other factors. However, other phenomena that we all see cannot be explained in terms of limited sensory capacity. Instead a central organizing mechanism seems to be at work. Gestalt psychologists have concentrated their attention upon such problems. For example, in figure 2, even under high visibility, one will see a vase or two faces. What we see is not due to limited sensory capacity. Most of us see a vase or a face, but not both simultaneously. At one time, you may see black figures, silhouette of faces on a white background, but at the next moment you may see a white figure, a vase, on a black background. We all agree this is what we see. But there are other situations where the same sensory input results in significantly different responses. In the case of the Rorschach test, standard inkblots are clearly seen. See figure 3. When subjects are asked, "What do you see?", individuals report different things, that is, interpret the inkblots differently. This is an example of the same visual stimulus evoking significantly different responses.

The intent of these examples is to demonstrate the role of past experience and emotional involvement in the perception or evaluation of the visual world. In the case of the reversible vase and face, most people in our culture will see a vase and face alternately, but even within the same culture the response to the Rorschach will vary greatly between individuals. The influence of these perceptual factors in user acceptance or work performance assessments cannot be underestimated. If the criterion is "how much light do we need to see," then we must minimize the perceptual inputs. This result can be accomplished by obtaining the experimental data from studies at the more basic level of the sensory process, rather than at the higher perceptual levels - likely to be contaminated by extraneous and uncontrolled variables.

8.0 VISIBILITY

The index of how well we see is visibility. But this index may vary as a function of the difficulty and complexity of the stimuli and the judgements required of the observer in extracting information from the visual environment. At the simplest visibility level is a detection task -- determining the presence or absence of an object in the field of view. In the laboratory we can have observers detect the presence of a disc. In industry, a practical example is the detection of a crack in machined or welded parts as seen on an X-radiograph. The defect in this instance is seen as an inhomogeneity in an otherwise homogeneous field and can range in visibility from near threshold (just barely being able to see the hairline inhomogeneity) to highly visible.

The next higher order of visual task performance is recognition. This requires the observer not only to detect the presence of an object, but also to recognize it as a member of a group. This visibility level will generally require shape or form discrimination. Laboratory recognition tasks, for example, typically require the discrimination of geometric forms or the determination of the minimum separation between two parallel lines not involving discrimination of details. Applications to the real world may be of the form: "The object I see is a triangle, a letter, a man, etc."

The detection and recognition levels of task performance are followed by the identification level. This level requires the prior performance of the first and second levels. In addition, the observer must be able to discriminate between members of the same group. The additional performance requirement is the perception of details, for example, facial features, type of letter, etc. A simple paradigm of the above discussion is: I see something (detection), it is a man (recognition) and this particular man is John Doe (identification). Or, I see something on the paper, they are letters and the letters are E's.

Three levels of visual task requirements have been described and differentiated according to how the visual input is used and also with respect to the amount of information processing required. A description of the three levels in terms of their psychophysical correlates is now necessary, to indicate the change in responses associated with each level.

The most basic and simplest response of the visual mechanism is the discrimination of differences in luminance. In a detection task, this discrimination between two luminance levels, or contrast information, is all that is required. In a recognition study, "the task consists of (1) detecting the presence of a signal, then (2) assigning this signal to a category which has definitive class properties. Whatever theoretical position investigators have adopted, all researchers agree that the contour (outline) of a figure is the 'cue' or 'information' carrier for shape."[14] Thus, for a detection task, a difference in luminance is sufficient to determine the presence of a signal, and defines the total requirement. For a recognition task, the additional requirement of contour discrimination is imposed. Identification differs from recognition in that the former involves the perception of details as well as contours and involves aspects of image quality that improve clarity of detail.

Additional indications of this progressive increase towards the need for more precise and detailed information from the target as we go from detection to recognition to identification is shown by studies of image enhancement techniques. Brainard and Caum[15] investigated the effects of modification of the edge gradients on visual performance by sharpening, that is, making the details less blurry. They found that the enhancement technique became more effective as the subject's task became more difficult, that is, as the tasks progressed from detection to recognition to identification. For example, by sharpening the edge gradients of their images, the relative improvement in performance was 35 percent for target detection tasks, but 110 percent for identification tasks. In another comparison, the relative improvement of 17 percent obtained for recognition tasks contrasted with a 57 percent improvement for the corresponding identification tasks. Improving the sharpness of the visual detail results in a progressively greater improvement in performance as we go from simple detection to recognition followed by identification.

The above studies are based upon threshold considerations, just barely being able to perform at some criterion level, e.g., "I just barely see the spot of light" (detection), "I just see that it is a ring" (recognition), "I can barely tell that the number is a three and not an eight" (identification). Therefore, these studies also involve different levels of task discrimination and information processing.

There are advantages to using the threshold definition of visibility. Threshold studies are all direct measures of performance, be they detection, recognition or identification. On the other hand, there is a major difficulty with such performance measures. The value of 100 percent performance is a limiting one. That is, we cannot assess differences in goodness of seeing beyond this 100 percent performance level, if in fact they do exist. No improvement in goodness of seeing beyond this point is assumed in threshold performance measures. Yet in our daily experience, we encounter numerous examples of being able to see objects or read printed matter with 100 percent accuracy, and yet we confidently state that one is better (easier to see) than another. This methodological limitation must be overcome if a viable experimental basis for lighting standards is to be developed.

Lighting standards based on threshold studies face another criticism. In most everyday office tasks involving predominantly a visual component, however, we are not working at threshold levels, or would be unhappy if we had to. For example, a reproduction of written or typed material which is so poor that all we can state is that something is on the paper (detection) is not acceptable. If the reproduction were sufficiently good to state that it is printed matter, it would still not meet our needs. If the copy were improved to the extent that we could, with some certainty, identify a given letter (e.g., discriminate between and E and B) but just barely make such a discrimination, the visual task would still be unsatisfactory. We would expect marginal task performance under this condition -- i.e., a high error rate and/or low production. Reproduced, written or typed materials however, is seldom this poor. Instead, for most typical office task conditions, the primary concern is how well written or typed material (original and/or reproduced), can be seen. The criterion for visual performance should therefore be based on goodness of seeing, e.g., "I see the letter E under both conditions, but it is clearer under condition A rather than B." Just barely being able to detect, recognize or identify an object is unacceptable in most everyday situations, where lighting is used to perform visual tasks.

We will now examine two different research approaches to develop standards for lighting level recommendations: threshold studies (9.0) and suprathreshold experiments (10.0). As we will see next, these two different approaches differ not only with respect to experimental methodology but also in terms of research assumptions, findings, and implications for lighting standards development.

9.0 THRESHOLD VISIBILITY STUDIES

Let us now consider a number of threshold performance studies in greater detail. (An extensive review of this topic is beyond the scope of this report. The interested reader can find a detailed treatment of the subject in references 17, 18 and 19. Figures 4 and 5 present some typical threshold type targets. Figures 4A and B are commonly used in detection threshold experiments. Figures 4C, D and E are recognition tasks commonly used in acuity threshold experiments. In C the task is to determine the minimum detectable separation between the two parallel lines, in D the smallest gap that can be seen in the broken circle (Landolt C) and in E the task is to recognize a grating pattern, i.e., alternating dark and light lines. Figure 5 is the Jeager Eye Chart, and example of an identification acuity test. Figures 6 and 7 are the results from contrast detection experiments. On the ordinate we have the contrast required to just detect a luminous spot against a darker background. All points falling on a given curve are equal in that they are detected the same percentage of times, for example 50 percent. Another way of describing these data is that the ability of the eye to perceive a luminance difference between the detail and its background is constant for all points falling on the curve, within experimental errors. But these equal threshold contours only account for the lowest portion of the infinite number of levels of seeing existing between threshold and high visibility targets.

Figure 8 presents the results from a recognition acuity threshold experiment, the open circle for a Landolt C target and the filled circles for a grating pattern. These curves are also equal visibility contours, the difference between this approach and the one described above is that acuity is now the measure of visibility. Acuity is defined as the reciprocal of the angular subtense of the detail (minimum width, separation, gap, etc.) in minutes of arc. The acuity threshold is higher on the visibility scale than detection thresholds but is still far from the higher legibility levels encounterd in typical office tasks. The detection and recognition threshold studies are similar in that the functions are monotonic, a continuously increasing or decreasing function as luminance is increased. In both cases performance level increases with increased luminance.

If threshold studies adequately describe the performance of the visual system for all levels of task difficulty and complexity, then we should establish that these detection threshold eye sensitivity functions are applicable for suprathreshold conditions. Tinker in 1948 made this point as follows: "But to prescribe standards in terms of scores derived from measurements made with the Visibility Meter (Luckiesh) is open to serious questions. The basic data are threshold scores. While the derived scores may appear logical, suprathreshold seeing is not the same situation as threshold seeing."[16]

What is needed are studies where visual performance is investigated beyond the level of minimum (threshold) performance. The laboratory experiment should be of the form: For a definitely identifiable or visible task (suprathreshold) is conspicuity (goodness of seeing) better under illuminance level A or B? More generally, we need a measure that covers the gamut of visual sensitivity (sensation) from barely detectable to highly legible.

10.0 SUPRATHRESHOLD VISIBILITY STUDIES

Since most real-world tasks are being performed at visibility levels significantly higher than the 'just detectable', 'recognizable' and 'identifiable' levels, we should investigate the function of the eye at levels beyond this minimum or threshold level. In other words the assumption that the function of the visual system is the same at threshold and suprathreshold levels must be tested. One way to test this assumption would be to obtain equal visibility contours at suprathreshold levels. The threshold contrast contour would be the lowest level visibility contour, in a series of such curves.

A technique used in determining the sensitivity of the eye to different wavelengths of light can produce the required suprathreshold visibility contours. In the study to be described, Gibson and Tyndall[20] were interested in determining the luminous efficiency of monochromatic radiant energy at suprathreshold levels, that is, spots of light which are always visible. They found that subjects had considerable difficulty in precisely matching two lights of different hues because of hue differences between the two lights being compared. The authors, therefore, had to devise a methodology to minimize the role of color (hue) differences when making brightness (luminance) matches.

Gibson and Tyndall[20] called the methodology the "step-by-step method." The luminosity (brightness) for an observer's eye under given conditions at any wavelength is measured simultaneously relative to that of a slightly different wavelength. The second wavelength is then compared to a third wavelength, and so on, step-by-step throughout the spectrum. The luminosity at each wavelength is compared with that of a closely adjacent wavelength. The step sizes between wavelengths are chosen so that little or no hue difference is perceptible between any two wavelengths being compared. With these successive "ratios of luminosity" the relative luminosity curve for the region of the spectrum studied can be computed. That is, a curve can be drawn depicting equal brightnesses as a function of radiant energy input per wavelength.

Figure 9 presents the results reported by Gibson and Tyndall as relative visibility vs. wavelength. Relative visibility is defined as $V\lambda$ = luminosity $(L\lambda)$/radiant power $(E\lambda)$. Since this was an equality of brightness match, luminosity or brightness is a constant, and therefore the product of $V\lambda$ and the radiant power required for the equality of brightness match is a constant.

Since this paper deals with visibility and levels of illumination the function of interest is equal conspicuity (analogous to equal brightness in the spectral luminous efficiency functions discussed above). Contrast when referred to in this paper is defined as:

$C(MTF) = (L_{max} - L_{min})/(L_{max} + L_{min})$ or;

$$C = \frac{L_B - L_D}{L_B},$$

where MTF is Modulation Transfer Function and subscripts B and D refer to Background and Detail, respectively.

The methodology used in the studies to be described requires subjects to make "step-by-step" matches of perceived contrast under different levels of illumination, similar to the brightness matches made for different wavelengths of light in the Gibson and Tyndall study cited earlier. More specifically, a test target of variable contrast is matched with a comparison target, identical in all respects, except for the luminance of the test target being slightly lower (higher) than the comparison. See figure 10. The subject is asked to match the two fields so that they are equal in conspicuity, i.e., the detail stands out from the background equally for both fields. The median of five conspicuity matches is taken as the measure of central tendency. This median contrast value then serves as the comparison target to be matched with the new variable contrast target whose luminance has been decreased (increased) so that the luminance difference between comparison and test targets is the same as the previous luminance difference between comparison and test targets. The median contrast value of this new test target then serves as the next comparison target, and so on. Thus, when plotting contrast vs. luminance, we have a series of points representing equal conspicuities. That is, each point is perceived to be equal in conspicuity* to the other points on the curve at different luminance levels.

The subject then performs another similar series, the only difference being that the starting comparison contrast is increased (decreased). The completion of a series of this kind results in another equal conspicuity contour. A complete description of the procedure is given in reference 21.

The suprathreshold technique described above was utilized to obtain equal conspicuity contours for a contrast vs. luminance function for levels of visibility above threshold levels.

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* The subjects are instructed to adjust the test target until the detail (bar, alphabet, numeral, etc.) stands out from the background equally for both targets.

11.0 SUPRATHRESHOLD FUNCTIONS

Suprathreshold data have been obtained using different stimuli. Figures 11 and 12 present equal conspicuity contours obtained with sine and square wave gratings, respectively, as the stimuli[21]. The grating patterns were projected on a screen. Figure 13 represents results from an experiment using alphabets (Jaeger chart) as the stimuli.[22] The open circles in fig. 14 are the results from a recently completed experiment[1] using 5-bar (see fig. 15) patterns as the stimuli. We observe the monotonically decreasing function for low contrast patterns, and a reversal in the slope of the functions or a monotonically increasing function for the higher contrast levels. The filled circles are results from the grating study discussed earlier. The bars in the square-wave grating subtended 7.7 min, and 6.0 min in the 5-bar pattern. Comparison of the filled and open circle curves indicates that the open circle curves may show an abrupt increase in contrast at lower luminance levels.

All of the results indicate a significant difference between the form of the curves for low contrast as compared to high contrast targets. For low contrast patterns the equal conspicuity contours are monotonically decreasing. But with higher contrasts, the curves indicate that as luminance is increased beyond a particular luminance level, the contrast required to match a pattern increases with further increases in luminance. That is, beyond some luminance level (which we have defined as the 'optimum' level), the sensitivity of the eye to contrast (as measured by perceived conspicuity) decreases with higher luminance levels. This suggests that the sensitivity of the eye at low and high contrasts differ not only quantitatively, but also qualitatively. For threshold or near threshold contrast levels, the sensitivity of the eye increases as luminance increases, up to the limits of the luminance levels investigated in these studies. But, for higher visibility targets, those more closely approximating everyday office tasks, the sensitivity of the eye decreases with increases in luminance beyond an optimum luminance level.

The low contrast or near threshold contrast equal conspicuity contours are similar to many threshold functions. Figures 6-8 present results from threshold experiments. Figures 6 and 7 are from contrast threshold experiments involving detecting the presence of a circular target lighter than the background. Figure 8 presents the results of an acuity experiment, where the dependent variables were the minimum gap perceivable in a Landolt C and resolution of grating lines.

Note that these curves are generally monotonic. As luminance is increased, contrast required for detection decreases (or acuity increases), monotonically. This same function appears in our near threshold contrast contours, but not when the higher contrast (visibility) contours are plotted. In popular terminology "more light leads to better sight" for near contrast threshold tasks, but for higher contrast tasks, light levels beyond an optimum lead to less "sight." These findings indicate that extrapolating data from threshold experiments to predict eye performance at suprathreshold levels is not a valid procedure. Cases can be cited from the literature where prediction of suprathreshold performance from threshold data did lead to erroneous predictions.

Poppel and Harvey[23] found that subjective brightness as a function of retinal eccentricity predicted from threshold data differed significantly from the empirical data obtained by experiments performed at suprathreshold levels. An example of this difference in photometry is the spectral luminous efficiency function, brightness sensitivity as a function of radiant energy evaluated wavelength by wavelength. The function describing the sensitivity of the eye to radiant energy from different parts of the visible spectrum is different when obtained at the detection (threshold) levels[24] as opposed to the equal brightness function obtained for suprathreshold stimuli[20]. In both examples, experiments conducted at suprathreshold levels indicate the inappropriateness of predicting suprathreshold functions from threshold data.

The findings obtained in the suprathreshold studies were unexpected, but careful checking of the literature indicates that these types of visual responses have been reported even for threshold studies. Wilcox[25] investigated the resolution separation for two parallel bars 2.25 minutes wide, as a function of retinal illuminance. In fig. 16, the lower curve (open circles) represents the resolution threshold for the separation of two dark bars on a lighter background. The form of the function is similar to the classical threshold functions, in that, as luminance is increased the threshold continuously decreases, but at a slower rate. But, when the resolution targets are two light bars on a dark background, the form of the threshold-luminance curves are significantly different from the "classical" curve. It is similar to that observed for the higher contrast targets in the suprathreshold experiments. The irradiation hypothesis (light scatter within the eye) postulated by Wilcox[25] may be a contributing factor for the optimum found at suprathreshold levels.

De Palma and Lowry[26] investigated the threshold contrast required to perceive the separation between lines for the sine wave gratings. The observers were asked to decrease the contrast until the pattern disappeared. Their results are presented in fig. 17. They found optimum line widths above and below which contrasts had to be increased for subjects to perceive the lines. Optimum line widths resulted from single line studies as well. Figure 18 is adapted from Fry[27]. In this study, the background luminance was kept constant at 74.3 nits (21.7 fL). The solid curve (squares) is the results for a single bright bar against a darker background and gives a monotonic function. The dashed curve (circles) represents the data from judgements of a single dark bar seen against a lighter background, and reverses itself after reaching an optimum width of about 10 minutes of visual angle.

Figure 8 presents a plot of visual acuity data against luminance for Landolt C and grating targets. In both cases, we observe the classical monotonic threshold function. Figure 19 summarizes the data in another visual acuity study using Landolt C's. In this study, Stevens and Foxell[28] used a high contrast (0.9930) test object, and instead of the classical monotonic function, found an optimum luminance level, but this optimum occurred at a high luminance level, about 2,000 cd/m^2.* These findings demonstrate that even at threshold performance levels, some conditions lead to decreasing visibility at higher luminances.

Khek and Krivohlahvy[29] had their subjects determine the orientation of the gap in a Landolt C. They found that the result they obtained was dependent on the response measure used. When the performance measure was time (information transmitted per second) the performance vs. illuminance function was monotonic, i.e., as illuminance was increased performance increased. But when they plotted error as their dependent variable, their function described an optimum level of performance. Figure 20 is a general form of the relation found by Khek and Krivohlahvy between performance and task difficulty in this case as a function of illuminance. The dashed curve labeled F describes performance in terms of error rate, and the solid curve P depicts time as the dependent variable. Note the monotonically increasing function for the temporal dependent variable, and an optimum perform wavelength for the error function.

The results obtained by Khek et al.[29] for prolonged visual activity (100 minutes of continuous reading of Landolt C's for every experimental condition) indicate a trend similar to that found in the NBS studies.[21, 22] The results are presented in fig. 21 where percent errors are plotted against illuminance. The parameters for the different functions are combinations of contrast and visual angle. The top function with the largest percent errors is for a Landolt C with a contrast of 0.78 with the gap in the C subtending 1' of visual angle. The curve with the second largest percent error is a less "difficult" task in that the contrasts are the same, but now the gap in the C has been increased to 2', making it a less difficult task. The next curve also has a 2' gap, but the contrast has been increased to 0.98. The curve with the least number of errors is that for the least difficult of the four conditions, 0.98 contrast with a 3' minute gap. Of greater interest in the context of the present paper is the trend indicated as illuminance is increased. The two easiest conditions indicate increases in number of errors at the highest illuminances, whereas the two more difficult tasks resemble the classical threshold functions. The percent error increases at higher illuminances is not strong (2-3 percent). It is possible that a more sensitive test of this phenomenon might clarify this finding -- i.e., one that more directly tests the visual sensitivity of the eye (e.g., the equal conspicuity contours methodology used in the NBS studies).

We will conclude the discussion by citing several suprathreshold studies, where gratings were used as stimulus objects. Unfortunately, the researchers performing these investigations were not primarily interested in luminance

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* A study by: Stone, P.T., Clarke, A.M., and Slater, A.I., "The Effect of Task Contrast on Visual Performance and Visual Fatigue at a Constant Luminance" was called to the attention of the writer after completion of the manuscript. They found that: "(a) the visual system experiences difficulty with tasks at very low contrasts, as would be expected and also (b) that very high contrast may inhibit task performance".

levels and limited their investigations to suprathreshold responses at low luminance levels. Bryngdahl[30] investigated subjective contrast of gratings at suprathreshold levels, but his range of luminances was limited, 5 to 20 cd/m^2 (1.5 - 5.8 fL). Kulikowski[31] in his contrast constancy experiments worked at low luminance levels, 0.1 to 1.0 cd/m^2 (0.03 -0.3 fL). Watanabe et al.[32] had subjects make equality of contrast judgments for gratings at mean luminances of 17 - 171 cd/m^2(5 - 50 fL) for many spatial frequencies, but only at a single low contrast level, 0.032.

Georgeson and Sullivan[33] report the importance of the distinction between apparent contrast and visibility. In the NBS studies, subjects were asked to vary the contrast until the details appeared to stand out from the background equally for both targets. In the Georgeson study,

> The observer's task was to adjust the variable until it matched the standard in apparent contrast. We were careful to stress the significance of the term contrast. Observers made judgements by <u>comparing the brightness differences</u> within each pattern. Over a wide variety of experimental conditions most observers found this reasonably easy to do; the judgement accorded with what is commonly understood by contrast. A particular concern was that the observers should <u>not</u> be misled into matching the patterns according to some impression of 'visibility'. As our results will show, it is often the case that when the subjective contrast of two patterns match, one pattern may be very much <u>easier to see</u> than the other. It was made clear to observers that they were not to be worried by this paradox and were only to pay attention to contrast.

Georgeson's observations[33] indicate that the NBS contours should be labelled 'equal conspicuity contours' and not equate apparent contrast and conspicuity. The interest is equality of visibility, how well the detail stands out from the background.

12.0 STANDARDS FOR LIGHTING

Should standards for lighting level recommendations be based on "How well we see," "What we see," "What we like to see," or "What we think we see?" How well we see, is a measure describing the goodness of the task in terms of being able to perceive details. On the other hand, how well we think we see, or what we (think) we see, include impressions resulting from interpretations.

Standards must satisfy the performance requirements for a building. The performance requirements, in terms of function and human occupancy, require the successful performance of the activities specified for that space while also satisfying the habitability criterion. In any space where visual task performance is an integral function of the space, the ability to see the task without difficulty is the fundamental requirement of any lighting criteria. The habitability criterion is met when the environment is said to be acceptable. It is not necessary that lighting standards include criteria that maximize comfort and satisfaction. These preferences may be highly individualistic and therefore difficult, if not impossible, to satisfy in a general way. The lighting criteria fulfill the performance requirements when the above conditions are met.

But, lighting can contribute more to the environment than enabling the occupant to see the task with ease. Moods and impressions may be created by the lighting system. These evaluations of the physical environment result in significantly different interpretations between individual or different socioeconomic, age, ethnic, etc., segments of the population although there are lighting effects that appear to have universal effects, e.g., phototropism, the attraction of people toward light. These evaluations of the environment should not be mandated as performance requirements. Instead, they should be considered in the design of a space if obtaining specific moods and impressions is an important function of the space.

In short, should standards for lighting levels be based on psychological, perceptual or sensory factors or should all three be considered? The preceding discussions indicate that the standards should be based on responses that are primarily dependent on physiological processes which minimize variability among observers. The visibility of a visual task can be described and quantified by psychophysical experiments. In logical terms, visual capacity information is necessary and sufficient for recommending levels of illumination for visual task performance. But when we consider recommending criteria which define desirable building performance rather than required performance, visual sensory considerations are necessary but not sufficient.

We should therefore have standardized light levels required to see, and may modify this level to include impressions leading to a more comfortable visual environment. But in doing so, we must realize that we are including subjective factors not to improve our ability to see, but to create an environment we like for considerations other than a direct assessment of optimum seeing. We should not conclude that higher (lower) light levels result in improved seeing, because they are the preferred levels. If the increases in preference cannot be shown to be due to improved "seeability," we should attribute it to another cause. If the other cause is not known, we should say so.

13.0 CONCLUSIONS

Lighting contributes more to the environment than the ability to see. These other contributions play a role in user satisfaction and work performance. They should be considered in the design of a space, but not serve as a basis for required light levels for visual task performance. These design considerations are generally used to create atmosphere and influence moods that are highly specific to the type of activity and population group.

Recommended light levels for commercial tasks should be based on laboratory studies of suprathreshold visibility. Lighting levels based on laboratory threshold performance are valid for detection type applications, like aircraft signalling lights or blips on a cathode-ray scope. (Assuming that more effective ways of improving the visibility of the task, i.e., increasing size or improving contrast, are not practical.) But for most real-world commercial tasks, the lighting conditions required are those that lead to ease of seeing, rather than the rare case of enabling people to barely see visual tasks.

The yardstick for visibility should be conspicuity or ease of seeing. Different levels of task visibility are encountered in the real world. Much work has been done on threshold type tasks, and data for the visual sensitivity function at thresholds are readily available. But, data for suprathreshold levels of seeing are limited even though most tasks, especially those encountered in offices, are at suprathreshold levels. Therefore, conspicuity studies for suprathreshold levels of seeing should be the basis for recommending light levels for most real-world tasks.

A further observation of the findings in this report, is that for task visibility above 100 percent detection performance, high luminance levels result in loss of visual sensitivity. This outcome should lead to a reconsideration of the slogan: "More light, better sight." The use of this motto may result in less efficient and effective use of lighting energy in the following way. Set the illuminance level for the work location to satisfy the illuminance requirement for the most difficult task. That this level will be the optimum illuminance level follows from the rationale that, if we have adequate lighting for the most difficult task (that requiring the highest light level) the other higher visibility or conspicuity tasks will only be enhanced in visibility, since more light equals better sight. But the present paper demonstrated the existence of an optimum luminance level for suprathreshold tasks. This indicates that with high lighting levels we may have losses in visibility for the higher contrast tasks, which may also be the tasks most frequently encountered at that work location. Setting light levels higher than necessary for an infrequently encountered difficult task is therefore not only wasteful of energy, but can lead to visibility losses for other more frequently encountered tasks. Overdesign in lighting to assure meeting specifications may not be accomplishing the desired end: good lighting for visual task performance.

14.0 REFERENCES

1. Yonemura, G. T., Rinalducci, E. J., Tibbott, R. L. and Fogelgren, L. A., "Equal Apparent Conspicuity Contours with Five-Bar Grating Stimuli," NBSIR 79-1925, 1980.

2. Roethlisberger, F. J. and Dickson, W. J., Management and the Worker, Harvard Univ. Press, Cambridge, Mass., 1939.

3. Parsons, H. M. What Happened at Hawthorne?, Science, 922-932, 1974.

4. Smith, S. W. and Rea, M. S., "Proofreading under Different Levels of Illumination," J. Ill. Eng. Soc., 8, 47-52, 1978.

5. Lofberg, H. A., Lofstedt, B., Nilsson, I. and Wyon, D. P., "Combined Temperature and Lighting Effects on the Performance of Repetitive Tasks with Differing Visual Content," CIE Proc. 18th Session, London, 1975, CIE Publication No. 36 (1976), 450-455, 4, Avenue Du Recteur Poincare, Paris.

6. Shigehisa, T. and Gunn, W. J., "Annoyance Response to Recorded Aircraft Noise. I. Effect of Intensity of Illumination," J. Auditory Res. 18, 175-183, 1978.

7. Fanger, P. O., Breum, N. O. and Jerking, N. O., "Can Colour and Noise Influence Man's Thermal Comfort?" Ergonomics, 20, 11-18, 1977.

8. Jay, P. A., "Lighting and the Search for Meaning," In Developments in Lighting-1, J. A. Lynes, Ed., Applied Science Publishers Ltd., 77-111, London, 1978.

9. Bartley, S. H. Principles of Perception, Harper and Brothers, New York, 1958, p. 450.

10. Leibowitz, H., Mitchell, E. and Angrist, N., "Exposure Duration in the Perception of Shape," Science, 120, 400, 1954.

11. Lam, W. M. C. Perception and Lighting as Formgivers for Architecture, McGraw-Hill Book Co., New York, 1977.

12. Boyce, P. R., "Under the Influence of Lighting," In Developments in Lighting-1, J. A. Lynes, (Ed.,) Applied Science Publishers Ltd., 47-76, London, 1978.

13. Flynn, J. E., Hendrick, C., Spencer, T., and Martyniuk, O., "A Guide to Methodology Procedures for Measuring Subjective Impressions in Lighting," J. Ill. Eng. Soc., 8, 95-110, 1979.

14. Fox, W. R., "Visual Discrimination as a Function of Stimulus Size, Shape and Edge-Gradient," In Wulfeck, J. W. and Taylor, J. H., (eds.), Form

Discrimination as Related to Military Problems, Publications 561, National Academy of Science-National Research Council, 168-175, 1957.

15. Brainard, R. W. and Caum, K. B., Evaluation of an Image Quality Enhancement Technique, AMRL-TR-65-143, Sept. 1965, NTIS No. AD624470.

16. Tinker, M. A. "Trends in Illumination Standards," Ill. Eng.,43, 866-881, (871), 1948.

17. Graham, C. H. (ed.) Vision and Visual Perception, John Wiley and Sons, New York, 1965.

18. Stevens, S. S. (ed.) Handbook of Experimental Psychology, John Wiley and Sons, New York, 1951.

19. Overington, I. Vision and Acquisition, Pentech Press, London, 1976.

20. Gibson, K. S. and Tyndall, E. P. T., "Visibility of Radiant Energy," Scientific Papers of the Bureau of Standards, No. 475, 1923.

21. Yonemura, G. T. and Kohayakawa, Y., "A New Look at the Research Basis for Lighting Level Recommendations," NBS Building Science Series 82, 1976.

22. Yonemura, G. T., Benson, W. M. and Tibbott, R. L., Levels of Ilumination and Legibility, NBSIR 77-1306, 1977.

23. Poppel, E., and Harvey L. O., Jr., "Differential Threshold and Subjective Brightness in the Periphery," Psychol.Forsch., 36, 145-161, 1973.

24. Commission Internationale de l'Eclairage (CIE), Comite D'Etudes sur la Lumiére et la Vision rapporteur, LeGrande, Y., Proceedings of the 12th session, Stockholm, Vol. 1, 1951.

25. Wilcox, W. W., "The Basis of the Dependence of Visual Acuity on Illumination," Proc. Nat. Acad. of Sciences, 18, 47-56, 1932.

26. De Palma, J. J. and Lowry, E. M., "Sine Wave Response of Visual System II. Sine-Wave and Square-Wave Contrast Sensitivity," J. Opt. Soc. Amer., 52, 328-335, 1962.

27. Fry, G. A., "The Optical Performance of the Human Eye." In Progress in Optics, E. Wolf, Ed., American Elsevier Publishing Co., Inc., New York, 51-131, 1970.

28. Stevens, W. R. and Foxell, C. A. P., "Visual Acuity," Light and Lighting, 48, 419-424, 1955.

29. Khek, J. and Krivohlavy, J., "Variation of Incidence of Error with Visual Task Difficulty," Light and Lighting, 59, 143-145, May 1966.

30. Bryngdahl, O., "Characteristics of the Visual System: Visual Response to Photopic Spatial Sine Waves," J. Opt. Soc. Amer., 56, 811-821, 1966.

31. Kulikowski, J. J., "Effective Contrast Constancy and Linearity of Contrast Sensation," Vision Res., 16, 1419-1431, 1976.

32. Watanabe, A., Mori, T., Nagata, S., and Hiwatashi, K., "Spatial Sine-Wave Responses of the Human Visual System," Vision Res., 8, 1245-1263, 1968.

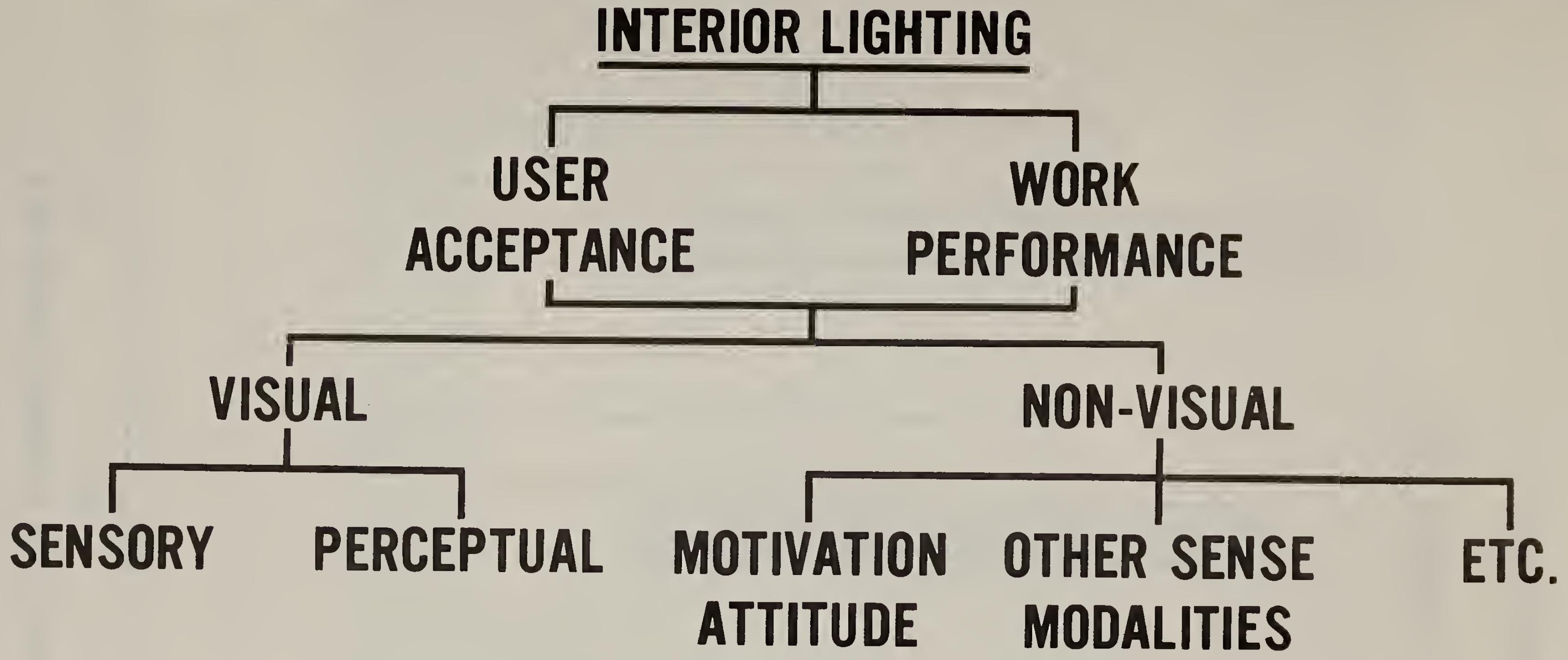
33. Georgeson, M. A. and Sullivan, G. D., "Contrast Constancy: Deblurring in Human Vision by Spatial Frequency Channels," J. Physiol, 252, 627-656, 1975.

34. Steinhardt, J., "Intensity Discrimination in the Human Eye I. The Relation of ΔI/I to Intensity," J. Gen. Physiol. 20, 185-209, 1936.

35. Blackwell, H. R., "Contrast Threshold of the Human Eye," J. Opt. Soc. Amer., 36, 624-643, 1946.

36. Shlaer, S., "The Relation Between Visual Acuity and Illumination," J. Gen. Physiol. 21, 1937, 165-188.

Diagram 1. Components needed in the assessment of the visual environment.



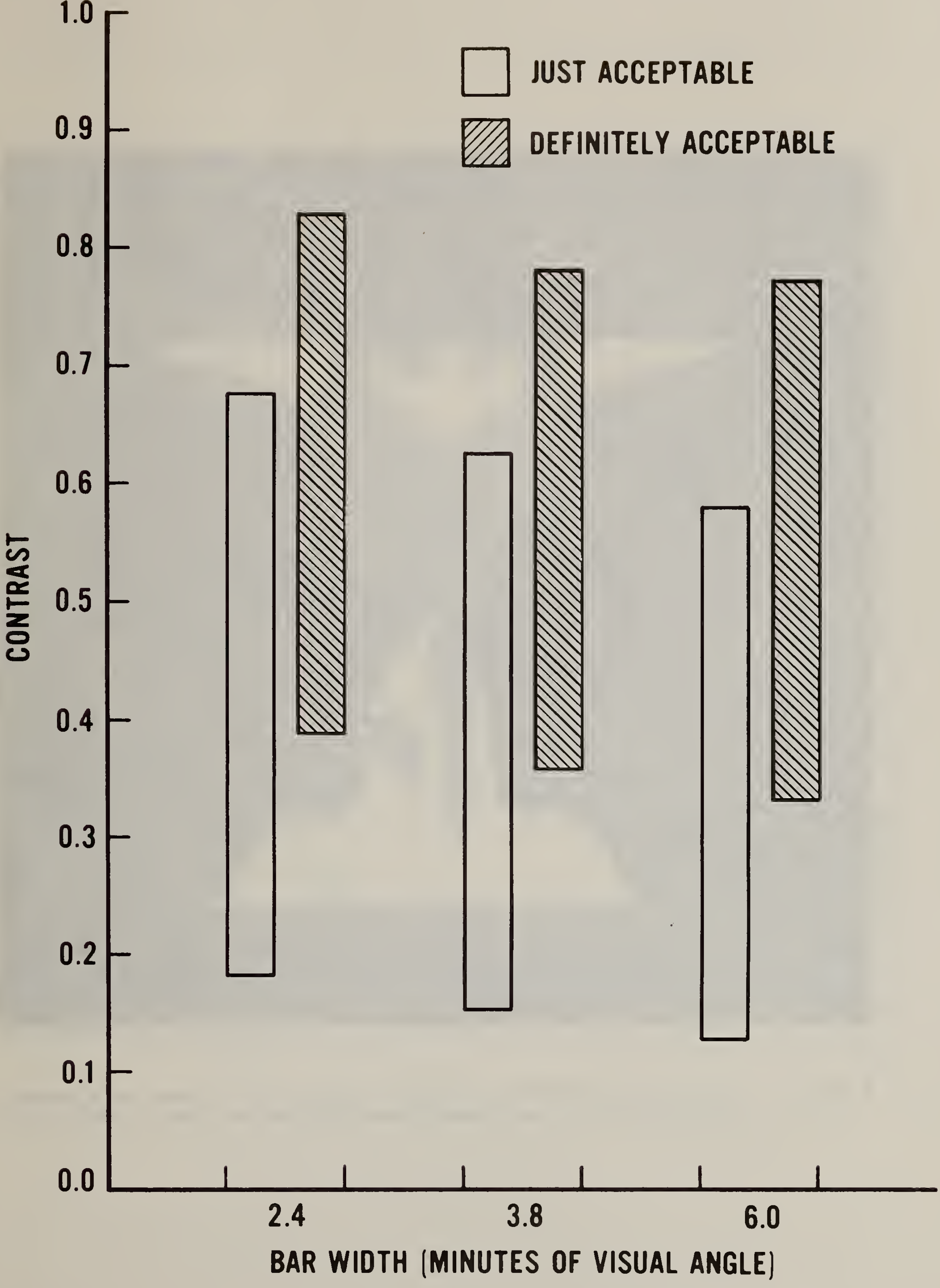


Figure 1. Ranges of contrast judged "just acceptable" and "definitely acceptable" for sustained reading. Five-bar grating pattern stimuli at luminance of 700 cd/m^2.

Figure 2. Reversible figures. You see a vase (white figure on a black background) or two faces (black figures on a white background).

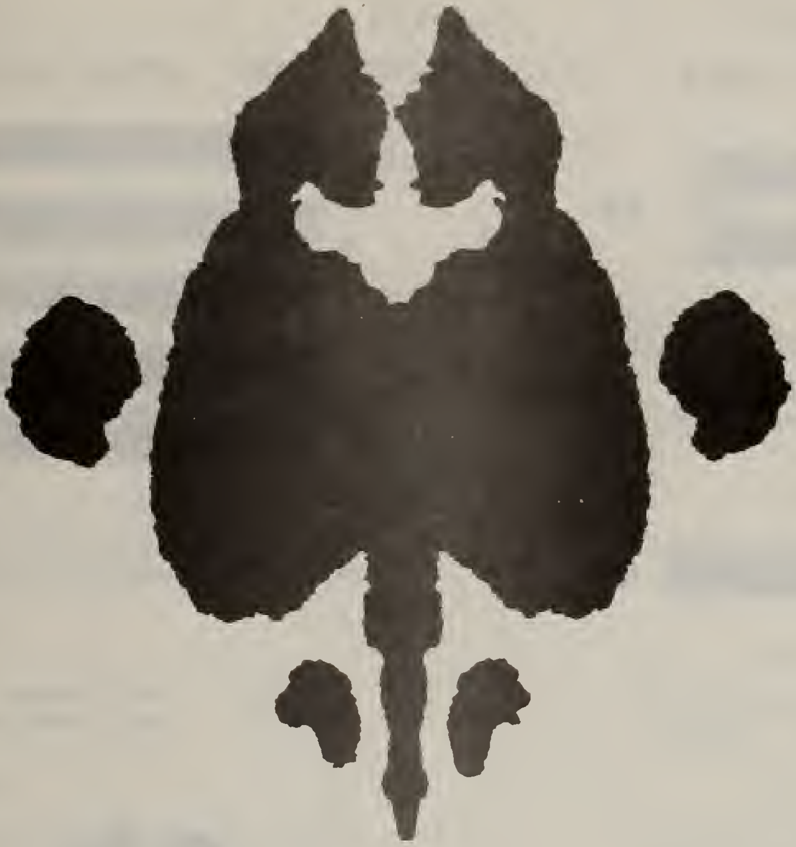


Figure 3. Example of Rorschach standard ink blot test.

Figure 4. Stimuli used in threshold experiments: A) disc; B) single line; C) two parallel lines, minimum separable; D) Landolt C, minimum gap and E) grating pattern.

Near V. E. %: 5
Jaeger 14
24 Point
Acuity: Approx. 0.12 (20/170)
Sight-saving texts.

man oxen
25 37 84 90
oxxo oxxx

Near V. E. %: 10
Jaeger 12
18 Point
Acuity: Approx. 0.15 (20/130)
Books, children 7-8 yrs.

raw see van
90 89 76 60 54
xoxxx oxooo

Near V. E. %: 15
Jaeger 10
14 Point
Acuity: Approx. 0.2 (20/100)
Books, children 8-9 yrs.

noon even mew
38 72 80 93 54 60 76
xxox xxxx ooox

Near V. E. %: 20
Jaeger 8
12 Point
Acuity: Approx. 0.25 (20/80)
Books, children 9-12 yrs.

war use worm eve
avenue ransom err
40 53 8
809 42
xoox oooxo ooxxx
remo romero suma

Near V. E. %: 30
Jaeger 7
Acuity: Approx. 0.28 (20/70)
Adult textbooks.

scum crease nervous
cocoon cannon saucer
98 67 45
456 309 5
xooo oxxo oxxx xxxx
saca zarco cascarron

Near V. E. %: 40
Jaeger 6
Acuity: Approx. 0.3 (20/65)
Magazines.

arrow scour noose razor
zone reverence sorceress
35 98 20 82
740 203 96
xxxo ooxx oxoox xoxox
remanso semana asma

Near V. E. %: 50
Jaeger 5
Acuity: Approx. 0.4 (20/50)
Newspaper text

amaze wares curve scarce
snooze caress sewer wax
82 34 65 90
426 397 564
oxxo oooo xoxx xxxx ooox
remesa suave arrancar

Near V. E. %: 90
Jaeger 3
Acuity: Approx. 0.5 (20/40)
Telephone directory.

comma worse reason measure vase
census arrears recover crane now
75 23 68 90 44
890 375 204 53
xoxx ooxo oxxo oxoo xxox oooo
resaca carecer crecer sazonar

Near V. E. %: 95
Jaeger 2
Acuity: Approx. 0.6 (20/30)
Want ads.

success numerous assurance consume
cocoa convex morocco uncommon err
56 87 92 30 47
209 354 872 40
xoxx ooox ooxo ooxxx xoxo xxox oxoo
sesos sucesor vaso zamarra azar

Near V. E. %: 100
Jaeger 1
Acuity: Approx. 0.8 (20/25)
Small bibles.

occurrence nevermore successor romance worm
craze arson crew amorous scow aroma samovar
72 05 40 58
284 454 306
xxxox xxoox ooxxo xoxox ooxxo xoxx
comarcano rosca serrano amanecer

Comparable:
Jaeger1 +
3 Point
Acuity: Approx. 1.0
Mailorder

xoxxo xxooo ooooo ooxoo
[illegible] serrano avance

Letter height—
0.3493 mm.
2 Point

Figure 5. Jaeger Chart.

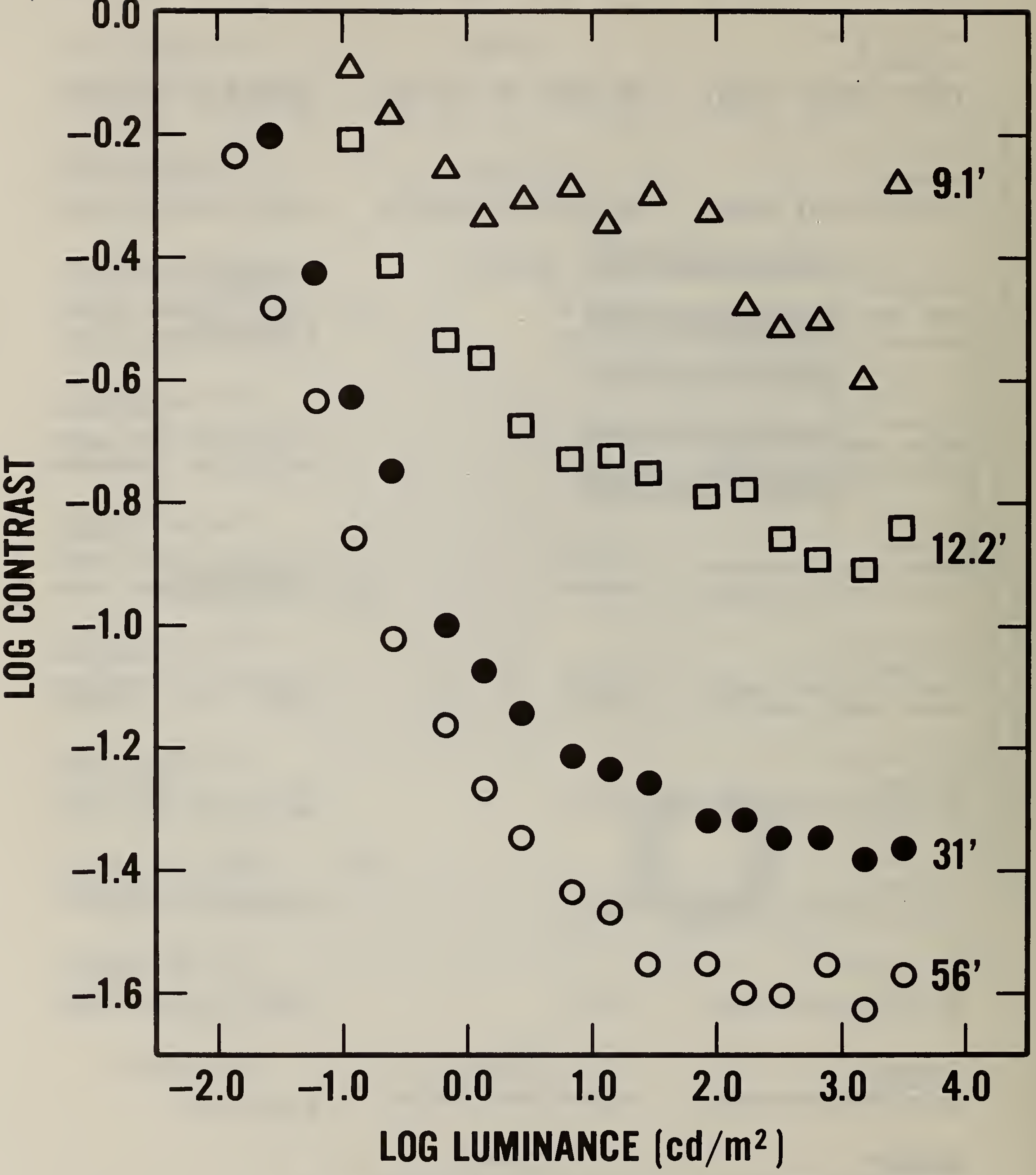


Figure 6. Luminance contrast threshold as a function of background luminance for disc diameters subtending 9.1, 12.2, 31 and 56 min. of arc. Adapted from Steinhardt[34].

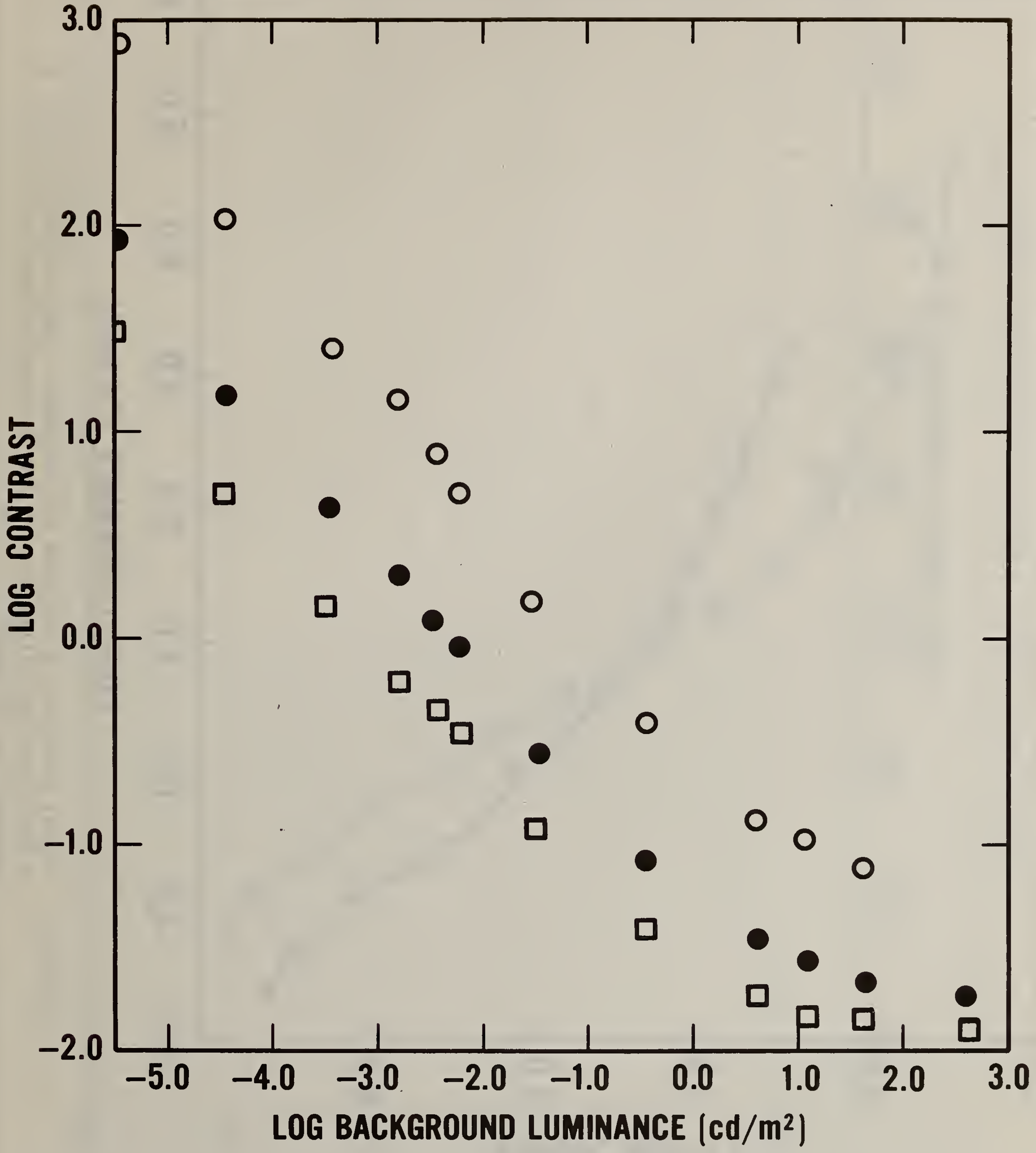


Figure 7. Luminance contrast threshold as a function of background luminance. Disc test stimuli with diameters: open circles = 3.6', filled circles 9.68' and open squares 18.2'. Adapted from Blackwell[35].

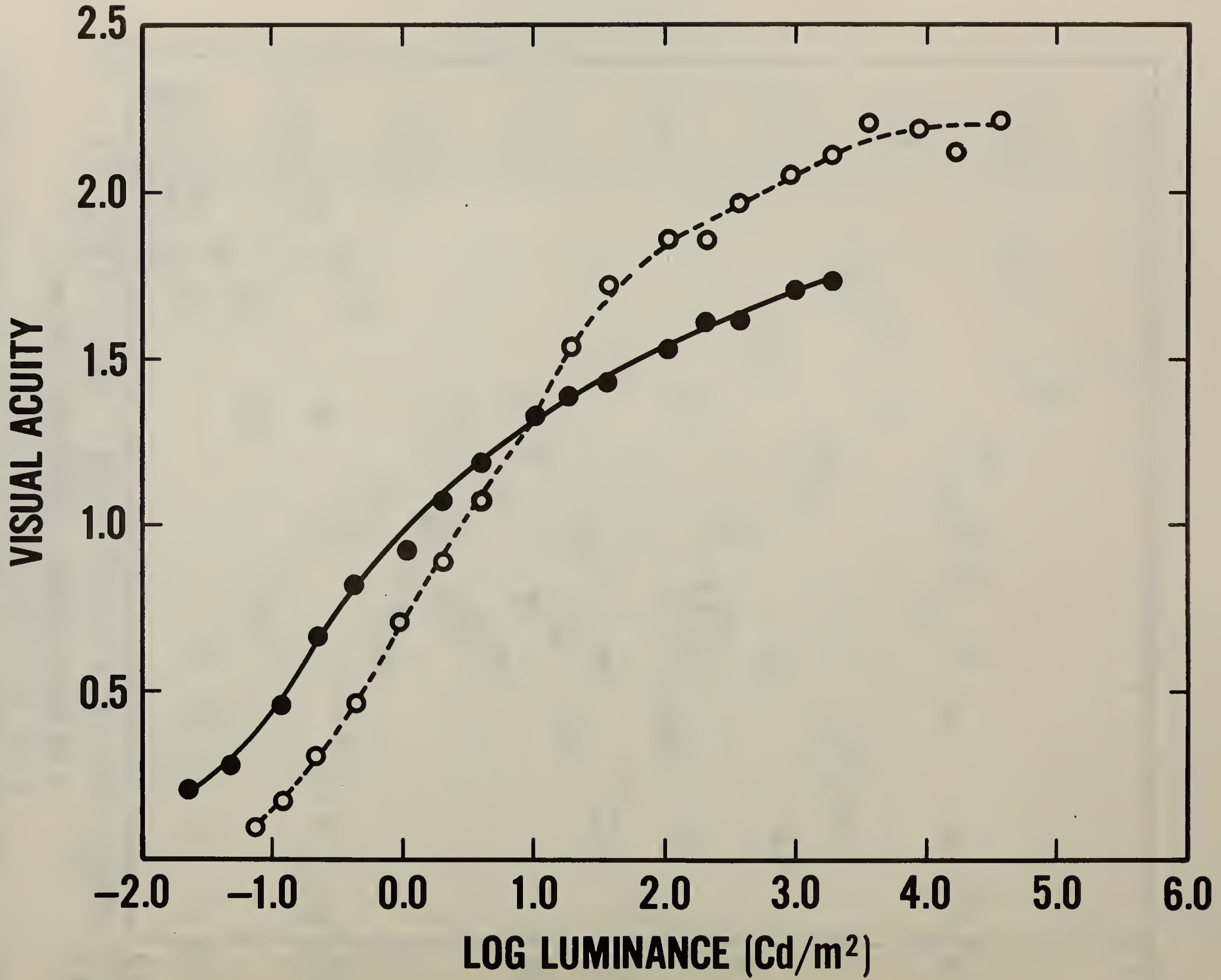


Figure 8. Visual acuity as a function of luminance. Open circles are for a Landolt C and filled circles for grating pattern test stimuli. Adapted from Shlaer[36].

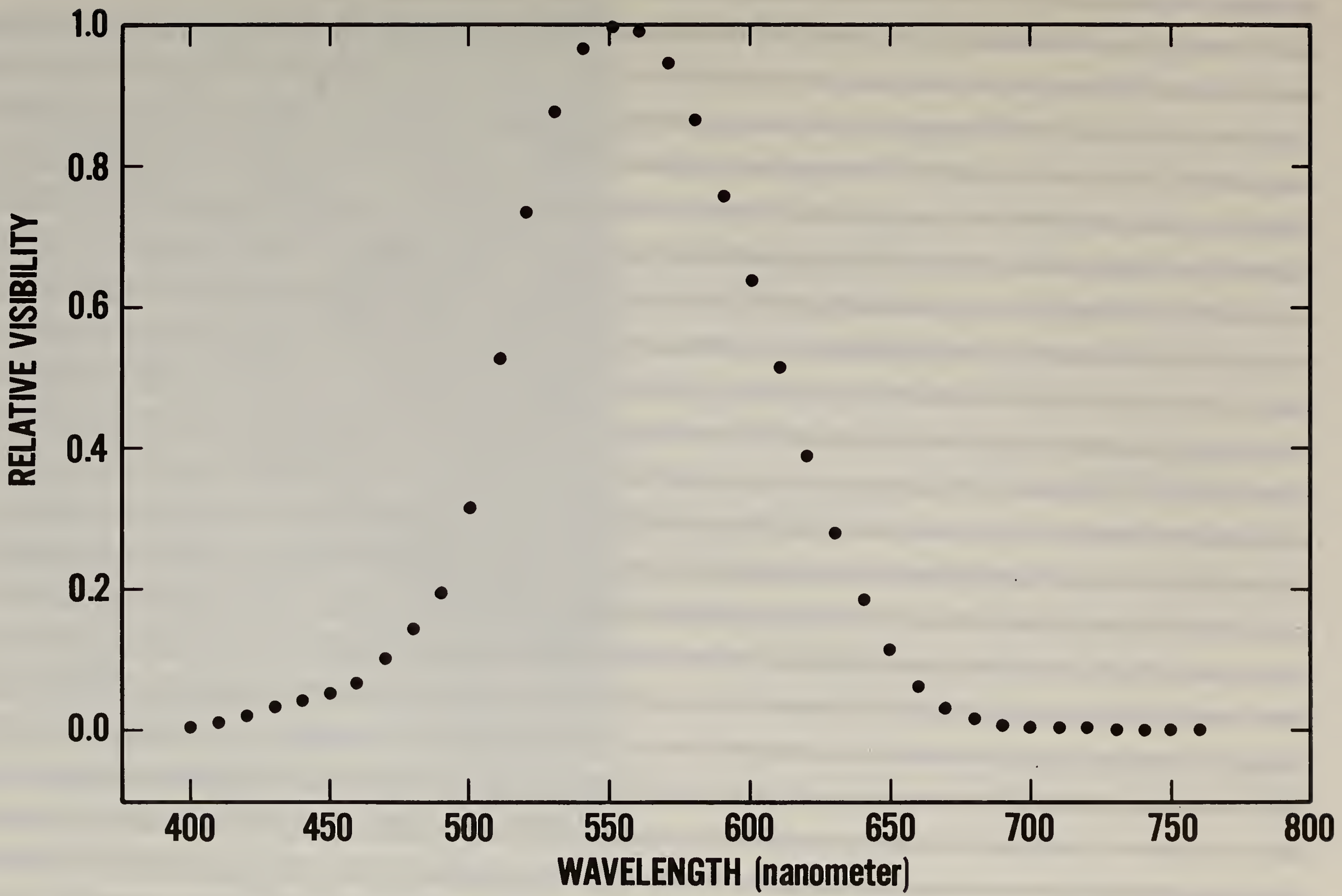


Figure 9. Relative visibility as a function of wavelength, evaluated at suprathreshold levels. Adapted from Gibson and Tyndall[20].

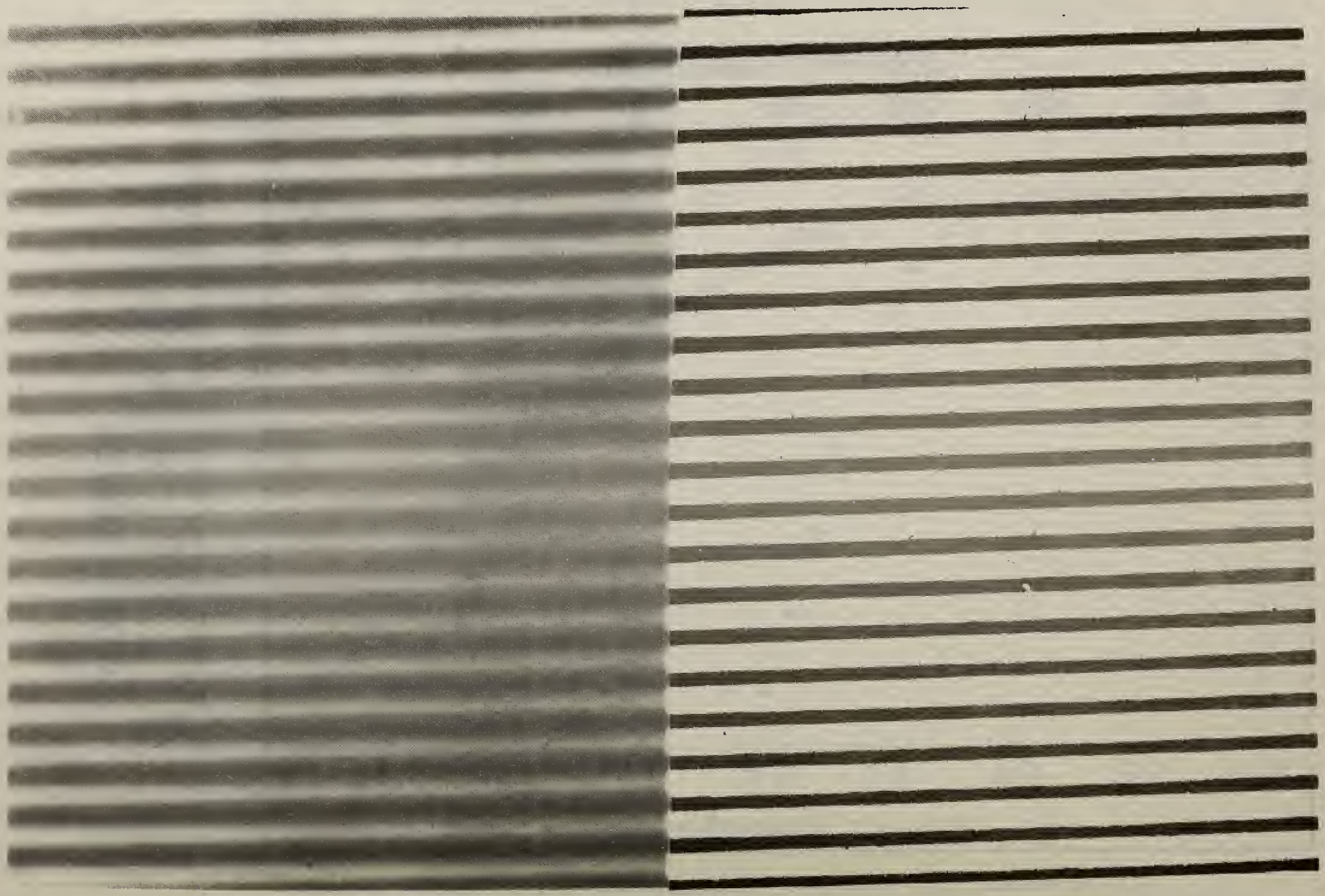


Figure 10. Test stimuli (sinusoidal gratings) used in equal clarity experiments.

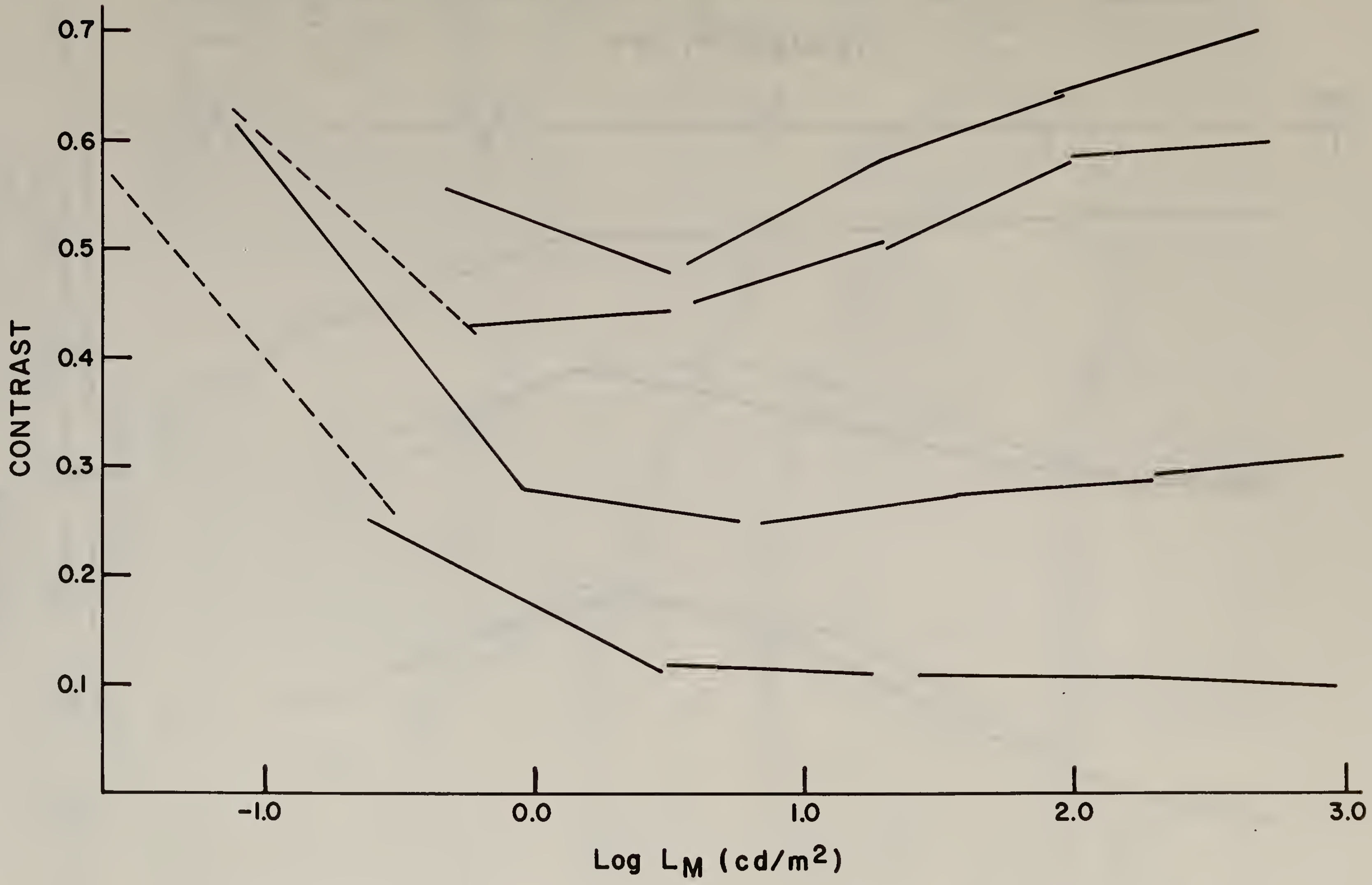


Figure 11. Equal conspicuity contours as a function of mean spatial luminance (L_m) for a 3.9 cyc/deg square wave grating[21]. The dashed lines represent contrast values which "almost" gave equal conspicuity matches, but was limited by the maximum contrast obtainable with the apparatus for the given conditions.

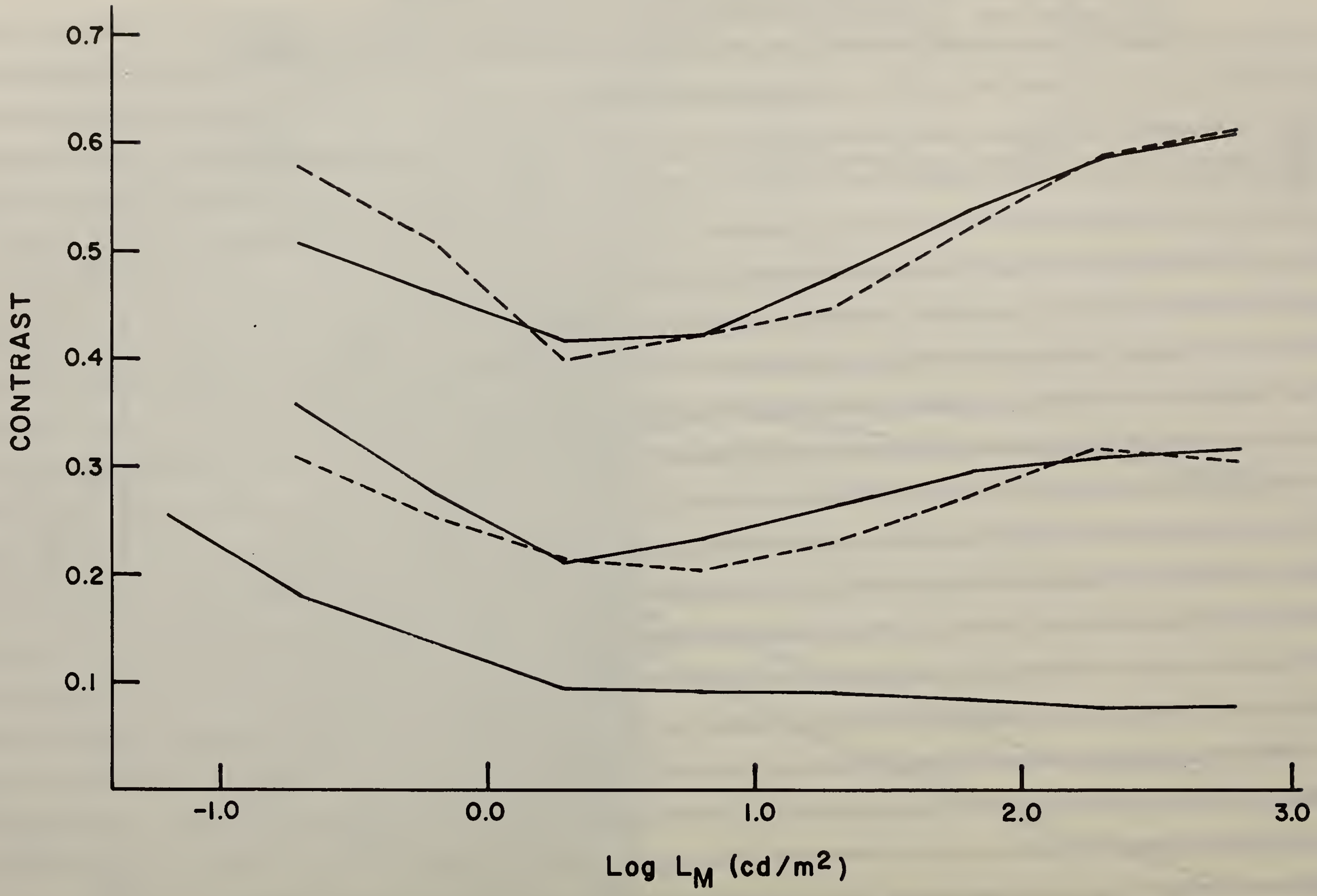


Figure 12. Equal conspicuity contours as a function of mean spatial luminance (L_m) for a 3.9 cyc/deg sine-wave grating[21]. The solid and dashed curves represent the results for two different observers.

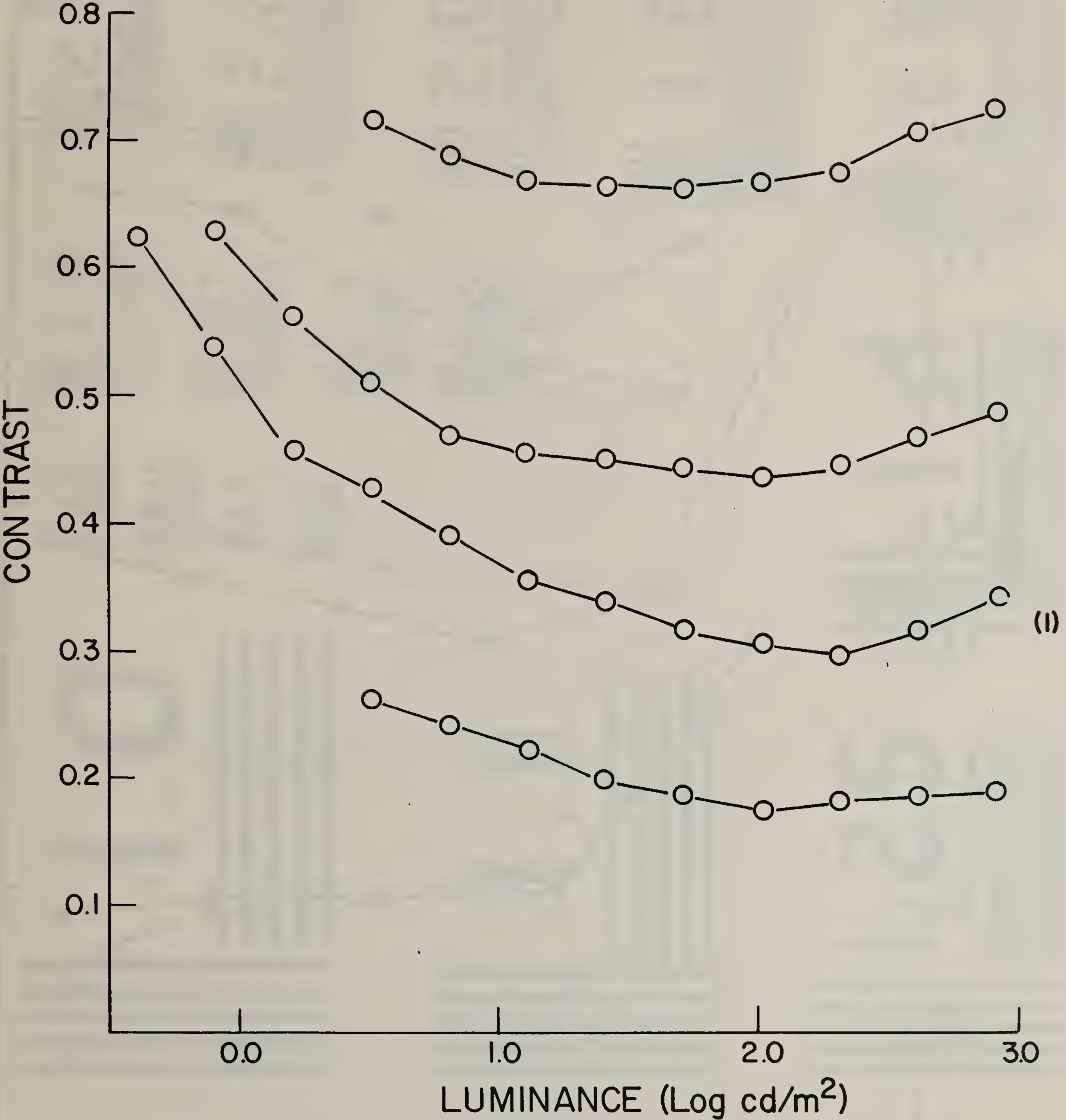


Figure 13. Equal conspicuity contours averaged over four subjects and alphabets of three stroke widths (6.5, 4 and 3.2 min. of visual angle), except for curve (1) which is the result for a single subject[22].

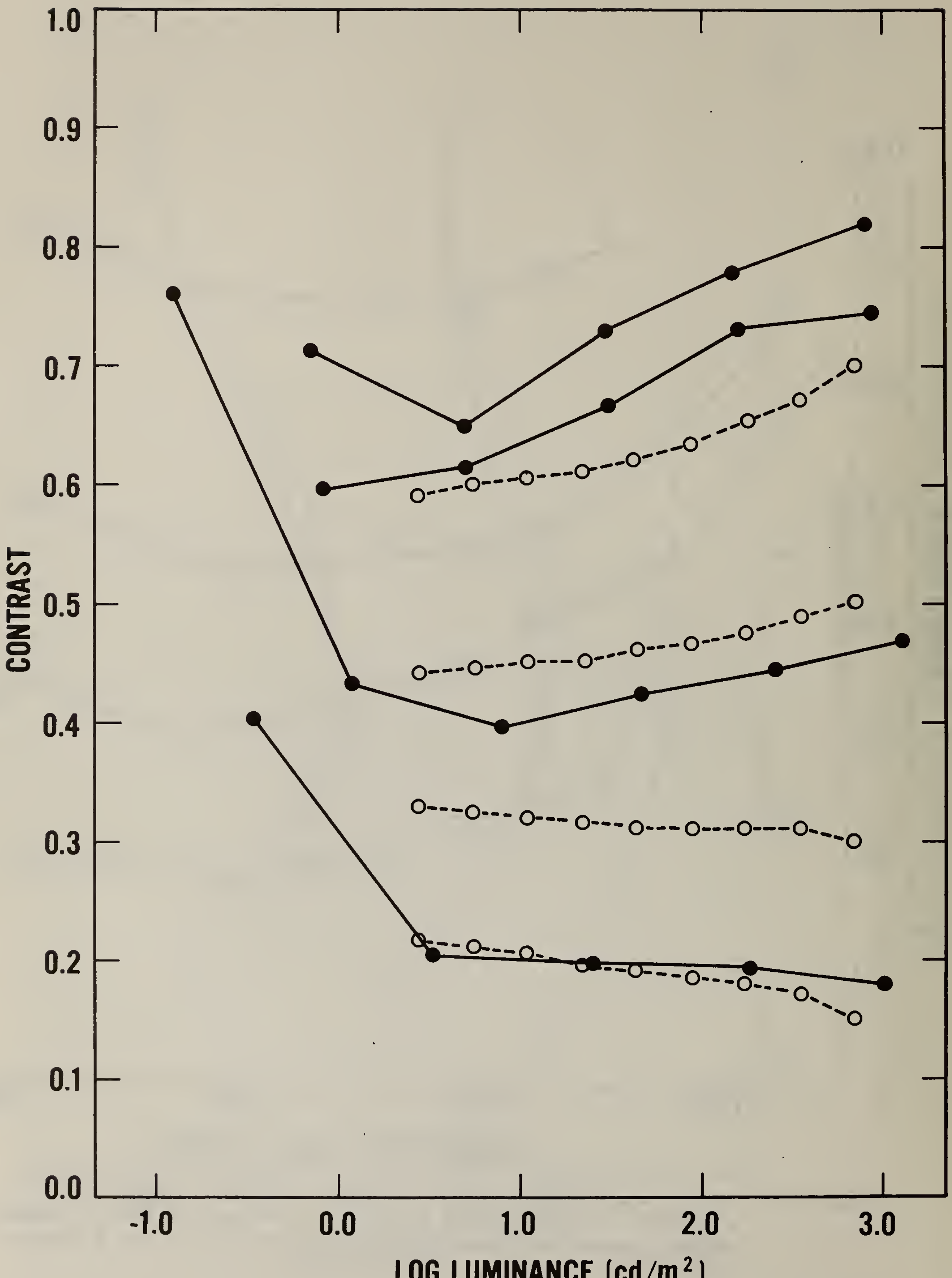


Figure 14. Comparison of equal conspicuity contours for five-bar[1] and square-wave grating[21] stimuli. Bar width is 6.0 and 7.7 min. of visual angle for five-bar and square-wave grating, respectively.

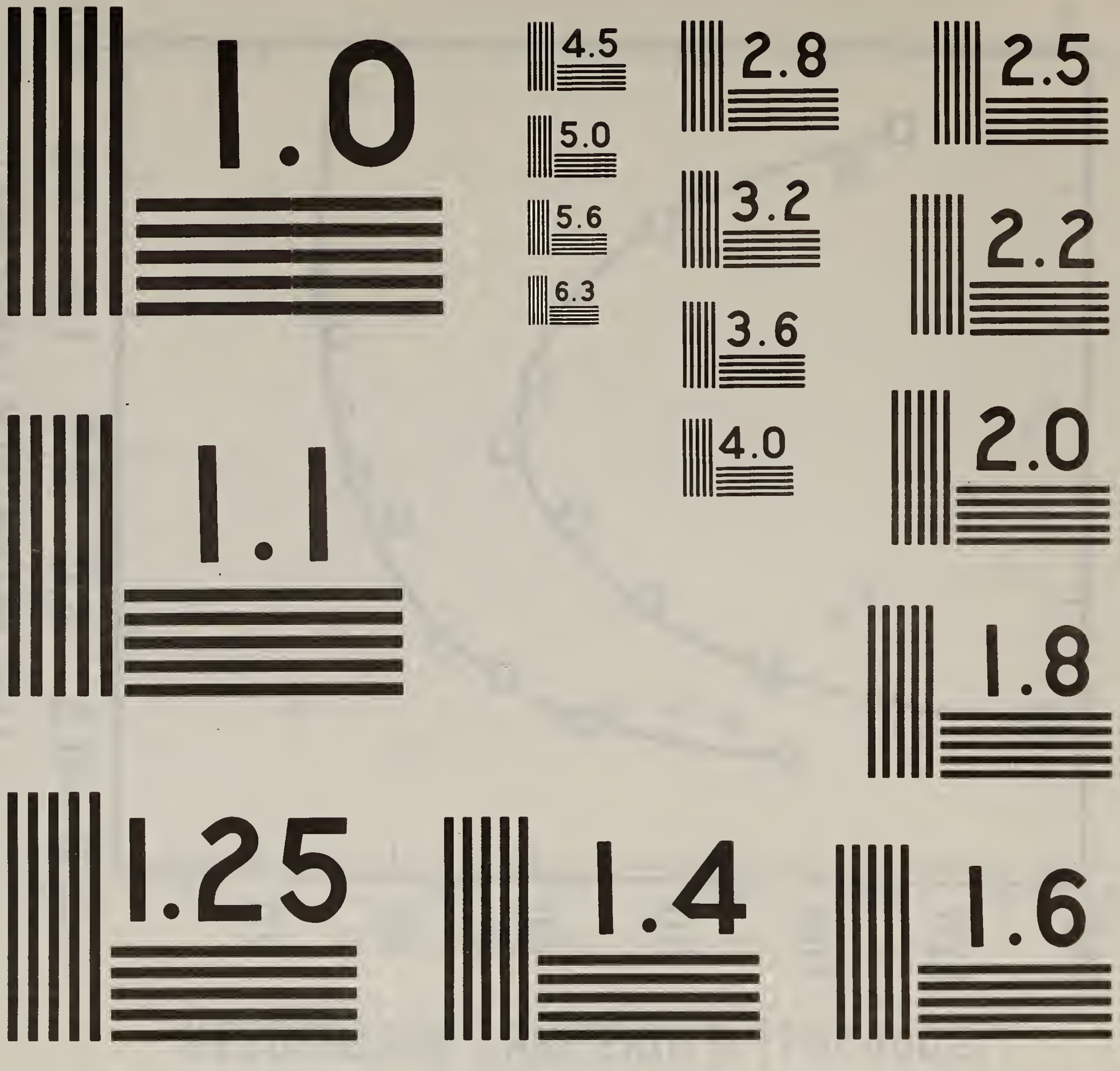


Figure 15. NBS Microcopy Test Chart.

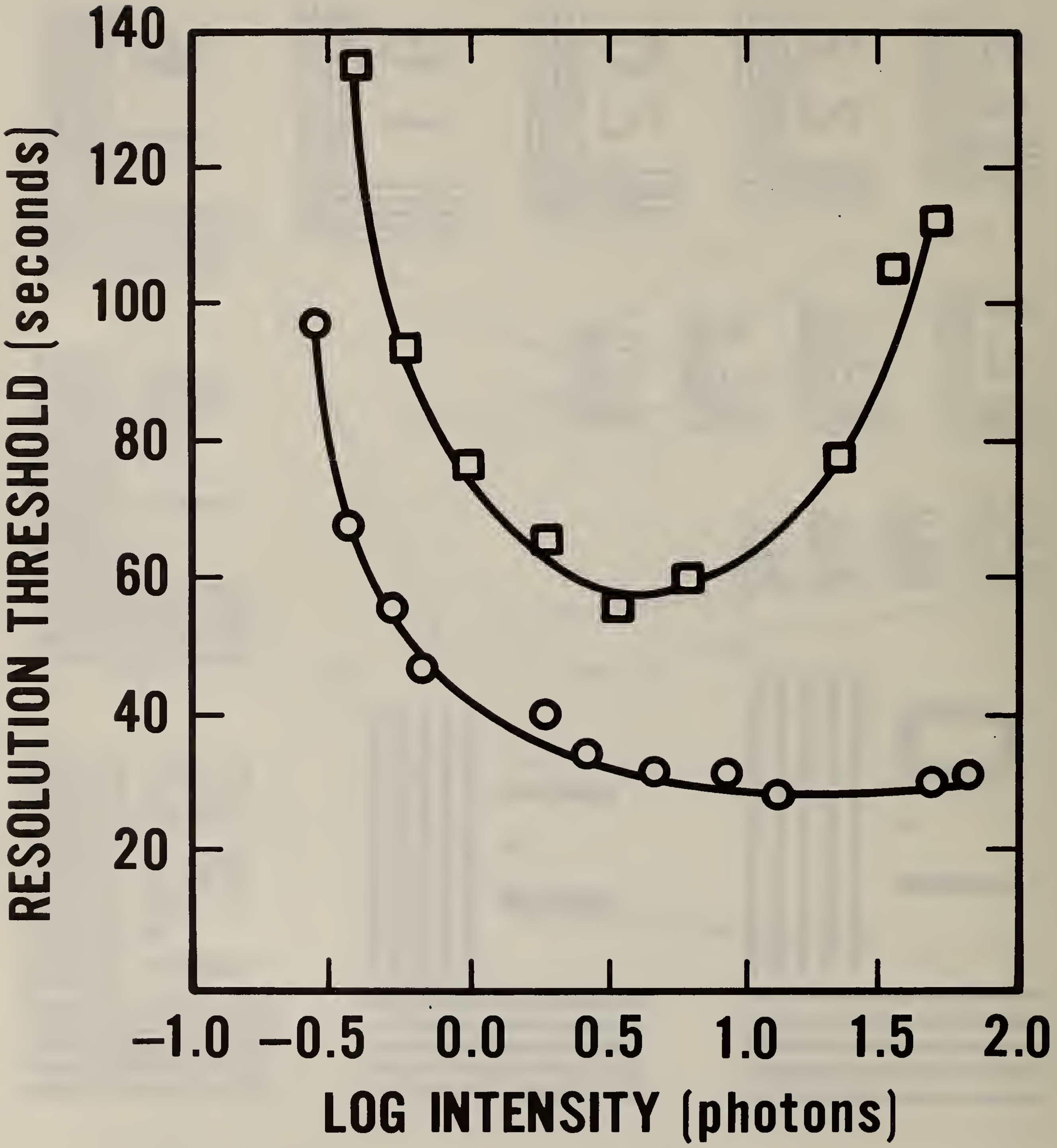


Figure 16. Resolution threshold for the separation of two parallel lines. Open circles are the results for the separation of two dark bars on a lighter background. Open squares are the resolution threshold for the separation of two light bars on a darker background. Adapted from Wilcox[25].

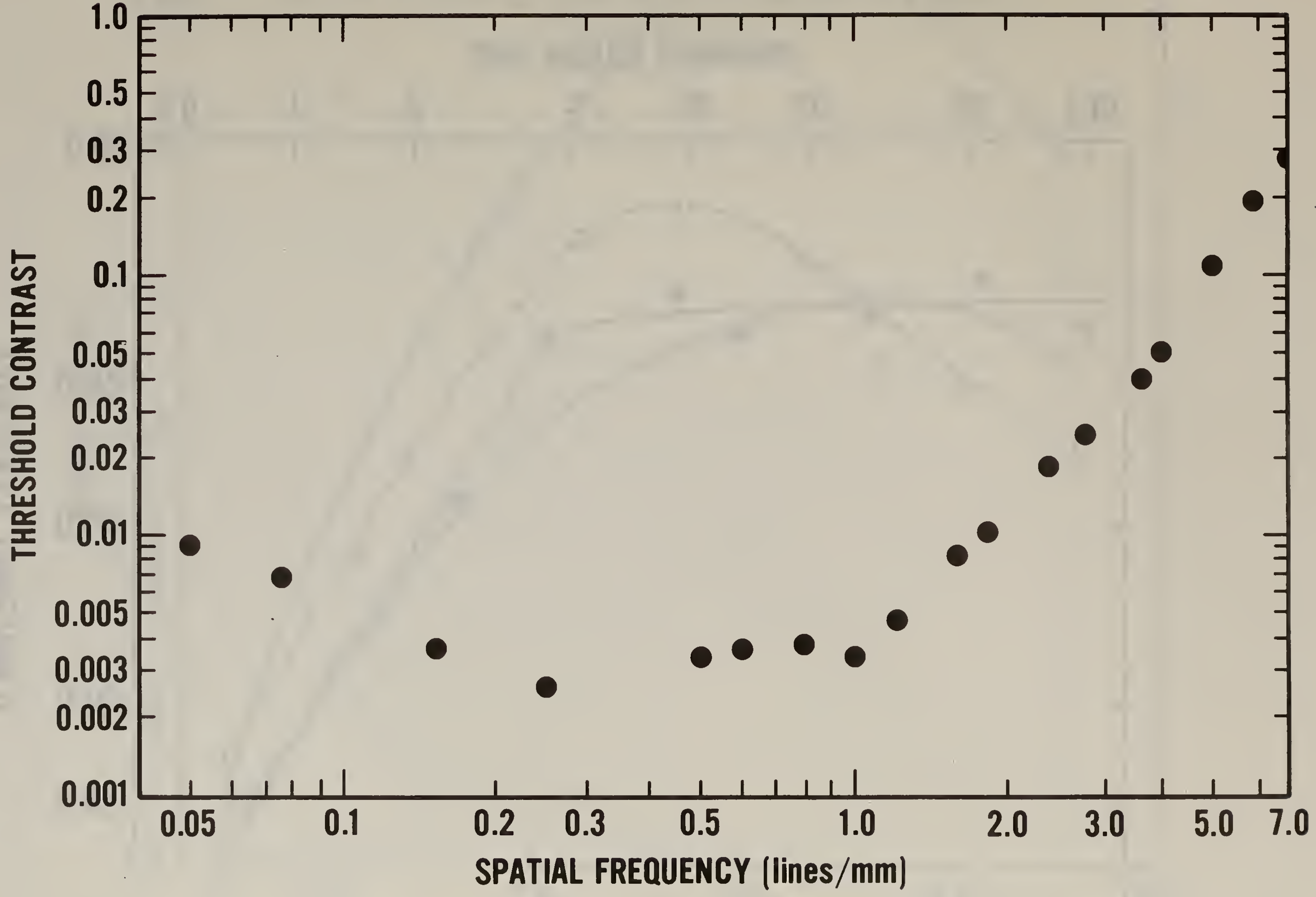


Figure 17. Threshold contrast for the resolution of sine-wave gratings as a function of spatial frequency. Adapted from De Palma and Lowry[26].

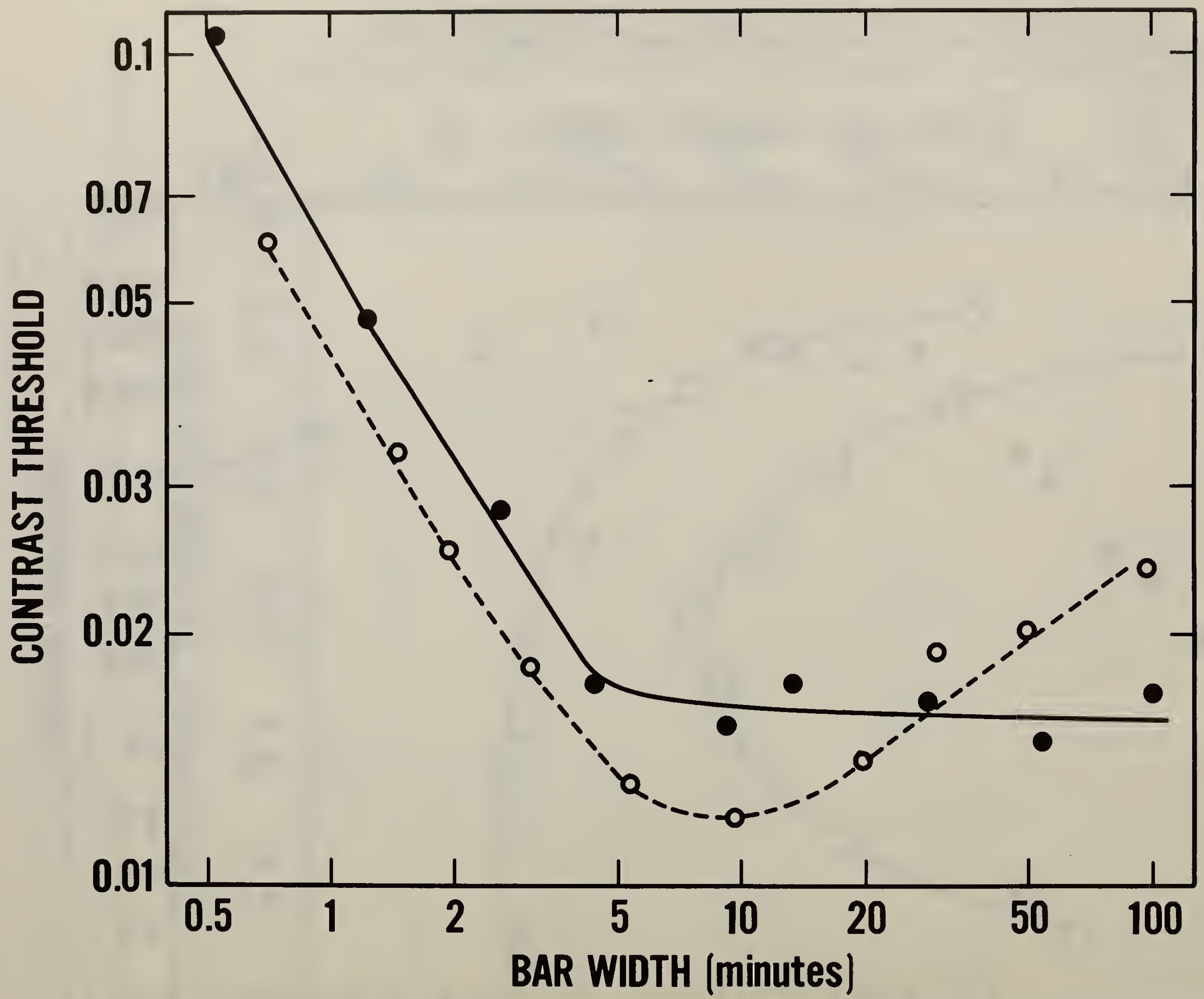


Figure 18. Contrast threshold for detection of a single line as a function of line width. The solid curve (solid lines) are the results for bright bar against a darker background and the dashed curve (open circles) is for a dark bar seen against a lighter background. Adapted from Fry[27].

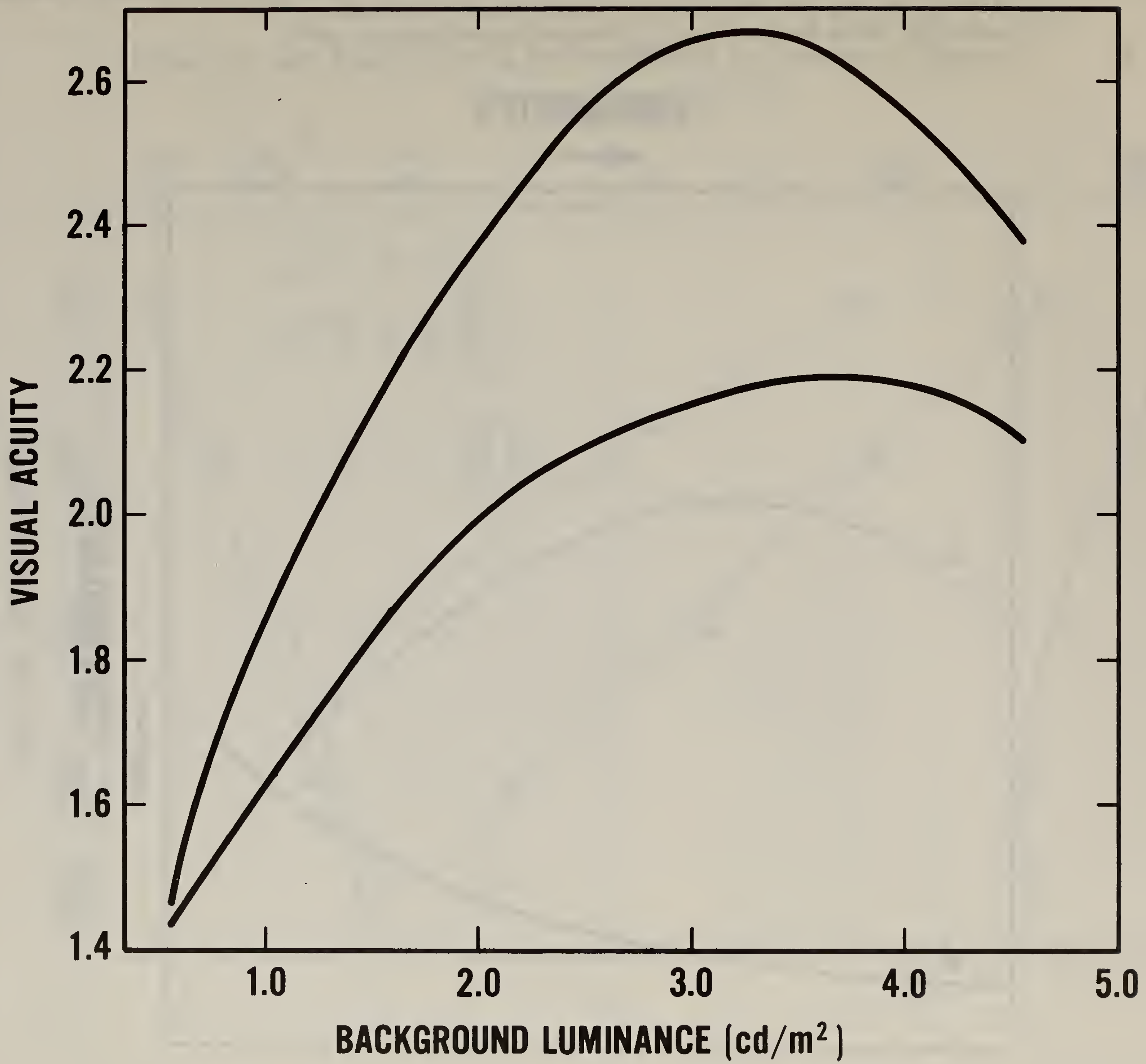


Figure 19. Visual acuity as a function of background luminance for a Landolt C target of high contrast. Adapted from Stevens and Foxell[28].

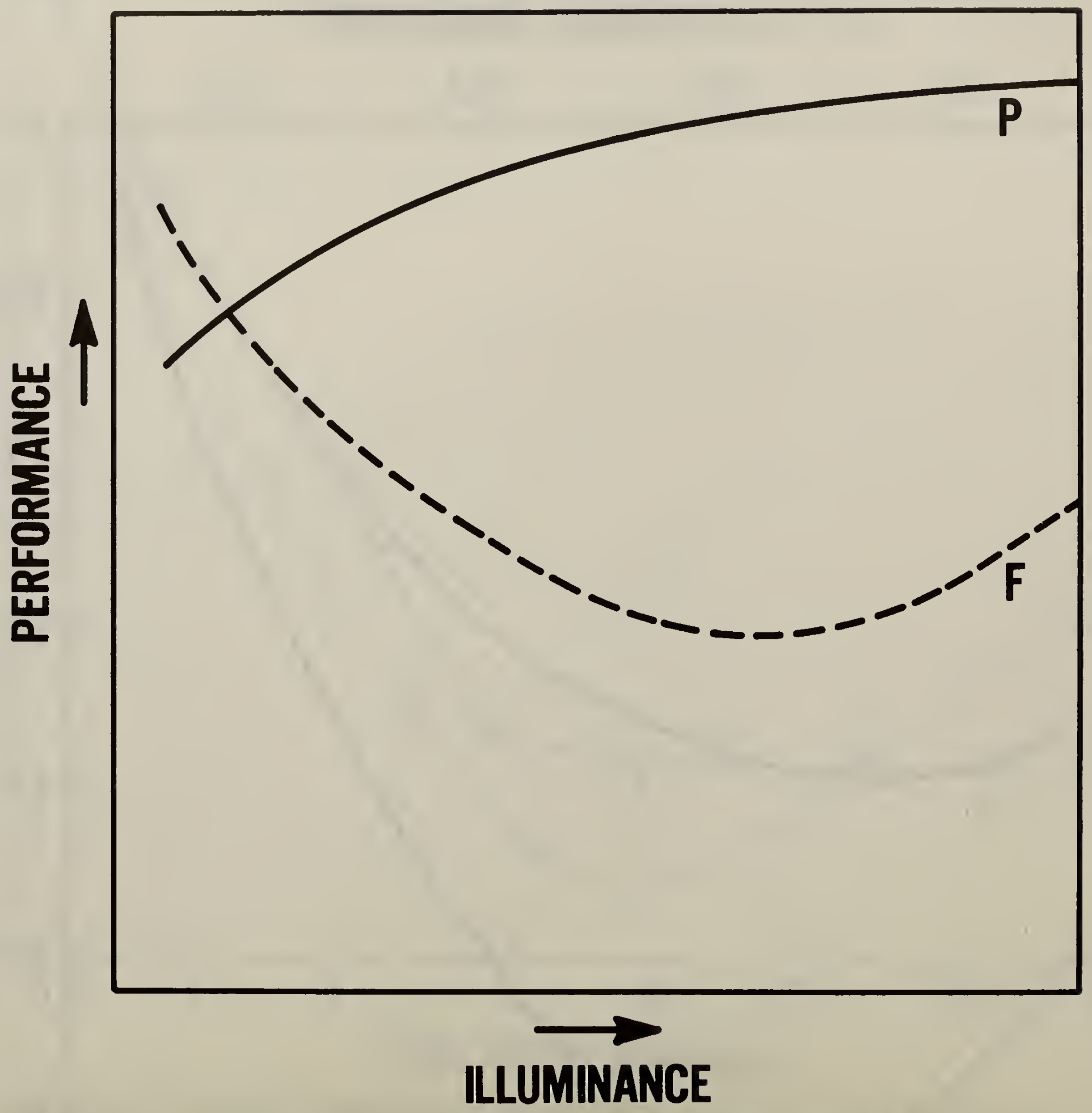


Figure 20. The general form of the performance vs illuminance function found by Khek and Krivolahvy[29]. The dashed curve (F) is when performance is evaluated as error rate, and the solid curve (P) is when time is the dependent variable.

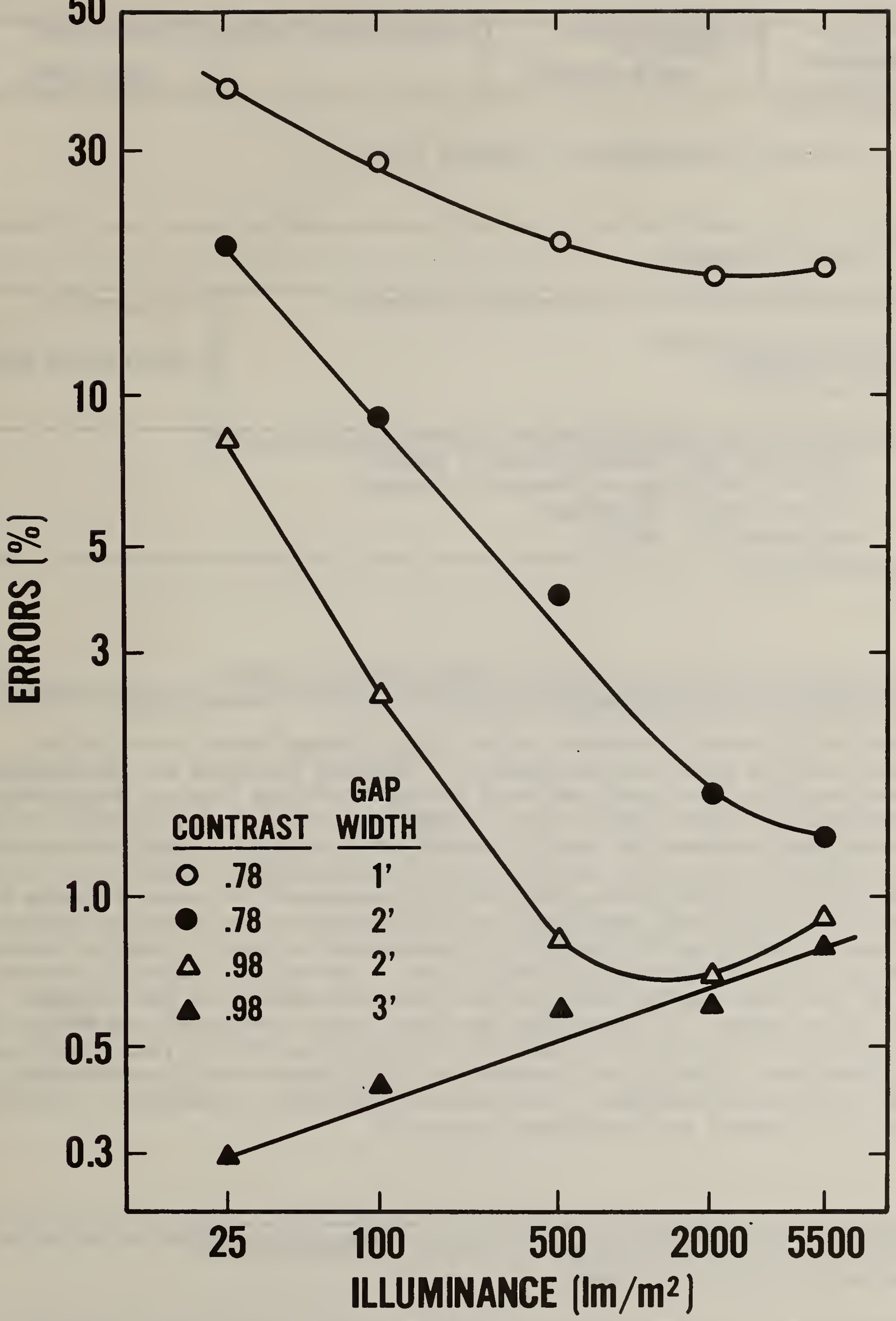


Figure 21. Percent error as a function of illuminance for continuous (100 min.) reading of Landolt C's. Adapted from Khek and Krivolahvy[29].

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The effect of lighting on behavior ranges from allowing simple detection of objects to creating moods and impressions. Lighting standards and recommendations for general applications should be based on the visibility (seeing) requirements where differences between individuals are minimal. Furthermore, lighting criteria or standards must evaluate the seeing process under stimulus conditions approximating those encountered in the real space. It is recommended that conspicuity, defined as: "how well the detail stands out from the background", or ease of seeing be the metric for visibility. Subjective visual response criteria cannot be universally applied where significant differences in interpretations and evaluations between individuals and/or groups of individuals occur. Instead they should be treated as design options to be applied when they are important apsects of the intended function of the space. In discussing the above issues, the paper identifies the major categories of variables included in the perception of the visual environment and organizes them logically with respect to their relationship in developing lighting criteria and standards. This analysis includes a breakdown of the visual processes into sensory and perceptual components.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*
Conspicuity; contrast; illumination; lighting; lighting levels; suprethreshold visibility; vision.

13. AVAILABILITY

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