http://www.nap.edu/catalog/916.html

We ship printed books within 1 business day; personal PDFs are available immediately.

Emergent Techniques for Assessment of Visual Performance

Committee on Vision, National Research Council

ISBN: 0-309-59166-X, 80 pages, 8.5 x 11, (1985)

This PDF is available from the National Academies Press at: http://www.nap.edu/catalog/916.html

Visit the National Academies Press online, the authoritative source for all books from the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council:

- Download hundreds of free books in PDF
- Read thousands of books online for free
- Explore our innovative research tools – try the "Research Dashboard" now!
- Sign up to be notified when new books are published
- Purchase printed books and selected PDF files

Thank you for downloading this PDF. If you have comments, questions or just want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, visit us online, or send an email to feedback@nap.edu.

This book plus thousands more are available at http://www.nap.edu.

Copyright © National Academy of Sciences. All rights reserved.
Unless otherwise indicated, all materials in this PDF File are copyrighted by the National Academy of Sciences. Distribution, posting, or copying is strictly prohibited without written permission of the National Academies Press. Request reprint permission for this book.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Emergent Techniques for Assessment of Visual Performance

Committee on Vision
Commission on Behavioral and Social Sciences and Education
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1985

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This work relates to Department of the Navy contract N00014-80-C-0159 issued by the Office of Naval Research under Contract Authority NR 201-124. However, the content does not necessarily reflect the position or the policy of the government, and no official endorsement should be inferred.

Available from: Committee on Vision, National Research Council, 2101 Constitution Avenue, Washington, D.C. 20418.

WORKING GROUP ON EMERGENT TECHNIQUES FOR ASSESSMENT OF VISUAL PERFORMANCE

IVAN BODIS-WOLLNER (Cochair), Department of Neurology, Mount Sinai Medical Center, New York (M.D., neurology)
LEWIS O. HARVEY (Cochair), Department of Psychology, University of Colorado (Ph.D., psychology)
JAMES P. COMERFORD, New England College of Optometry, Boston (O.D., Ph.D., optometry, psychophysics)
ANN B. FULTON, Department of Ophthalmology, Children's Hospital, Boston (M.D., ophthalmology)
ARTHUR P. GINSBURG, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio (Ph.D., psychophysics, engineering)
JAMES E. GOODSON, Naval Aerospace Medical Institute, Pensacola, Florida (Ph.D., physiological psychology)
FREDERICK KITTERLE, Department of Psychology, University of Toledo (Ph.D., psychology)
HERSCHEL W. LEIBOWITZ, Department of Psychology, Pennsylvania State University (Ph.D., psychology)
D. ALFRED OWENS, Department of Psychology, Franklin and Marshall College (Ph.D., psychology)
RANDOLPH BLAKE, Consultant

COMMITTEE ON VISION

ROBERT SEKULER (Chair), Departments of Psychology, Ophthalmology, and Neurobiology/Physiology, Northwestern University
ANTHONY J. ADAMS, School of Optometry, University of California, Berkeley
IRVING BIEDERMAN, Board of Studies in Psychology, University of California, Santa Cruz
RONALD E. CARR, New York University Medical Center
NIGEL DAW, Departments of Physiology and Biophysics, Washington University, St. Louis
SHELDON EBENHOLTZ, Department of Psychology, University of Wisconsin
DONALD A. FOX, College of Optometry, University of Houston
LLOYD KAUFMAN, Department of Psychology, New York University
JO ANN KINNEY, Surrey, Maine
DONALD G. PITTS, College of Optometry, University of Houston
WAYNE SHEBILSKE, Study Director
LLYN M. ELLISON, Administrative Secretary
GORA P. LERMA, Administrative Secretary

PREFACE

The Committee on Vision is a standing committee of the National Research Council's Commission on Behavioral and Social Sciences and Education. The committee provides analysis and advice on scientific issues and applied problems involving vision. It also attempts to stimulate the development of visual science and to provide a forum in which basic and applied scientists, engineers, and clinicians can interact. Working groups of the committee study questions that may involve engineering and equipment, physiological and physical optics, neurophysiology, psychophysics, perception, environmental effects on vision, and treatment of visual disorders.

In the past several years, the Committee on Vision has formed a number of working groups and sponsored symposia to consider guidelines for specifying the measurement of vision. The working groups have made recommendations on the testing of color vision, visual fields, and visual acuity; a recent symposium sponsored by the committee concentrated on clinical applications of visual psychophysics (Proenza et al., 1981). In contrast to these studies of accepted practices, this report focuses on emerging techniques that could help determine whether people have the vision necessary to do their jobs. Its purpose is to examine some of these emerging techniques, to point out their usefulness in predicting performance on other visual and visual-motor tasks, and to make recommendations for future research.

The members of the working group were chosen for their expertise in vision research, and the report reflects their evaluation of which techniques are important and worthy of wider appreciation and application in the screening of vision and visual performance. They did not consider the appropriateness of these new methods for medical diagnosis or for clinical evaluation.

Funds for this study were provided from the general budget of the Committee on Vision, which is sponsored by the U.S. Army, Navy and Air Force, the National Institute on Aging, the National Institute of Handicapped Research, the National Science Foundation, the Office of Special Education, the Veterans Administration, and from the American Academy of Ophthalmology and the American Optometric Association.

The committee gratefully acknowledges the efforts of those who worked on the report. Randolph Blake, of Northwestern University, made a major contribution to this study by reviewing all the materials that had been

prepared and writing a paper that provided a framework for the report. The final report was prepared by Lewis Harvey and Ivan Bodis-Wollner. Key Dismukes played an important role as study director in the early stages of the study. Production of the report was effectively assisted by Llyn Ellison and Gora Lerma of the committee staff.

Robert Sekuler, Chair
Committee on Vision

CONTENTS

EMERGENT TECHNIQUES FOR ASSESSMENT OF VISUAL PERFORMANCE

INTRODUCTION

Recent vision research has led to the emergence of new techniques that offer exciting potential for a more complete assessment of vision in clinical, industrial, and military settings. Four areas of vision testing are examined in this report; the working group believes that each area offers potential for improved assessment of visual capability:

(1) Contrast sensitivity function;
(2) Dark-focus of accommodation;
(3) Dynamic visual acuity and dynamic depth tracking; and
(4) Ambient and focal vision.

Each of these topics is discussed in a separate section of the report; each section focuses on issues related to screening industrial and military visual functions. The report concludes with summary recommendations for research that will have great value and impact 5 or 10 years from now. The report is followed by four appendixes that give additional information and detail on spatial contrast sensitivity, detection sensitivity and response bias, Fourier analysis, and the use of tests for screening and selection.

The content and conclusions of this report have serious policy implications for screening industrial and military visual function. For instance, it may eventually be possible to use the techniques described to identify subjects who are exceptionally good at certain visual performance tasks and, conversely, to screen for deficiencies not detected by current procedures. Adoption of new screening procedures would entail policy issues because of the potential shift in standards for personel. Similarly, if new techniques for assessment of visual impairment came into standard clinical use, policy for the provision of social services might eventually be affected. Although we appreciate this fact, we have not recommended any policy changes. We believe that policy recommendations should be left to groups more appropriately constituted to make them. Our role has been to point out the value of using these new methods. We believe that, if the proper research is carried out in these areas, we will avoid the mistake of adopting testing methods or standards that are arbitrary or not soundly based on basic research .

CONTRAST SENSITIVITY FUNCTION

BACKGROUND

The most widely used measure of visual resolution is visual acuity. It is used both for clinical diagnosis and evaluation and for legal screening and selection. (See the report of another working group, National Research Council 1980, for a discussion of methods and standards for the measurement of visual acuity.) Acuity is based on the size of the smallest detail in a visual target (optotype) that permits some criterion level of identification or detection performance (75 percent correct, for example). The smaller the size of this critical detail, the better the vision of the observer. The value of visual acuity measurements is well proven for correcting refractive errors. Under some conditions, however, individual variation in standard measurements of visual acuity often is not able to predict individual variation in performance on some visual tasks, such as target detection and identification (Ginsburg, 1983; Ginsburg et al., 1982, 1983).

A considerable body of empirical knowledge has been gained about the stimulus factors, such as size, exposure duration, contrast, and adaptation level, that influence detection of simple disk-shaped targets (Graham and Margaria, 1935; Lukiesch and Moss, 1940; Blackwell, 1946). Although these data in some circumstances do quite well in predicting detection of more complex targets, they often are inadequate in predicting recognition and identification of these targets. In addition, individual differences in performance with simple targets are not easily related to any measured characteristics of vision, nor were they related via any satisfactory theoretical framework.

In the past two decades, a new method of assessing vision has emerged that may provide a universal language. This method is the measurement of the contrast sensitivity function and, for some purposes (described below), it complements visual acuity. The first study that demonstrated the power of contrast sensitivity to supplement acuity measures employed low contrast Landolt C target (Hecht et al., 1949). Today, however, the contrast sensitivity function is typically measured using sinusoidal grating patterns as targets. This use of sine wave gratings was first introduced in vision by Schade (1956) and was subsequently used by early investigators to measure basic visual sensitivity (Westheimer, 1960; DePalma and Lowry, 1962; Campbell and Robson, 1968).

Sinusoidal gratings vary in frequency, contrast, and phase. In Figure 1 the left side shows such a grating pattern, and the right side shows the sinusoidal variation in luminance across space. The number of light-dark cycles of the grating that subtend 1 deg visual angle is a measure of the spatial frequency of the grating, expressed in cycles per degree (cpd). The human visual system is able to detect spatial frequencies up to about 60 cpd. There is no lower limit, but gener ally measurements are not made below about 0.1 cpd, often because of practical limits of display size. Borrowing the term octave (a doubling of frequency) from audition, the range of spatial frequencies usually measured by the contrast sensitivity function is about 10 octaves. A low spatial frequency consists of broad black and white bands; a high spatial frequency grating has thin black and white bands. Spatial frequency is therefore related to the size of conventional objects. When viewing distance and slant are held constant, higher spatia frequencies correspond to smaller objects.

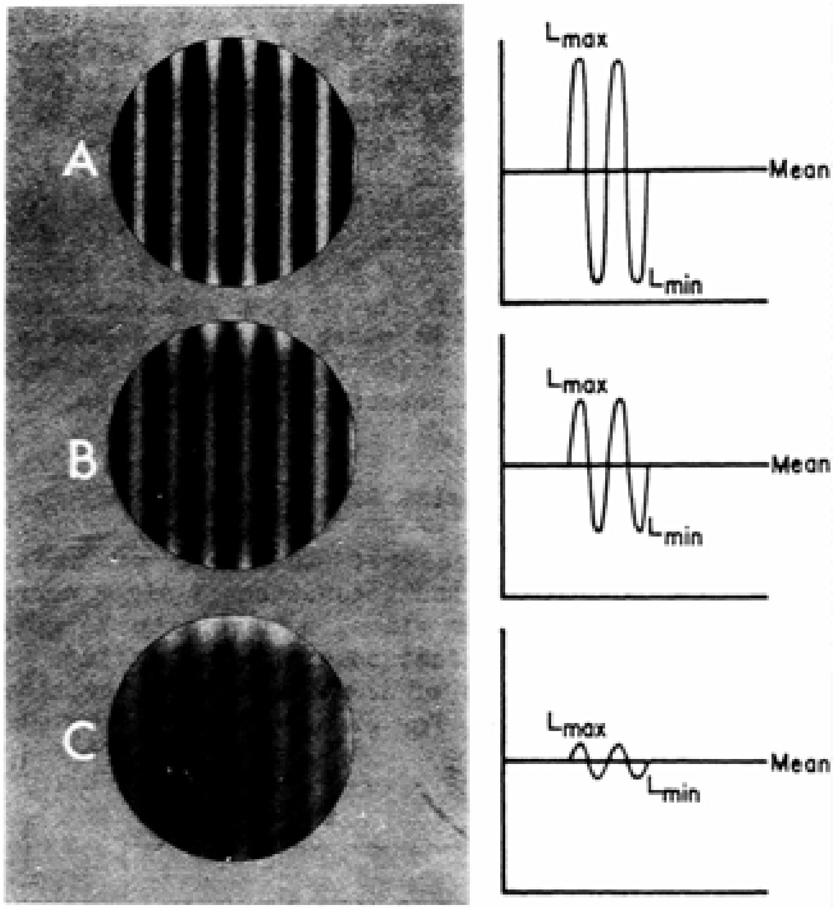


FIGURE 1 Photographs (left) and horizontal luminance profiles (right) of vertical sinusoidal grating patterns, electronically generated at three levels of contrast. The contrasts of the gratings were 0.85 (A), 0.50 (B), and 0.10 (C).
SOURCE: Photographs taken from transparencies provided by Michael Miller, Department of Neurology, Mount Sinai School of Medicine, and Wolkstein et al., 1980. Reprinted with permission from I. Bodis-Wollner. Copyright 1980 by J. B. Lippincott Company.

The contrast of a sinusoidal grating is based on the maximum luminance (L_{max}) and the minimum luminance (L_{min}) in the grating (see Appendix A). It is a dimensionless variable having values ranging from 0.0 (a uniform field) to 1.0, the maximum possible. The phase of a grating measures its position in space relative to some predetermined reference point.

The minimum contrast at which a grating can be distinguished from a uniform field with some fixed level of accuracy is the contrast threshold. The reciprocal of threshold contrast is called contrast sensitivity. The contrast sensitivity function is obtained by measuring contrast thresholds over a range of spatial frequencies. A typical photopic contrast sensitivity function is shown in Figure 2. What is important about the contrast sensitivity function seen in Figure 2 is that there is a range of spatial frequencies around 2 to 5 cpd where sensitivity is maximum. Sensitivity falls off for lower spatial frequencies and rapidly falls off for higher spatial frequencies. Eventually a high spatial frequency is reached that requires a contrast of 1.0 to detect (the high frequency cutoff). Spatial frequencies higher than this cutoff frequency cannot be detected by an observer.

Relationship Between Acuity and Contrast Sensitivity

Visual acuity, because it is measured in terms of the smallest identifiable, high-contrast target, and because small sizes correspond to high spatial frequencies, measures visual sensitivity largely in the higher frequency regions of the contrast sensitivity function. In brief, visual acuity is measured in terms of the size of the critical detail (stroke width of the Snellen letter, for example), but this feature is

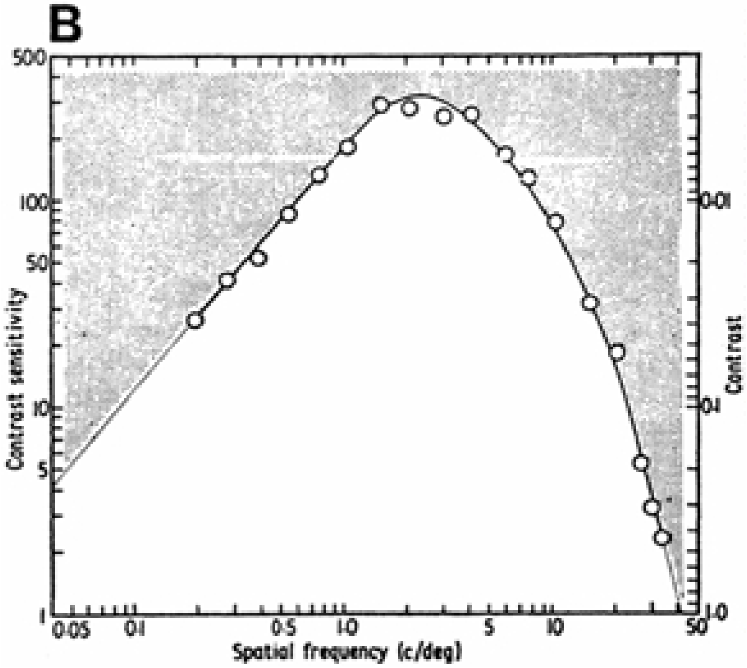


FIGURE 2 Photopic contrast sensitivity function of the human visual system for sinusoidal gratings. Both coordinates are logarithmic.

SOURCE: Campbell and Robson, 1968. Reprinted with permission from F. W. Campbell and J. G. Robson. Copyright 1968 by The Physiological Society.

not the only important one. Snellen acuity letters corresponding to acuity of 1.0 have a height of 5 min arc. The spatial frequencies necessary (but not sufficient) for correct identification after detection of these small letters fall in the approximate range from 18 to 30 cpd (Ginsburg, 1981a). This range of critical spatial frequencies necessary for identification of letters at a visual acuity of 1.0 is shown with the contrast sensitivity function in Figure 3. Does the measurement of sensitivity within this range of spatial frequencies (as with visual acuity) adequately describe the rest of the contrast sensitivity function? Extensive psychophysical data that deal with abnormal contrast sensitivity and individual differences in contrast sensitivity functions, independence of contrast thresholds at different spatial frequencies, and masking and adaptation experiments lead us to conclude that the answer is no.

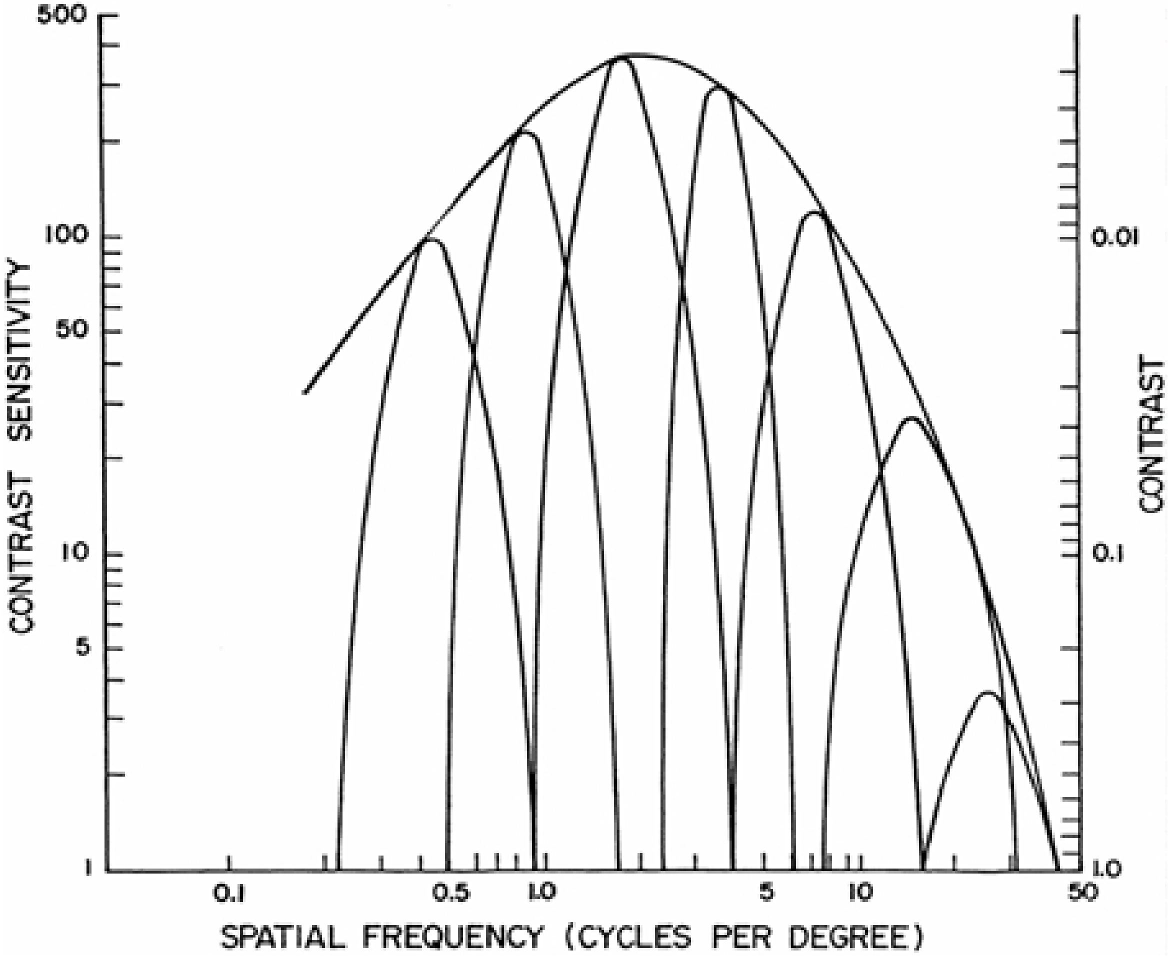


FIGURE 3 Photopic contrast sensitivity function showing the range of spatial frequencies necessary to achieve a visual acuity of 1.0 with Snellen letters.

SOURCE: Ginsburg, 1981a. Reprinted with permission from A. P. Ginsburg. Copyright 1981 by Cambridge University Press.

Visual acuity measurements, which are related primarily to high spatial frequency sensitivity, cannot predict contrast sensitivity to low spatial frequencies because thresholds of spatial frequencies separated by more than about a factor of 2 (one octave) are statistically independent of each other (Blakemore and Campbell, 1969; Graham and Nachmias, 1971; Sekuler et al., 1984). This independence of widely separated spatial frequencies is consistent with a model of the visual system containing separate mechanisms, each of which is selectively sensitive to a limited range of spatial frequencies (Campbell and Robson, 1968; Blakemore and Campbell, 1969; Graham and Nachmias, 1971; Stromeyer and Julesz, 1972; Ginsburg, 1984a). The contrast sensitivity function has the potential of adding more information about the functioning of the visual system than that given by visual acuity, because it assesses sensitivity over a wide range of spatial frequencies, while visual acuity measures primarily sensitivity at the high spatial frequencies. A primary source of evidence showing that visual acuity measurements do not characterize the whole contrast sensitivity function comes from clinical studies of people having abnormal visual function. People with identical high spatial frequency sensitivity may have very different low spatial frequency sensitivity (Bodis-Wollner, 1972; Bodis-Wollner and Diamond, 1976; Regan et al., 1981). The clinical applications of contrast sensitivity function are summarized in Proenza et al. (1981).

This dissociation between visual acuity and the contrast sensitivity function was first established in patients with cerebral lesions who, although they had visual acuity of 0.5 or better, complained of blurred vision. The contrast sensitivity functions of these patients are shown in Figure 4. A convenient way to illustrate the changes of sensitivity seen in Figure 4 is by plotting deviations from the “normal” contrast sensitivity, as shown in Figure 5. In the upper part of Figure 5 are two contrast sensitivity functions: one for normal observers and one from a patient complaining of reduced vision. The contrast sensitivity function of this patient shows that sensitivity is reduced at all spatial frequencies. The difference between the normal sensitivity curve and that of the patient is plotted in the lower part of Figure 5.

This plot of the difference (on a logarithmic scale) between the normal sensitivity and that obtained for an individual is called a visuogram (see Lundh and Arlinger, 1984, for a discussion of three different ways to construct a visuogram). A visuogram is the visual equivalent of an audiogram, used by audiologists and otologists to illustrate deviations from normal auditory sensitivity at different frequencies. The audiogram has proved valuable in identifying different types of deafness and in making diagnoses about their causes (Davis and Silverman, 1960). Perhaps this same value will be realized in vision once a large enough demographic data base for the contrast sensitivity function becomes available.

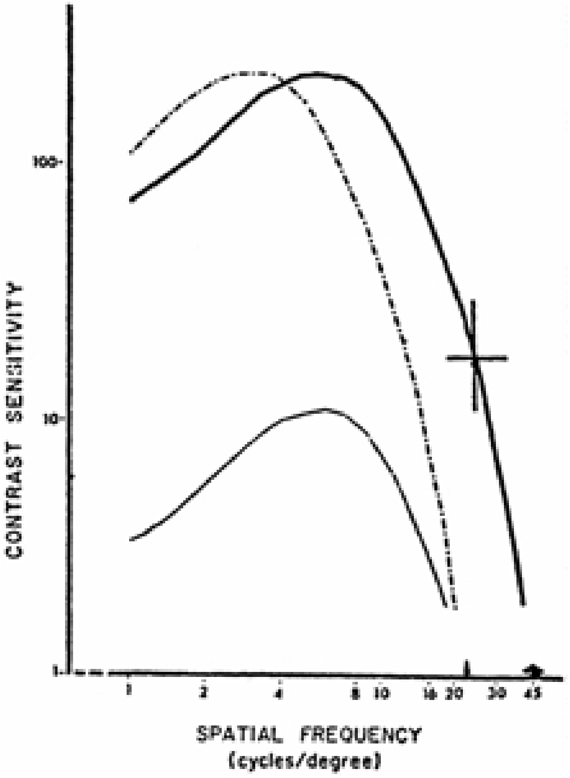


FIGURE 4 The normal contrast sensitivity function, shown with heavy lines, based on data from 10 observers. The two other curves represent patients having the same visual acuity, but vastly different contrast sensitivity functions. SOURCE: Bodis-Wollner and Diamond, 1976. Reprinted with permission from I. Bodis-Wollner. Copyright 1976 by Oxford University Press.

Pathophysiological studies of contrast sensitivity function reveal that loss of sensitivity can occur at all spatial frequencies or at only restricted bands of spatial frequencies (e.g., Bodis-Wollner and Diamond, 1976; Proenza et al., 1981). The major point to be taken from these data is that identical visual acuity may be found in people with different contrast sensitivity and that a single measure, such as visual acuity, cannot predict sensitivity at other sizes or spatial frequencies. This dissociation between visual acuity and contrast sensitivity has been found in patients; but what about people with "normal" vision?

Figure 6 illustrates three different contrast sensitivity functions from three Air Force pilots having visual acuities of 1.33, 1.00, and 0.80. The visual acuities of the pilots are predicted from the contrast sensitivity in the high spatial frequency range. The higher the high frequency sensitivity, the higher the visual acuity. Note the wide variations in low and high frequency sensitivity, and that a low sensitivity at high frequencies does not necessarily imply a low sensitivity at low spatial frequencies.

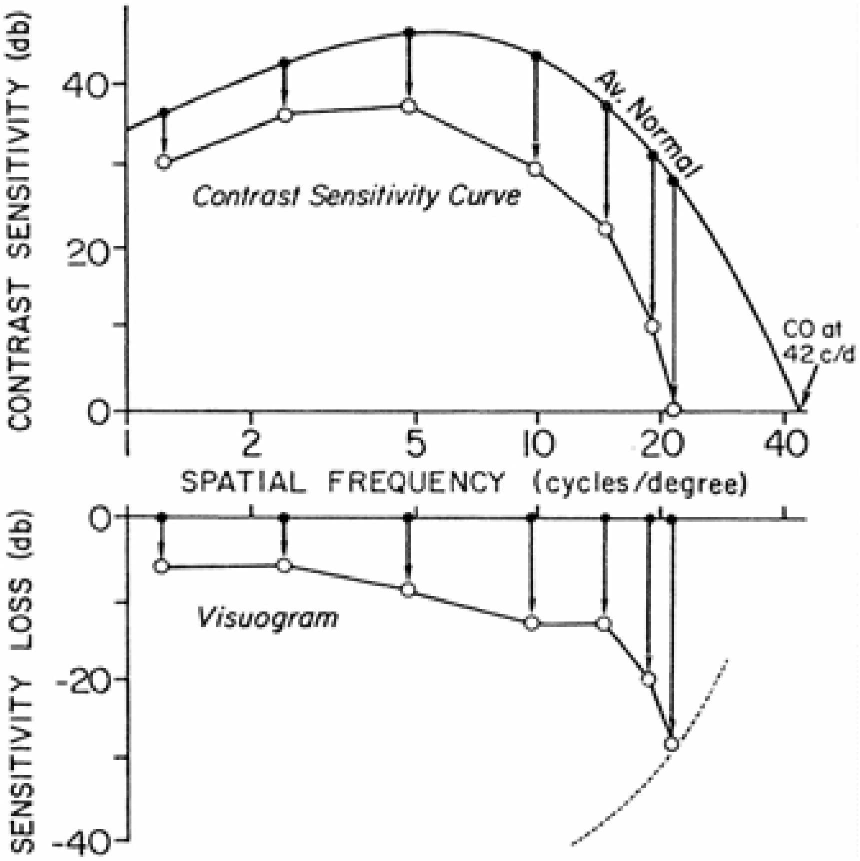


FIGURE 5 Contrast sensitivity function (top) and visuogram (bottom). The upper plot shows two contrast sensitivity functions: the average contrast sensitivity functions of normal subjects with acuity of 1.0 (smooth curve), and a contrast sensitivity of a patient with visual defects (open circles). Contrast sensitivity (ordinate of upper plot) is specified on a logarithmic scale in decibels. The lower plot is a visuogram. It shows the contrast sensitivity deficit (downward arrow) at each of the tested spatial frequencies for the patient whose contrast sensitivity is given above. A loss of 6 db signifies a twofold reduction of contrast sensitivity; a loss of 20 db signifies a tenfold reduction. The spatial frequency scale (abscissa) of the visuogram is the same as that of the contrast sensitivity function above it.

SOURCE: Wolkstein et al., 1980. Reprinted with permission from I. Bodis-Wollner. Copyright 1980 by J. B. Lippincott Company.

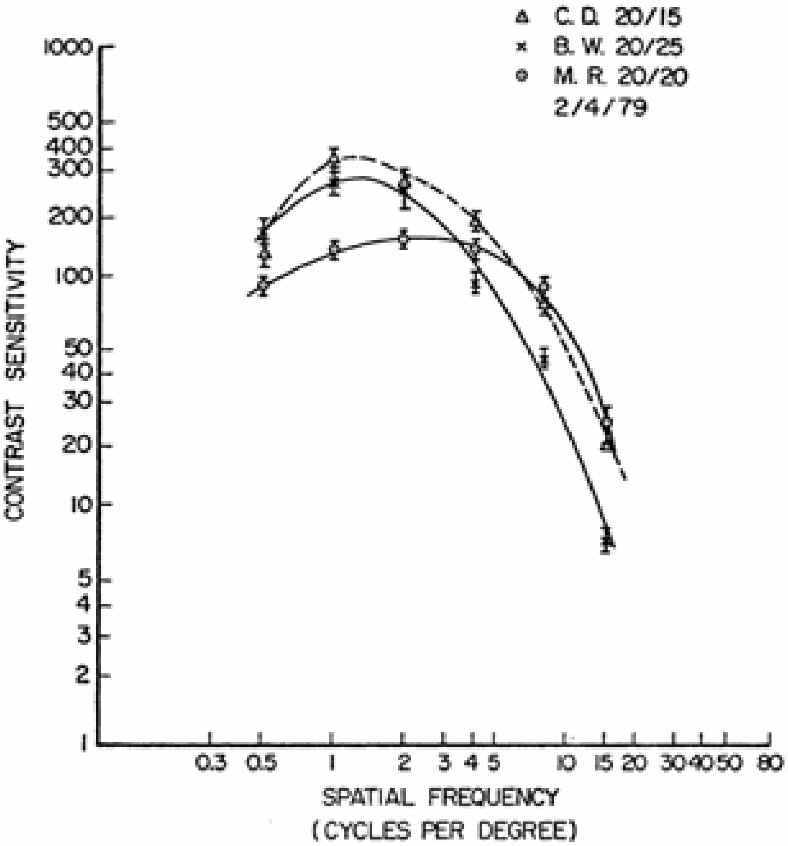


FIGURE 6 The contrast sensitivity function of three pilots having visual acuities of 1.33, 1.00, and 0.80. Note the variation of sensitivity below 7 cpd.

SOURCE: Ginsburg, 1981b. Reprinted with permission from A. P. Ginsburg. Copyright 1981 by the Air Force Aerospace Medical Research Laboratory.

Visual Acuity and Contrast Sensitivity Function in Normal Vision

While visual acuity cannot predict the spatial contrast sensitivity function in people with abnormal vision, visual acuity also cannot predict contrast sensitivity in people with assumed normal vision. There are individual differences in contrast sensitivity as well as changes in the contrast sensitivity function with age (Ginsburg, 1981a, 1984b; Ginsburg et al., 1984; Owsley et al., 1983). These findings raise important questions: Does an observer with 1.33 acuity have a correspondingly higher contrast sensitivity function than one having acuity of 1.0? Or does the first have a slightly wider contrast sensitivity function? Is it better to have a higher peak contrast sensitivity function or a broader one for performing various visual tasks? There is some experimental evidence that under some conditions peak contrast sensitivity may be more important than visual acuity for predicting detection and identification of objects (Ginsburg, 1981b).

Contrast sensitivity functions are measured with sinusoidal grating patterns. Although contrast sensitivity functions could be measured with a wide assortment of targets differing systematically in size and contrast, the human visual system seems to be especially sensitive to sinusoidal targets (Guth and McNelis, 1969; Watson et al., 1983; Ginsburg, 1984b). These sinusiodal gratings have important mathematical properties (see Appendix A and Appendix C) that allow the application of linear systems analysis to the human visual system. This approach allows both the visual stimulus and the visual system to be described with the same language: that of sinusoidal spatial frequencies. The visual system is not completely linear, however, and there may be other types of visual targets (low contrast letter optotypes, for example) that may be particularly effective in detecting certain types of visual defects (Regan and Neima, 1983, 1984). The working group does not wish to preclude the use of other types of visual targets if their utility can be demonstrated.

Contrast Sensitivity Function and Visual Performance

Because the image of any object can be described as a set of spatial frequencies at various orientations, amplitudes, and phases (see Appendix C), there is the potential that an observers contrast sensitivity function can be used to predict visual performance with more complex visual material. The working group evaluated the evidence that the contrast sensitivity function can predict visual performance with complex stimuli and found that considerably more research in this area is needed. If the potential of these early experiments is verified by further studies, we believe that we will have a powerful way of studying individual differences in vision and accounting for some of the variability of individual performance on a wide variety of tasks that are primarily dependent on vision.

There is some experimental evidence suggesting that the contrast sensitivity function can predict certain types of visual performance better than other measures can. In one series of experiments, subjects were asked to judge the visual similarity between all possible pairs of random complex grating patterns. These studies found that the similarity judgments were accurately predicted by using the spatial frequency content of the gratings in conjunction with the human contrast sensitivity function (Harvey and Gervais, 1978, 1981; Gervais, 1978). In another study, subjects were required to identify letters of the alphabet 6 min arc high presented for 30 msec (Gervais, 1978; Gervais et al., 1984). The researchers tried several models of visual processing to predict the pattern of identification confusions found among all 26 letters of the alphabet. The model with the greatest predictive power was one based on the amplitude and phase information in the spatial frequency content of each letter filtered by the human contrast sensitivity function. Gervais et al. (1984) also provide a critical review of other studies that have failed to find an advantage in spatial frequency models.

The contrast sensitivity function of infants has been used to successfully predict the amount of time that infants spend looking at different types of visual stimuli. Prior to using contrast sensitivity measures, the best predictor of looking time was thought to be the amount of contour in the stimulus, the contour density (Karmel, 1969). One study demonstrated that when stimuli were equated for contour density, infants still preferred some stimuli over others. These preferences were predicted by the spatial frequency characteristics of the stimuli (Banks and Stephens, 1981). Another study showed that when the spatial frequency content of the stimulus patterns were combined with the infant's contrast sensitivity function, both the infant's looking preferences and looking times were better predicted than by the contour density measure (Gayl et al., 1983).

Finally, individual differences in contrast sensitivity functions may be the basis of individual differences in performance on complex tasks. Figure 7 shows the contrast sensitivity functions of three observers having visual acuities of 1.00, 0.66, and 0.40 (Ginsburg, 1981b). The two subjects with the acuity below 1.00 required optical correction but were tested without their glasses. These observers had their contrast thresholds measured for the detection and identification of both letters of the alphabet and airplanes of different angular size. The individual differences seen in the detection and identification of letters and planes were predictable from the relevant spatial frequencies of those targets required for detection and identification and the individual contrast sensitivity functions. Note in Figure 7 that the observer having the highest contrast sensitivity in the middle spatial frequencies also was best at the target detection and identification tasks, even though his visual acuity was not the best of the three. A second study of 11 Air Force pilots (Ginsburg et al., 1982) indicated that contrast sensitivity, not visual acuity, predicted simulated air-to-ground target detection. Visual acuity and contrast sensitivity functions were measured under high and low photopic levels of luminance. The correlations between the acuity measures and detection range was not statistically significant. There was a significant correlation (0.83, $p < 0.01$) between detection range and the peak sensitivity of the contrast sensitivity functions measured at low photopic levels. In a third study (Ginsburg et al., 1983), 84 Air Force pilots took part in field trials that required them to detect an approaching airplane from the ground; 10 sets of field trials were run under widely differing visibility conditions, with about 8 pilots participating in each set. An interesting pattern of correlations emerged between the distance of target detection and the contrast sensitivity at six different spatial frequencies. These correlations tended to be significant for frequencies greater than 8 cycles per degree under high visibility conditions. In contrast, the correlations tended to be significant at 8 cycles per degree and below under low visibility conditions. These results suggest that contrast sensitivity measurements taken over a range of spatial frequencies has potential for predicting detection performance under a variety of visibility conditions. Further studies are needed to determine the full potential for predicting this important kind of performance.

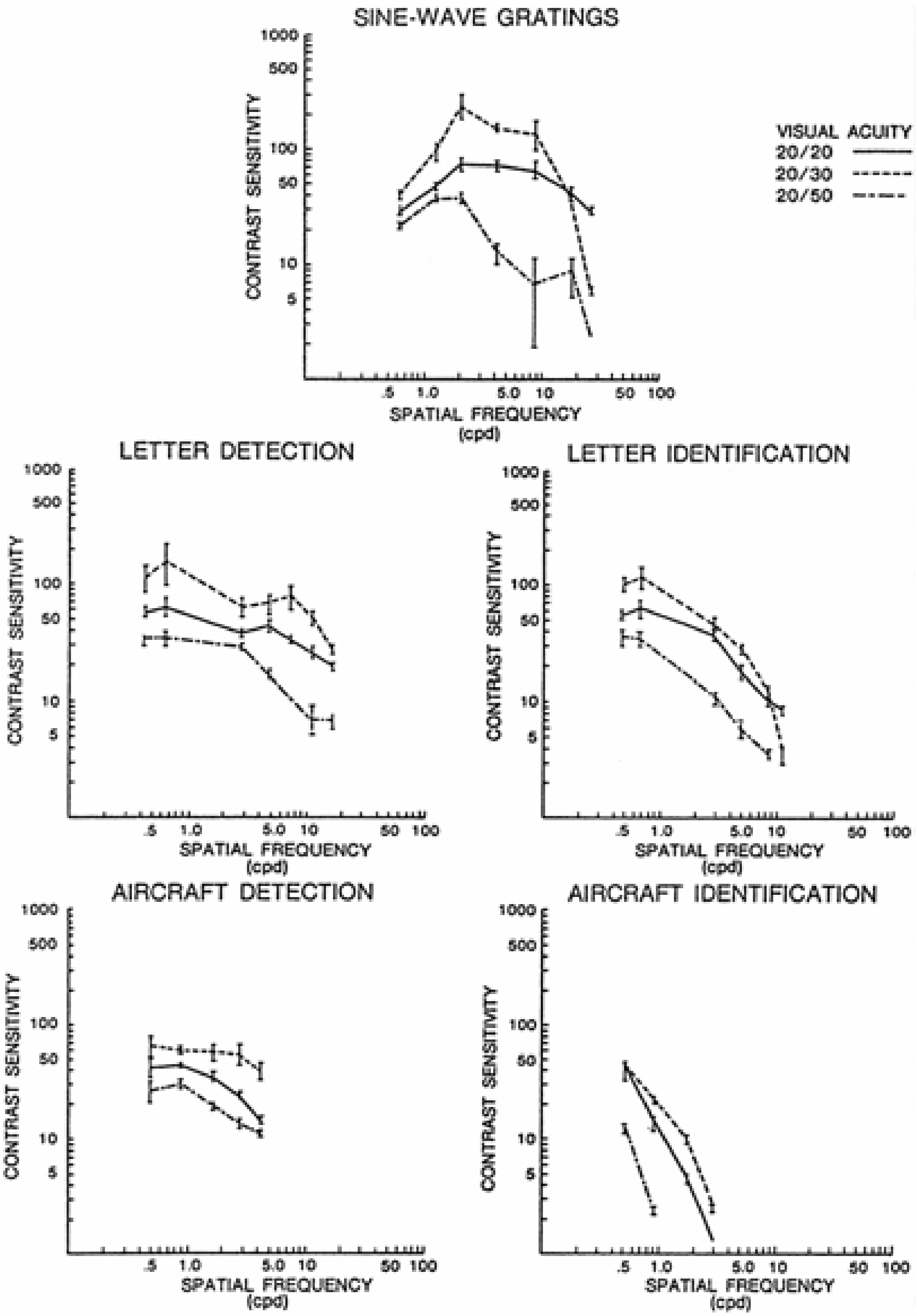


FIGURE 7 Contrast sensitivity to sine wave gratings, detecting and identifying letter and aircraft silhouettes for two subjects having 0.4 and 0.6 Snellen acuity without their glasses and one subject having uncorrected acuity of 1.0. SOURCE: Ginsburg, 1981b. Reprinted with permission from A.P. Ginsburg. Copyright 1981 by the Air Force Aerospace Medical Research Laboratory.

Suprathreshold Contrast Functions

The human visual system responds to suprathreshold grating patterns quite differently than it does to threshold patterns. Although the amount of contrast required for detection of gratings is heavily dependent on the spatial frequency of the grating, this dependency breaks down in the perception of apparent contrast of suprathreshold gratings (Georgeson and Sullivan, 1975; Cannon, 1979; Ginsburg et al., 1980). This effect, called contrast constancy, is found when subjects adjust the physical contrast of different frequency gratings in order to achieve the perception of equal apparent contrast. Particularly at high levels of physical contrast, the contrast required for constant apparent contrast is virtually independent of spatial frequency.

There also can be a dissociation between detection sensitivity and spatial frequency discrimination (Began et al., 1982). Following adaptation to a suprathreshold sine wave grating, although detection threshold is greatly elevated at the adaptation spatial frequency, discrimination threshold is unaffected. Discrimination threshold is maximally affected at a frequency about twice that of the adapting frequency (Regan and Beverley, 1983).

Studies using visual evoked potentials have also found a dissociation between the response to low contrast gratings and the response to high contrast gratings (Bodis-Wollner et al., 1979). We cite this evidence to point out that extrapolation from threshold measurements of contrast sensitivity to predictions of responses to suprathreshold patterns is theoretically and practically a complicated issue. This complication does not deter the working group from looking at the empirical evidence relating to the usefulness of the contrast sensitivity function in predicting visual processing of complex targets.

Sensitivity to Phase

The spatial phases of the sinusoidal components of complex patterns are as important as their amplitudes. There is growing evidence that the contrast sensitivity function does not capture all important individual differences, that phase sensitivity must be considered as well. The abnormal vision of some amblyopic patients is not well explained by changes in the contrast sensitivity function (Hess, 1984). These patients report perceptual distortions that seem like phase distortion effects when viewing sinusoidal gratings. The ability to discriminate between gratings containing two harmonically related spatial frequencies that differ only in their phase relationships is markedly reduced in the amblyopic eye.

The ability of the human observer to recognize or identify an object is remarkably robust to distortions of the spatial frequency amplitude spectrum of the object but not to a distortion of its phase. A small amount of phase distortion renders the picture unrecognizable. Sensitivity to phase distortions both in photographs of objects and in random checkerboard textures is relatively independent of spatial frequency (Caelli and Bevan, 1982).

CONCLUSIONS AND RECOMMENDATIONS

The working group concludes that the contrast sensitivity function offers potential for characterizing individual differences not captured by conventional high contrast visual acuity measures. We further conclude that the contrast sensitivity, possibly combined with some measure of phase sensitivity, offers potential for predicting real-world performance on tasks involving complex visual stimuli.

We therefore recommend that applied studies on the relationship between contrast sensitivity functions and visual task performance be carried out. We recommend at least two types of studies:

(1) The value of the contrast sensitivity function in predicting performance on complex visual tasks and in discriminating among individuals in their ability on these tasks needs to be further explored and
(2) The relationship between amplitude and phase information in the perception of simple and complex stimuli must be better understood.

DARK-FOCUS: ANOMALOUS REFRACTIVE ERRORS AND ACCOMMODATION

Predicting an individuals performance under adverse conditions poses an important challenge to vision research and assessment. Present techniques have proven to be invaluable for screening and optimizing visual performance under ideal stimulus conditions, such as reading high contrast text or distant signs in bright illumination. They often fall short, however, when visibility is reduced by low illumination or inclement weather. Individuals who have comparable visual capabilities under normal conditions can differ greatly under adverse viewing conditions. It is not uncommon, for example, to find two pilots who both have excellent visual acuity in the examining room, yet, at night or in a bright empty sky, one can consistently detect and identify targets faster than the other. Recent research on visual accommodation reveals one of the mechanisms responsible for individual differences in target detection and recognition, and it has led to the development of a new approach to predicting and to optimizing performance under low visibility conditions.

BACKGROUND

The major insight from this research can be summarized quite simply. Whenever visual stimulation is degraded, as it is at night or in bad weather, the eyes tend to adjust involuntarily for a distance determined by the individual's “resting” or “tonus” state. This resting focus, also referred to as the “dark-focus” and “tonic accommodation,” usually corresponds to an intermediate distance, but it varies widely across observers. Figure 8 shows the distribution of dark-focus values of 220 college students who were either emmetropic or were wearing their normal refractive corrections (Leibowitz and Owens, 1978). Individual dark-foci ranged from slight hyperopia (−0.25 diopters) to strong myopia (4.0 diopters), with an average value of 1.5 diopters, which corresponds to a focal distance of only 67 cm.

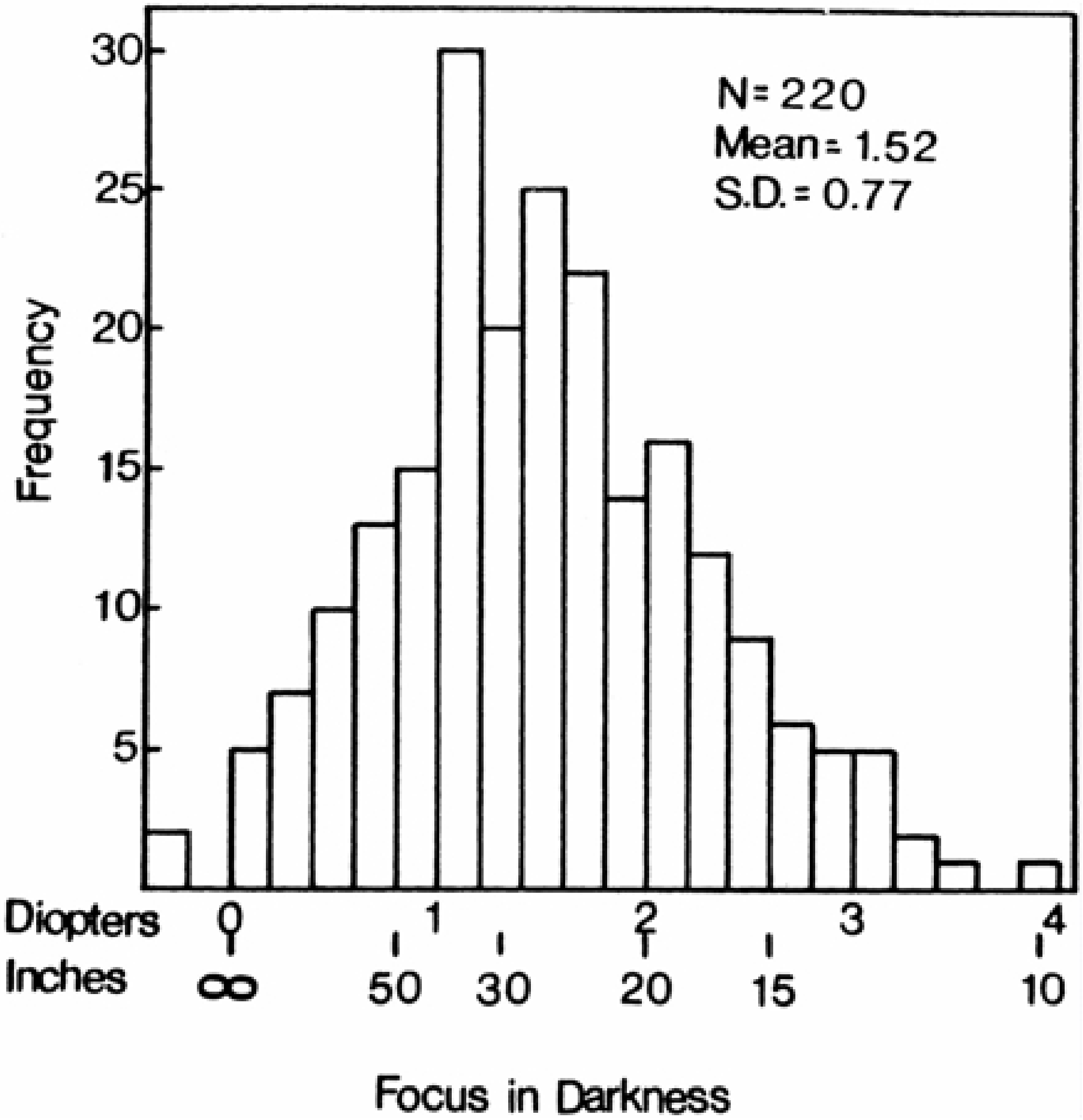


FIGURE 8 Distribution of dark-focus values of 220 college students. All measures were taken with a laser optometer in total darkness with the subjects' normal refractive correction in place.

SOURCE: Leibowitz and Owens, 1978. Reprinted with permission from H. W. Leibowitz. Copyright 1978 by Dr. W. Junk Publishers.

Low Visibility Conditions

As visibility of a stimulus is reduced, accommodation is progressively biased toward the individual's dark-focus. This phenomenon is illustrated in Figure 9 for a hypothetical subject whose dark-focus corresponds to 1.0 diopter. Note that the accuracy of accommodation depends on two factors: the quality of the stimulus and the subject's characteristic dark-focus. For strong stimuli, such as a bright acuity chart, accommodative responses are fairly accurate, producing a response function with a slope that approaches the ideal value of 1.0. With weaker stimuli, the eyes' focusing range gradually diminishes, producing response functions with progressively shallower slopes. With very weak stimulation, accommodation remains at the dark-focus regardless of stimulus distance (Johnson, 1976). Thus, the eyes become functionally “presbyopic” when stimulation is degraded; they become “myopic” for targets located beyond the dark-focus and “hyperopic” for targets nearer than the dark-focus, focusing accurately only for targets located at the same distance as their dark-focus.

A similar bias toward the dark-focus is observed when the eye's depth of focus is increased by reducing pupillary diameter (Hennessy et al., 1976). In this case, the loss of accommodative responsiveness presumably results from “opening the loop” of the accommodation control system rather than from degrading the visual stimulus. Thus, whenever variations of the eye's focus have no appreciable effect on the quality of the

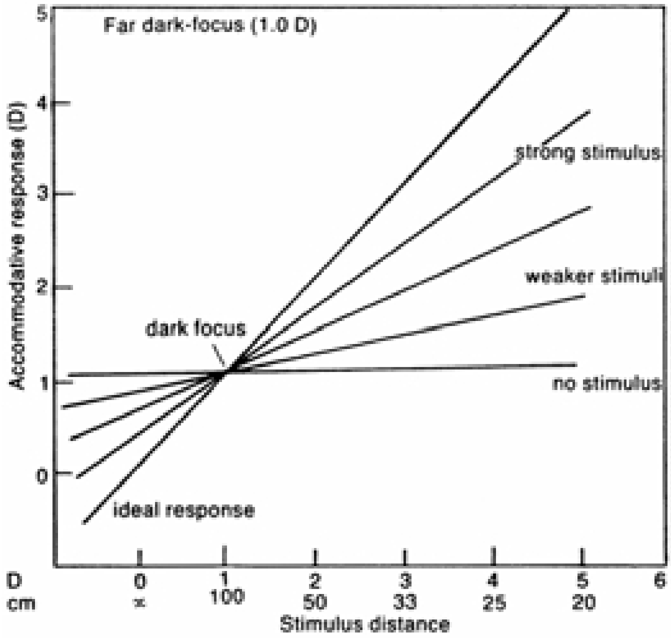


FIGURE 9 Hypothetical response functions illustrating the effect of reduced stimulation on accommodative responsiveness.

SOURCE: Owens, 1984. Reprinted with permission from D. A. Owens. Copyright 1984 by Sigma XI Scientific Research Society.

retinal image, as with small pupils or with images formed by optical interference in the plane of the retina, accommodation returns to the individual's dark-focus adjustment (Leibowitz and Owens, 1978). This phenomenon is most commonly encountered when using optical instruments such as binoculars or microscopes (Hennessy, 1975), and it may be related to problems of size and distance perception that occur with artificial display systems.

This normal variation of the eyes' focusing behavior can greatly hinder the ability to detect weak stimuli and to resolve fine details, and it provides a basis for understanding and correcting a variety of anomalous refractive errors that have puzzled vision specialists for years. Nearly 200 years ago, the British astronomer Nevil Maskelyne reported that he became myopic in dim illumination (Levine, 1965). This problem, called night or twilight myopia, was rediscovered on several occasions and was a topic of great research interest during the 1940s and 1950s (e.g., Wald and Griffin, 1947). These studies found large individual differences in the magnitude of night myopia that were not predictable on the basis of standard clinical examinations. Furthermore, they revealed that similar anomalous myopias occur under bright-light conditions, including “empty-field” or “space myopia” (Whiteside, 1952, 1957; Westheimer, 1957) and “instrument myopia” (Schober, 1954; Hennessy, 1975). Later work showed that some individuals also become “myopic” when viewing distant objects through an intervening surface or screen, a phenomenon called the Mandelbaum effect (Mandelbaum, 1960; Owens, 1979).

Optical Corrections

We now know that these anomalous “myopias” are not refractive errors in the usual sense; that is, they are not due to structural characteristics of the eyes; rather they arise from normal variations of accommodative responsiveness. When stimulation is weak, the eye tends to stay at its resting focus (Figure 9). Since the resting focus is not closely correlated with refractive status, these focusing errors are not predictable on the basis of standard measurements of refraction (Maddock et al., 1981; Simonelli, 1983). They can be corrected, however, by simply providing a spectacle prescription based on the individual's dark-focus. In effect, this prescription optically repositions the individual's dark-focus so that it matches the distance of the visual task.

The visual enhancement resulting from these special optical corrections depends on two factors: (1) the individual's characteristic dark-focus and (2) the quality of the available stimulation. In general, the greatest benefits for distance vision are obtained under the most degraded stimulus conditions and for subjects who have a relatively near dark-focus. Spectacle corrections based on the dark-focus were found to enhance visual resolution by as much as 25 percent under simulated night driving conditions (Owens and Leibowitz, 1976b). Even greater benefits have been obtained with corrections of empty-field myopia, a problem of special concern to pilots. One study found that the detection range of a small target (1 min arc) in a bright ganzfeld (an evenly illuminated field without focusable contours) improved from 26 to 315 percent, depending on the subject's dark-focus distance (Post et al., 1979). Another study found that spectacle corrections based on the dark-focus improved contrast sensitivity by as much as a factor of six for circular targets (diameter from 1.0 to 7.5 min arc) in a ganzfeld (Luria, 1980). Generally, the smaller the stimulus, the greater the effect of space myopia. In all cases, the greatest improvements were obtained for subjects with relatively near dark-focus values. It is interesting to note that the subjects exhibiting the greatest and the least improvement in Luria's (1980) study were both clinically emmetropic--i.e., standard clinical tests of refractive error indicated that neither subject required corrective lenses.

We want to emphasize that the same dark-focus prescription is not appropriate for all low visibility conditions. Since accommodative responsiveness decreases gradually with reduced stimulation, optimal correction for moderate visibility conditions, such as night driving, is a compromise between the individual's usual daytime prescription and the full dark-focus correction (Owens and Leibowitz, 1976). In contrast, performance in empty-field conditions is best with the full dark-focus correction (Post et al., 1979).

The Mandelbaum Effect and Dirty Windscreens

Accommodative biases toward the resting focus are not confined to low visibility conditions. As mentioned earlier, despite effort to see a distant object, the eyes will involuntarily focus for an intervening screen that is positioned near the distance of the dark-focus (Owens, 1979). This phenomenon, the Mandelbaum effect, could be especially hazardous to pilots who are attempting to see distant aircraft or beacons through a dirty or scratched windscreen, and Roscoe (1982; Roscoe and Hull, 1982) has argued that this problem should be an important consideration for cockpit design. Other studies have shown that accommodation for cathode ray tube (CRT) displays is also biased toward the user's resting focus (Kintz and Bowker, 1982), suggesting that reading glasses prescribed on the basis of the resting focus may be of some benefit for near visual tasks (Weisz, 1980).

Space Perception and Interactions With Binocular Vergence

Accommodation and binocular vergence have been recognized for centuries as potentially important determinants of visual space perception, and modern theorists generally agree that these oculomotor processes affect the perception of distance, size, depth, and velocity. The efficiency of space perception deteriorates greatly under the reduced stimulus conditions encountered at night or in an empty sky. Gogel (1977) and others have argued that many of the spatial illusions found under reduced cues are related to systematic misperception of distance. In general, people tend to underestimate far distances and to overestimate near distances, thus exhibiting a perceptual bias that is qualitatively similar to the oculomotor response biases found under reduced stimulus conditions.

Other studies indicate that distance perception in the dark is unrelated to the resting focus but is significantly correlated with the resting or tonus state of binocular vergence (Owens and Leibowitz, 1980; 1983). Post and Leibowitz (1982) have found that illusions of motion under impoverished stimulus conditions can result from an inappropriate vestibulo-ocular reflex determined by the observer's tonic vergence state. A growing body of evidence indicates that adaptive variations of oculomotor tonus play an important role in the adaptation of space perception to optical displacement and near work. Reviews of this literature have been published by Ebenholtz (1981), Ebenholtz and Fisher (1982), Shebilske (1981), and Owens and Leibowitz (1983).

IMPLICATIONS

The evidence indicates that the resting state of the eyes may be a key factor for predicting and optimizing visual performance under a wide variety of conditions. It allows correction of anomalous refractive errors that can seriously limit detection and identification under low visibility conditions, and it may be useful for prescribing glasses to optimize performance on near visual tasks. These applications follow the principle of matching the individual's dark-focus to the visual task by optical means. An alternate approach might be to use the dark-focus as a criterion for selecting personnel for tasks that involve predominantly near or distant vision. In addition, the resting states of accommodation and binocular vergence appear to be an important factor for understanding and predicting individual differences in space perception (Owens, in press).

The dark-focus should also be considered when developing clinical tests of contrast sensitivity (see the previous section). Research has shown that the spatial frequency response of accommodation is similar to that of the contrast sensitivity function. Focusing responses are most accurate for intermediate spatial frequencies (3-5 cpd) and are progressively less accurate for higher and lower spatial frequencies (Owens, 1980; Bour, 1981). Moreover, relatively high levels of contrast are required to stimulate accommodation (Raymond et al., 1984a, 1984b). Unless care is taken, therefore, the grating target will not be focused properly on the retina, resulting in an underestimation of sensitivity, particularly at high spatial frequencies at which focus is most important. This problem can be minimized either (1) by placing the test field at the optical distance of each individual's dark-focus or (2) by providing a high contrast accommodative stimulus on or around the test field.

RECOMMENDATIONS

The working group believes that decisions regarding the value of routine assessment and utilization of the dark-focus would benefit from further information about four issues: (1) population norms; (2) stability and variation of the dark-focus; (3) development and comparison of different techniques for measuring the dark-focus; and (4) the relationship between the dark-focus and performance on detecting, recognizing, and localizing targets. Our recommendations are summarized below.

Population Norms

While it is clear that the dark-focus exhibits great individual differences that are not detected by standard clinical refraction, we do not yet know the parameters of such variation in the general population. Studies of college students indicate that the average dark-focus corresponds to about 1.5 diopters of myopia, with a standard deviation of 0.77 diopters. Studies of subjects of comparable age from outside the college population, however, report dark-focus values that are somewhat less myopic (Epstein et al., 1981; Owens et al., 1982). There is also some evidence that the distance of the dark-focus gradually recedes with age (Bentivegna et al., 1981; Simonelli, 1983) and that there is a weak negative correlation between the dark-focus and refractive status (Maddock et al., 1981). These findings suggest that the parameters of the target population must be assessed in order to predict the probable impact of spectacle prescriptions or personnelselection based on measurements of the dark-focus.

At present, it appears that the primary target populations among Navy and Air Force personnel are pilots, who should benefit from correction of empty-field and night myopia, and personnel such as operators of radar and video display terminals, who have critical near vision tasks and may benefit from optical corrections for near visual tasks based on the dark-focus. The working group therefore recommends that initial screen studies and field evaluations concentrate on pilots and radar operators and others engaged in demanding visual tasks.

Stability and Variation of the Dark-Focus

Several studies have shown that the dark-focus of a given individual is relatively stable over time periods ranging up to a year (Miller, 1978a; Mershon and Amerson, 1980; Owens and Higgins, 1983). Other research, however, indicates that the momentary value of the dark-focus can be influenced by a number of situational variables, including near visual tasks (Ostberg, 1980; Ebenholtz, 1983, 1984; Owens and Wolf, 1983; Schor et al., 1984), emotional arousal (Westheimer, 1957; Leibowitz, 1976), mood (Miller, 1978b), and anxiety (Miller and LeBeau, 1982). Fixation on distant targets also is capable of shifting the dark-focus toward the far point (Ebenholtz, 1983, 1984).

It appears that some individuals are more susceptible than others to such transient changes. Owens and Wolf (1983), for example, found that near reading induces a myopic shift of the dark-focus in subjects whose initial resting state was less than 1.5 diopters while inducing no change in those whose initial resting state was greater than 3 diopters.

Research by Miller and his associates indicates that the effects of mood and psychological stress on the dark-focus depend on specific personality traits (Miller, 1978b; Miller and LeBeau, 1982).

Although the mechanisms for intraindividual variations of the dark-focus are still obscure, they probably reflect changes in the tonus of the ciliary muscle due to prolonged focusing effort or to systemic variations in autonomic arousal. In any event, the presence of such variations could have an impact on the prescription of optical corrections or selection of personnel on the basis of dark-focus, and further research should be directed toward clarification of their prevalence and underlying causes.

Clinical Measurement of the Dark-Focus

Most of the basic research on the dark-focus has utilized the laser optometer (Hennessy and Leibowitz, 1972). While this instrument has several advantages for laboratory applications, its limited reliability and demanding measurement task make it less appropriate for clinical use. “Dark retinoscopy” represents a promising alternative to the laser optometer for clinical assessment of the dark-focus. With this technique the examiner uses conventional static retinoscopy to measure refraction in total darkness. The retinoscope beam is not an adequate stimulus for monocular accommodation, and the patient's eye therefore remains at the dark-focus during the dark retinoscopy procedure (Owens et al., 1980).

For dark retinoscopy to be successful, it is critically important that: (1) the test room be entirely dark with no visible stimuli other than the retinoscope beam, (2) the patient must view the retinoscope beam monocularly to avoid convergent accommodation, and (3) the examiner must take care to maintain a fixed working distance so that the dark refraction can be derived by subtracting the dioptric value of the working distance from the power of the neutralization lens. Preliminary investigations have shown this technique to be an effective means for prescribing corrections for night myopia (Owens et al., 1982). To our knowledge, no one has yet applied dark retinoscopy to correction of empty-field myopia or other anomalous refractive errors. Extensions of this sort may be a useful step toward evaluating and implementing dark retinoscopy for clinical assessment of the dark-focus. In addition, evaluation of other refractive techniques, modified to use low illumination conditions, may be worthwhile.

The Relationship Between Dark-Focus and Pilot Performance

Although the dark-focus has been linked to pilot performance (e.g., Post et al., 1979; Roscoe, 1982), further studies are needed to increase our understanding of the ways in which the dark-focus influences performance under operational conditions. These studies should include not only measurements of target detection and recognition but also measurements of target localization. They should also include evaluations of interactions of accommodation and vergence eye movements and measurements of dark vergence as well as measurements of the dark-focus.

The intermediate resting states of accommodation and vergence, and their substantial intersubject variation, may provide new insights for predicting individual differences in the ability to localize objects under adverse visual conditions. It may also be fruitful to examine whether these basic individual differences in oculomotor behavior are related to performance on tests of dynamic acuity and motion in depth. Of more immediate concern for applications of the dark-focus, further research should be devoted to interactions of accommodation and vergence eye movements. Under most conditions, accommodation and vergence exhibit strong synergism; stimulation of either response initiates a correlated change in the other. Clinically, these interactions are most familiar in terms of the AC/A and CA/C ratios. In contrast to the strong synergy of their active responses, the resting states of accommodation and vergence appear to be relatively independent. Individual differences in the dark-focus and tonic vergence are not highly correlated; their average values are significantly different; and adaptive changes induced by optical displacements or near visual tasks can selectively affect either the resting state of accommodation or that of vergence (Owens and Leibowitz, 1983; Owens and Wolf, 1983). Although the resting states per se may be independent, adaptive or stress-related changes of either resting state are likely to influence the interactions of accommodation and vergence. Their synergism might also be affected by visual aids (e.g., night glasses) prescribed on the basis of the dark-focus, particularly if the aid were used in the presence of adequate stimulation. Furthermore, a target that may be inadequate for accommodation may nevertheless stimulate fusional (i.e., disparity) vergence, thereby producing a certain degree of vergence accommodation away from the expected dark-focus position (Miller, 1980). Measurements of interaction between accommodation and vergence could therefore play an important role in systematic investigations of dark-focus relationships to visual performance.

DYNAMIC MEASURES

Most measures of vision and visual capacity have been static--that is, both the observer and the visual stimuli have been stationary. Yet many real-world tasks involve movement of the observer and/or the stimulus. The working group has identified two existing measures of visual ability that show promise of giving a better prediction of performance of real-world tasks: dynamic visual acuity and dynamic depth tracking.

DYNAMIC VISUAL ACUITY

Background

Dynamic visual acuity is measured using acuity optotypes, such as Landolt C's, Sloan or Snellen letters, and checkerboard patterns, but under conditions in which these optotypes are moving and the observer must track them. During the past 30 years some 73 researchers have generated 81 reports on this topic, but, apart from the pioneering work by Ludvigh and Miller (1953, 1958; Miller and Ludvigh, 1953, 1962) and subsequent applications by Burg and coworkers (Burg, 1966, 1967, 1968; Burg and Hulbert, 1961; Henderson and Burg, 1973), there has been little sustained, programmatic effort to further develop measurement methodology or to understand the basis of dynamic visual acuity. There is general agreement that it decreases as a function of the acuity target's angular velocity with respect to the observer (Miller and Ludvigh, 1962; Morrison, 1980). This decrease in acuity is found for horizontal target movement (Ludvigh and Miller, 1953, 1958), vertical target movement (Miller and Ludvigh, 1953; Miller, 1958), and circular target movement (Ludvigh, 1949; Miller, 1956). Decrease in acuity is also found when a moving observer views a stationary target (Miller, 1958; Goodson and Miller, 1959).

Other general findings are that dynamic visual acuity decreases with decreased exposure duration (Elkin, 1962; Miller, 1959; Mackworth and Kaplan, 1962; Crawford, 1960a, 1960b, 1960c) and increases with increased target contrast (Mayyasi et al., 1971). Dynamic visual acuity continues to improve with increasing luminance well above levels for which static acuity has reached an asymptote (Ludvigh, 1949; Miller, 1956, 1958). Males have slightly better dynamic visual acuity than females (Burg, 1966; Burg and Hulbert, 1961; Weissman and Freeburne, 1965). Dynamic visual acuity declines more rapidly with age than does static visual acuity (Burg, 1966; Reading, 1972a, 1972b). The correlation between dynamic and static visual acuity is generally low--i.e., there are large individual differences in dynamic visual acuity among subjects with similar static visual acuities (Ludvigh and Miller, 1954, 1958). The correlation between dynamic and static visual acuities is increased with lower target speeds, binocular viewing conditions, increased exposure durations, and free head movement (DeKlerk et al., 1964; Burg, 1966; Burg and Hulbert, 1961; Weissman and Freeburne, 1965).

Most likely, dynamic visual acuity tends to be poorer than its static counterpart because, at high target velocities, the eyes fail to track the moving target accurately. This explanation was offered by Ludvigh and Miller (1958; Ludvigh, 1949), even though they did not have the benefit of direct measurements of tracking eye movements. Although this explanation has occasionally been questioned (Westheimer and McKee, 1975), it has enjoyed considerable experimental support (Murphy, 1978; Morgan et al., 1983). Of particular practical importance is the fact that Ludvigh's hypothesis seems to be able to account for individual differences in dynamic visual acuity as well as for the substantial changes in it that accompany practice (Murphy, 1978).

Implications

Although the relationship between dynamic and static visual acuities is not well understood and although there has not been an effective standardization of measures of dynamic visual acuity, the working group found much evidence that dynamic visual acuity is often more predictive of real-world task performance than are static acuity measures of vision. So it may be that combining measurement of contrast sensitivity function with dynamic, moving-target testing conditions can lead to more powerful measures of visual assessment that are predictive of visual task performance. DeKlerk et al. (1964) tested 30 pilots in their performance on in-flight measures of instrument, formation, and night flying ability. They reported that dynamic visual acuity correlated more highly than did static visual acuity with each of these performance measures. Burg (1967, 1968) investigated the relationships between a battery of seven vision tests (including dynamic visual acuity, static visual acuity, visual fields, and lateral phorias) and people's automobile driving records. He reported that dynamic visual acuity had the strongest relationship to automobile driving records of all the vision measures studied. Henderson and Burg (1973) studied the accident record of truck and bus drivers and found that there was a significant inverse relationship between dynamic visual acuity and accident record.

Although the relationships between dynamic visual acuity and task performance discussed above are not particularly strong, they are stronger than those found with static measures. The working group concludes that these relationships found despite the coarseness of the measures, the large within-subject variability on dynamic visual acuity tests, and the lack of standards for measuring dynamic visual acuity warrant further investigation. The working group concludes that dynamic visual acuity has real potential for the assessment of vision.

Recommendations

The working group recommends that a study be conducted to investigate the relationship between dynamic visual acuity and some important real-world task such as flying ability. The working group further recommends that a dynamic contrast sensitivity function be measured using grating targets moving with a range of angular velocities, and that it be compared with measurements of static contrast sensitivity function in their relationship to flying ability. Sinusoidal grating targets having the general form of Gabor functions (see Appendix C) would seem useful in the dynamic contrast sensitivity task. It would be highly desirable to measure both eye movements and accommodative states in taking both static and dynamic contrast sensitivity measurements in order to better understand the relationship between them.

DYNAMIC DEPTH TRACKING

Background

In many real-world visual motor tasks, the retinal image of an object expands or contracts, as a result of object motion toward or away from the observer, observer motion toward or away from the object, or a combination of both types of motion. Recent psychophysical (Beverly and

Regan, 1975, 1980) and physiological data (Regan and Cynader, 1982) suggest the existence of specialized visual mechanisms sensitive to object movement in depth. Perimetric analysis of sensitivity to motion in depth (Beverly and Regan, 1983) reveals large individual differences and considerable heterogeneity. Some individuals are unable to discriminate an expanding retinal image fromSome individuals are unable to discriminate an expanding retinal image froma a lateral motion, while others are highly sensitive to the difference. Because of these individual differences and because this sensitivity to depth may be highly correlated with a pilot's flying ability (see below), the working group concludes that this area should be more extensively investigated.

In one study, pilots were measured on their sensitivity to motion in depth (Kruk et al., 1981). The pilots viewed a square on a display screen that randomly expanded or contracted in size, simulating motion in depth. The pilots were instructed to keep the size of the square as constant as possible using a control that counteracted the size change. Accuracy in performing this task was taken as an index of depth sensitivity. The pilots were also tested on an Air Force flight simulator on flying tasks such as landing in fog, formation flying, and low-level bombing accuracy under counterattack. Pilots who performed well on the depth-tracking task also performed well on the flying tasks. In another study, sensitivity to depth motion was found to correlate well with flying performance in an actual airplane that was tracked by means of telemetry (Kruk and Began, 1983).

Conclusions and Recommendations

The working group concludes that the depth motion tracking task has potential for screening pilots and others involved in precise visual-motor tasks and that its potential should be further developed and explored. Like measures of dynamic visual acuity, dynamic depth tracking involves both the visual system and the oculomotor system. Superior performance on both of these tasks probably involves the integration of these two systems. The working group believes that the existence of a rather simple dynamic tracking task, which is rather easy to administer and which predicts the ability to perform complex flight tasks, would be a significant development in the assessment of vision.

The working group recommends that further studies of this technique be undertaken. These studies should focus on finding the optimal test conditions giving the highest predictability of actual flight performance as well as other visual-motor tasks such as vehicular driving.

TWO MODES OF VISUAL PROCESSING

BACKGROUND

Vision plays a role not only in the perception of objects but also in spatial orientation (maintenance of body posture, perception of self-motion, and locomotion). The function of vision in spatial orientation as well as its controlling parameters is different in many fundamental ways from its contribution to the resolution of fine detail. In particular, fine detail is unnecessary for many visually controlled tasks (Leibowitz et al., 1980). The concept of two visual systems or two modes of processing visual information (Held, 1968, 1970; Ingle, 1967; Schneider, 1967; Trevarthen, 1968; Leibowitz and Post, 1982) is helpful to clarify these differences. The two modes of visual processing are focal and ambient.

The focal mode in general answers the question of "what" about objects perceived. Most studies of vision, particularly in relation to performance evaluation, have been concerned with focal vision. The ambient mode is concerned with "where" objects are located relative to the observer and where the observer is located in space. Focal and ambient vision differ in a number of ways.

(1) The focal mode is almost exclusively visual, while the ambient mode acts in concert with the vestibular, somatosensory, and auditory senses to subserve spatial orientation, posture, and gaze stability.
(2) Object recognition by the focal mode can operate over the full range of spatial frequencies. The ambient mode is adequately activated by low spatial frequencies typically stimulating large areas of the visual field.
(3) Adequate luminance and lack of refractive error are critical for some aspects of focal vision (visual acuity, for example) but play a much less important role in ambient vision. The low spatial frequencies subserving ambient vision are less sensitive to the degradation of retinal image quality by refractive error or by reduction of illumination.
(4) Focal vision is less efficient in the peripheral visual field. Although ambient functions are less efficient if restricted to a small area of the periphery compared with central vision, unlike focal vision, ambient functions improve when larger areas of the visual field are stimulated.
(5) Focal vision typically involves attention, while ambient visual functions are more reflexive in nature. Reading while walking illustrates the fact that although attention is dominated by the focal-mediated reading task, spatial orientation is adequately maintained by the ambient mode with little or no conscious effort.

IMPLICATIONS

The idea of two modes of visual processing has important implications in several areas of vision. This section indicates specific directions for future research in areas for which there is a need to increase our understanding of the role of the different modes of processing.

Spatial Disorientation and Motion Sickness

In recent years, the importance of sensory mismatch within the ambient mode has come to be recognized as a cause of spatial disorientation and motion sickness. Whenever there is disagreement, based on previous experience, between the sensory input provided to the gaze stability and the spatial orientation systems, for example, a person can experience disorientation and/or nausea (Reason and Brand, 1975).

Vehicle Guidance and Night Driving

The two modes of processing can be functionally dissociated. Spatial orientation is adequate in the absence of the ability to recognize objects due to refractive error or reduction of luminance level. This selective degradation may be a factor in nighttime driving accidents. Vehicle guidance is a dual task: steering relies on ambient vision while recognition of signs and hazards is mediated by focal vision. At night, ambient vision functions as well as in daylight. Since the driver's self-confidence derives from the ability to steer the vehicle, and since he or she is not aware of the reduction in the ability to recognize hazards with the degraded focal system, nighttime driving speeds are often too fast to permit a timely response to infrequent and unexpected hazards on the roadway (Leibowitz and Owens, 1977).

Visual Narrowing Under Stress and Cortical Brain Damage

The two modes can be dissociated in other situations as well. Under various kinds of stressors, reaction time to objects imaged in the peripheral visual field may be increased, or the objects may not be detected at all. This phenomenon is referred to as tunnel vision or narrowing of the visual field (Leibowitz et al., 1982). Even more dramatically, studies of patients with cortical brain damage have demonstrated that spatial orientation can be carried out completely without awareness when the stimuli are imaged on areas of the visual field that are scotomatous as tested by conventional perimetry (Weiskrantz et al., 1974). Thus, focal and ambient vision can be dissociated either by brain damage or by the nature of the attentive demands in certain tasks such as occur when driving a vehicle. An implication of this functional dissociation is that the phenomenon of visual narrowing could result from the concentration of focal vision due to shifts of attention. Ambient vision, which does not require attention, is probably unaffected by attentional narrowing. A critical factor is that traditional static perimetry makes use of a focal task requiring attention that can be redirected by the observer. Ambient vision seems largely to be reflexive and therefore may not be as susceptible to modification by attention shifts. Whether selective degradation of focal vision while ambient function remains intact is also characteristic of visual narrowing resulting from stressors, such as hypoxia or excessive gravitational forces, has not yet been determined.

Because both focal and ambient vision are critical in human performance, it is important that visual tests be employed that are sensitive to both functions. Most tests of vision in current use evaluate only focal vision and are therefore of limited usefulness in predicting performance in many situations, particularly those involving spatial orientation.

Aircraft Instrumentation

Because ambient visual functions are reflexive, they present potential advantages with regard to the display of orientation information in aircraft over symbolic displays that involve learning and interpretation (Leibowitz and Dichgans, 1980). As pointed out by Head (1918), processes that require higher levels of information processing are more vulnerable to loss during stress than reflexive functions. This concept is incorporated in the Malcolm Peripheral Vision Horizon Display, which provides a wide-angle artificial horizon in order to more adequately stimulate the ambient system (Malcolm et al., 1975).

Gaze Stability

Most tests of visual resolution involve a stationary observer viewing a static target that requires gaze stability but places minimum demands on these systems. In many real-life situations in which the observer and/or the target is moving, smooth eye movements are subserved by both a reflexive and a voluntary system. The reflexive system is activated either by moving visual contours typically stimulating large areas of the visual field (optokinetic nystagmus) or by acceleration of the head (vestibulo-ocular reflex). Analogous to ambient function, this system is reflexive and does not involve awareness. Its function is to maintain a stable retinal image during head movement. Voluntary fixation in foveated animals is subserved by the phylogenetically newer pursuit system. Since the principal function of this voluntary system is to facilitate object recognition by maintaining images on the fovea, it subserves focal vision (see the section on dynamic visual acuity).

Interaction Between Focal and Ambient Vision

Although the ambient system can function adequately in the absence of focal vision, focal vision is not independent of disturbances of the ambient system. Disruption of gaze stability mechanisms, either vestibular or optokinetic, when the head is in motion results in retinal image motion. Such inappropriate image movement lowers contrast and reduces spatial resolution. Another consequence of ambient dysfunction is disorientation and/or motion sickness. Gastric symptoms associated with intersensory mismatch within the ambient system demand attention and interfere with object recognition and visually mediated judgments. Illusory object or self-motion frequently occurs when, in order to compensate for ambient dysfunction, the pursuit system is activated to preserve gaze stability (Leibowitz and Post, in press). Such illusory motion is difficult if not impossible to distinguish from true object or self-motion.

RECOMMENDATIONS

The working group recommends that research be conducted on how to integrate tests of ambient vision with tests of focal vision. For example, the contrast sensitivity function represents a significant improvement in the evaluation of focal vision. Some tests of ambient vision are available, but they are not as well developed. Although there exist excellent techniques for assessing vestibular sensitivity, the integrated function of the components of the ambient system has not been extensively investigated. Quantitative evaluation of body sway has shown considerable promise in clinical diagnosis and represents a potentially powerful methodology for assessing task performance (Dichgans and Brandt, 1978). Individual differences in illusory self-motion (vection) and induced tilt are marked, but their origin and significance are unknown. Sensitive measures of optokinetic nystagmus are in extensive clinical use, but the visual parameters have not been studied in detail. Questions such as the relative contribution of various areas of the visual field and the role of spatial frequency, contour extent, and contrast remain to be answered. In many respects, then, the ambient system and in particular its visual component represents an uncharted frontier with important implications for psychophysics, medicine, and human engineering. In evaluating the role of vision in adjustment, tests of focal function are indispensable but incomplete. Tests of spatial orientation are wanted and wanting.

SUMMARY RECOMMENDATIONS

In the body of this report the working group has discussed the value or potential value of four emerging techniques of assessing visual function: (1) contrast sensitivity function; (2) dark-focus of accommodation; (3) dynamic visual acuity and depth tracking; and (4) the distinction between ambient and focal modes of visual function. The detailed recommendations made at the end of each section are often for further research.

In this section the working group offers summary recommendations based on the content of the previous sections. These recommendations are designed to meet some immediate needs about improving the assessment of vision and to provide a knowledge base that, 5 or 10 years from now, will be extremely valuable in the application of the emerging techniques to practical problems. Their ultimate goal is to provide a large data base of basic measures and to provide further insight into the relationship between these measures and performance of real-world visual tasks. In order for the data to be useful to a wide variety of investigators, they must be collected with a reasonably uniform degree of reliability and must be free of the confounding effects of response bias. Therefore, we recommend:

1. That a large scale program of measurement and evaluation of the contrast sensitivity function and the dark-focus on personnel entering pilot training be initiated. Both the dark-focus and the contrast sensitivity function should be measured using psychophysical methods that control response bias and give a known level of statistical reliability. Personnel performing high-stress or visually critical tasks should be periodically reexamined.
2. That selected personnel be studied in greater depth to determine the relationship between performance on specified visual or visual-motor tasks and their contrast sensitivity function, dark-focus, and dynamic visual acuity. An example of such an area of study is pilots and pilot performance during training and during operational duty. No personnel selection based on either the dark-focus or the contrast sensitivity function should be made at this point. The large quantities of information collected would yield solid normative data that could be used in the future for selection, should this phase of the study show any systematic relationship between the basic measures and performance.
3. That these data be stored in a computer-based data access system and be made available to the vision research community for further study. The data on contrast sensitivity, dark-focus, and dynamic visual acuity could be used to explore many interesting issues, such as possible progressive changes in vision during a pilot's career. A large data base would provide prevalence data on variability and prevalence of different types of contrast sensitivity functions and dark-focus variability. The data base would also serve as large-scale screening for the early detection of visual pathology.
4. That an advisory panel be formed to make specific recommendations concerning the implementation of this research program. This panel should be composed of vision researchers in the relevent fields with the appropriate expertise.

Such an undertaking will be an exciting challenge. Although many decisions not covered by this report will have to be made, the potential benefits are enormous. A rational basis for personnel selection based on visual tests may be developed, avoiding the waste associated with training individuals for tasks that they will not be able to perform. Normative standards will emerge against which an individual can be compared; the prevalence of various types of functions will be known. A deeper understanding of vision and its relationship to task performance will emerge.

APPENDIX A: BASIC FACTORS IN SPATIAL CONTRAST SENSITIVITY

The dependent variable that is the basis of the contrast sensitivity function is the contrast of the sinusoidal test grating. The most commonly used definition of contrast is:

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where L_{max} is the maximum luminance at the peak and L_{min} is the minimum luminance at the trough of the sine wave. Contrast may vary from 0.0 (a field of uniform luminance) to 1.0 (where $L_{min} = 0.0$ and $L_{max} = 2.0 * L_{mean}$ since $L_{mean} = (L_{max} + L_{min})/2$). It is not possible to have a real sinusoidal grating of contrast greater than 1.0, because luminance cannot be less than 0.0.

At this time there are no standards for the measurement of the contrast sensitivity function, although there is general understanding of the factors that influence its shape. These factors are discussed below.

MEAN LUMINANCE

The mean luminance of the sinusoidal gratings has a profound effect on the contrast sensitivity function. At high photopic levels of mean luminance, the normal contrast sensitvity function has a peak sensitivity at about 5 cpd and a high frequency cutoff at about 60 cpd. As mean luminance is lowered, not only do the frequencies of the peak sensitivity and the high frequency cutoff become lower, but also the height of the peak is reduced (Figure 10). At mesopic levels of mean luminance the peak in the contrast sensitivity function has practically disappeared. This peak, which is so prominent at high luminances, is generally believed to reflect the dynamic interaction between excitatory and inhibitory influences in the visual system.

RETINAL LOCUS

Compared with the contrast sensitivity function measured at the fovea, the contrast sensitivity function measured for eccentric retinal loci shows a progressive shift to lower spatial frequencies for both the high frequency cutoff and the frequency of peak sensitivity (Figure 11). In addition there is a progressive lowering of overall contrast sensitivity. This change is believed to reflect the unequal way in which the retinal visual field is projected onto the visual cortex (Daniel and Whitteridge, 1961; Schwartz, 1980). When measured at different retinal eccentricities using sinusoidal gratings whose size and spatial frequency have been adjusted to stimulate equal amounts of visual cortex, the contrast sensitivity function is approximately the same at all retinal loci (Virsu and Rovamo, 1979; Rovamo and Virsu, 1979) as is shown in Figure 12.

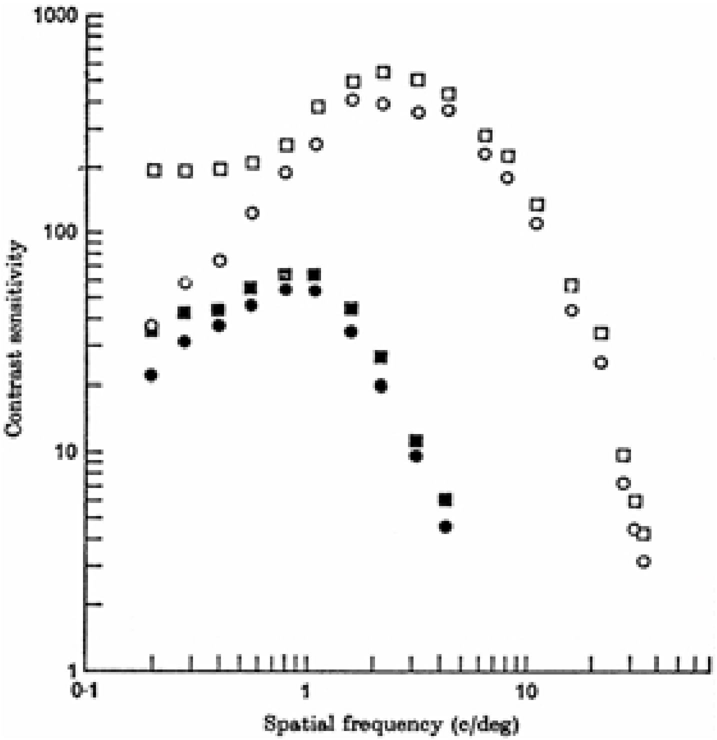


FIGURE 10 Contrast sensitivity functions for different levels of mean luminance. The upper curves were measured with gratings having a mean luminance of 500 cd/m^2. The lower curves were measured at 0.05 cd/m^2.

SOURCE: Campbell and Robson, 1968. Reprinted with permission from F. W. Campbell and J. G. Robson. Copyright 1968 by The Physiological Society.

FIELD SIZE

Visual sensitivity at a particular spatial frequency depends on how many cycles of the sine wave grating are included in the pattern. Sensitivity increases as more cycles are included up to about 10 complete cycles (Figure 13). Usually the low frequency limit of testing is limited by the largest possible field. For example, in order to measure maximum sensitivity at 0.5 cpd, one would need a test field 20 deg square to have 10 complete cycles.

TEMPORAL CHARACTERISTICS

Both the exposure duration of the grating target and the time course of its onset influence the contrast sensitivity function, especially at the lower spatial frequencies. Figure 14 shows the contrast sensitivity function measured with two different stimulus duration characteristics. Notice that with brief exposure duration or with rapid onset of the grating stimulus, sensitivity to low spatial frequencies is enhanced compared with longer duration, more gradual onset stimuli. If gratings are modulated sinusoidally in time, the temporal frequency influences the measured contrast sensitivity function. The interaction between temporal frequency and spatial frequency are represented by a contrast sensitivity surface, as shown in Figure 15 (Kelly, 1979). Notice that contrast sensitivity at low spatial frequencies is higher when the grating is flickered at a relatively high temporal modulation compared with a low temporal modulation.

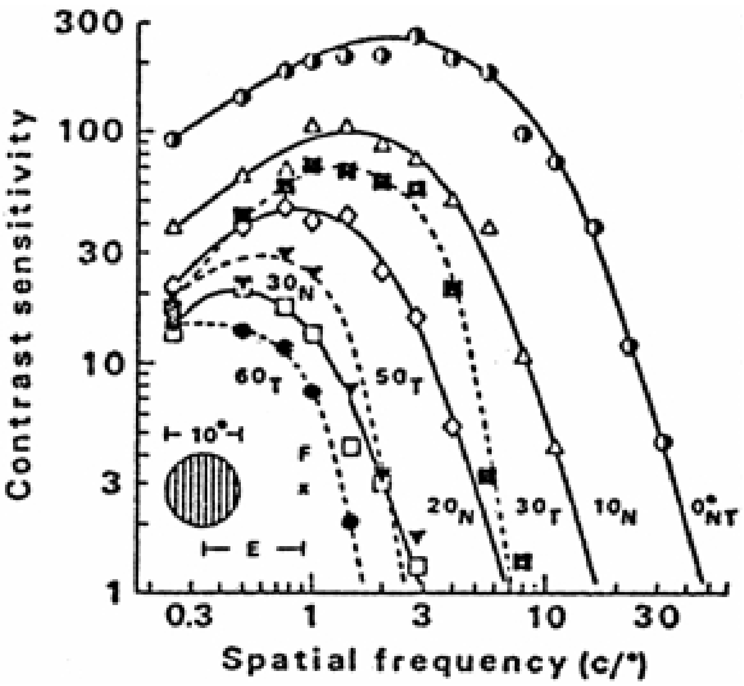


FIGURE 11 A comparison of contrast sensitivity functions for the nasal visual-field half-meridian of the right eye (open symbols and continuous lines) and for the temporal half-meridian of the left eye (filled-in symbols and dashed lines). The values of eccentricity were measured as the angular distance of the fixation point from the middle of the gratings that subtended 10 deg. The nasal eccentricities were 0 deg (half-filled circles), 10 deg (triangles), 20 deg (diamonds), and 30 deg (squares). The temporal eccentricities were 0 deg (half-filled circles), 30 deg (filled squares), 50 deg (filled triangles), and 60 deg (filled circles). The foveal functions were similar for both eyes and are not drawn separately.

SOURCE: Rovamo and Virsu, 1979. Reprinted with permission from J. Rovamo and V. Virsu. Copyright 1979 by Springer-Verlag.

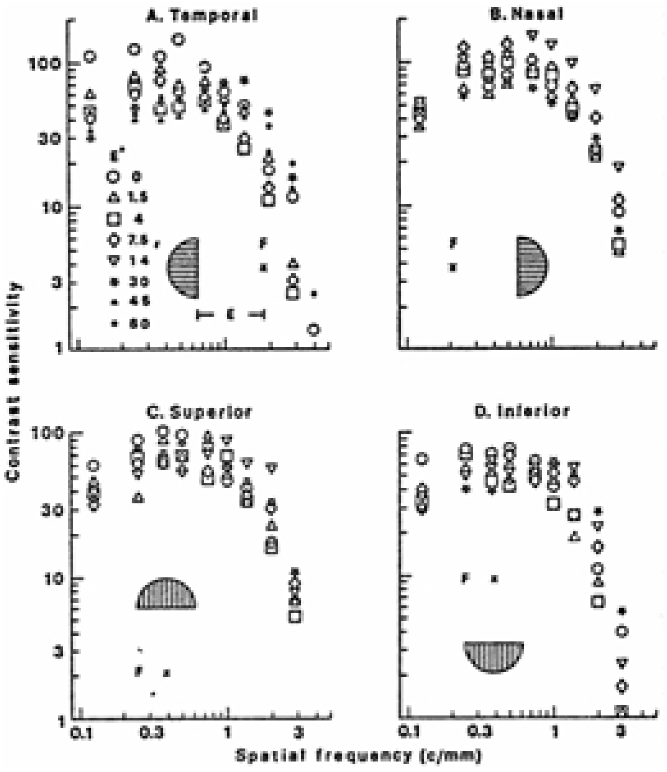


FIGURE 12 The photopic contrast sensitivity functions for 25 locations of the visual field. The eccentricities were measured along the various half-meridians of the visual field as indicated on the graphs and in A for the different symbols. The retinal dimensions of the gratings were scaled for equivalent calculated cortical representations. Contrast sensitivity is shown as a function of spatial frequency in the calculated cortical projection images (cycles per millimeter of cortex). In contrast to the data in Figure 12, the contrast sensitivity functions at the different retinal eccentricities are almost identical.

SOURCE: Rovamo and Virsu, 1979. Reprinted with permission from J. Rovamo and V. Virsu. Copyright 1979 by Springer-Verlag.

ORIENTATION

The visual system is more sensitive to horizontal and vertical gratings than to other orientations, an example of the oblique effect (Appelle, 1972) wherein horizontal and vertical orientations are more important in vision than are obliques. Figure 16 shows the contrast sensitivity function measured with vertical gratings and for 45 deg orientation gratings. The contrast sensitivity, especially for the high spatial frequencies, is reduced for oblique orientations relative to horizontal and vertical orientations. This orientation anisotropy may be important for calculations of the "effective" visual stimulus.

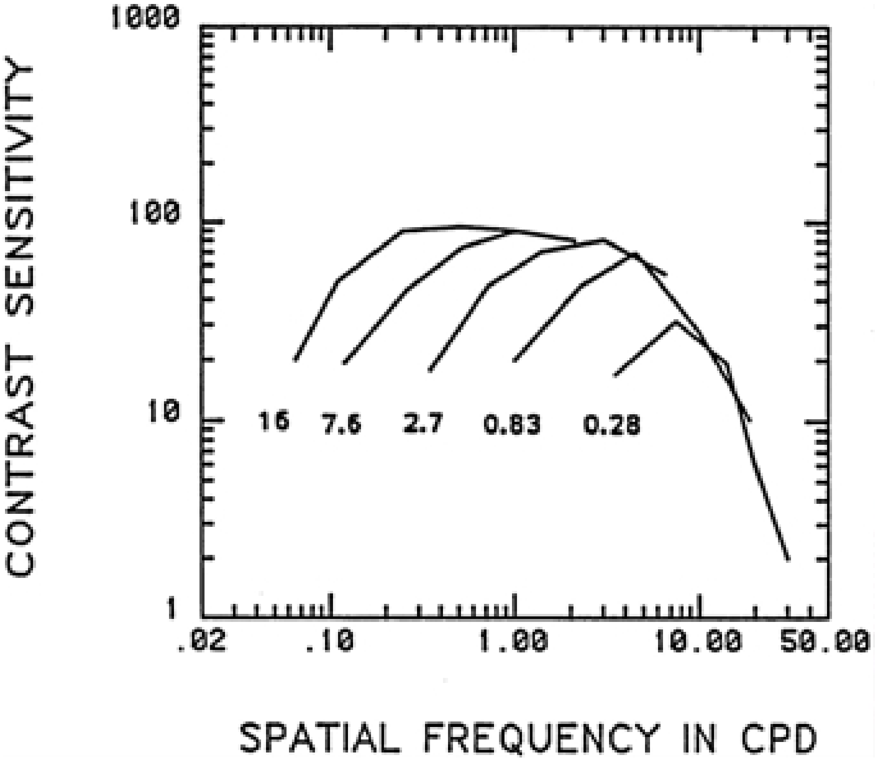


FIGURE 13 Contrast sensitivity as a function of the test field size in degrees of visual angle. The number of cycles in each stimulus is the product of the field size and the spatial frequency. Based on data reported by McCann, Savoy and Hall.
SOURCE: McCann et al. (1978).

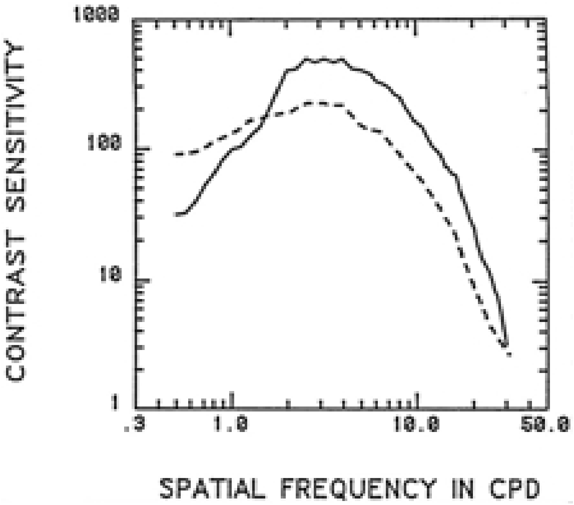


FIGURE 14 Contrast sensitivity functions for long exposure time with gradual onset and offset (sustained presentation) and for short exposure time with rapid onset and offset (transient presentation). Note that low frequency sensitivity is enhanced and high frequency sensitivity is reduced with transient presentation. Based on data reported by McCann, Savoy, and Hall.

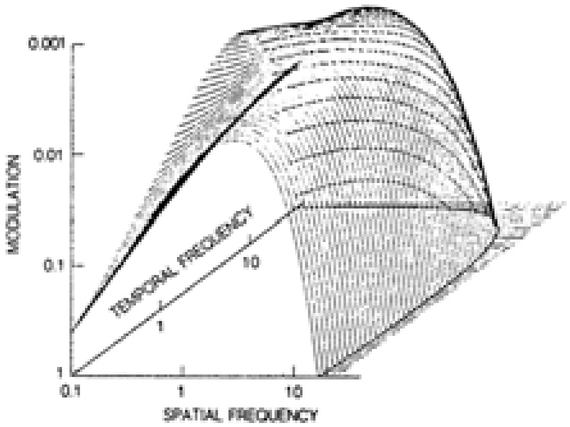


FIGURE 15 Contrast sensitivity as a function of both spatial and temporal frequency. Each individual curve represents the spatial frequency response at a fixed temporal frequency.
SOURCE: Kelly, 1979. Reprinted with permission from D. H. Kelly. Copyright 1979 by the American Institute of Physics in the Journal of the Optical Society of America 69.

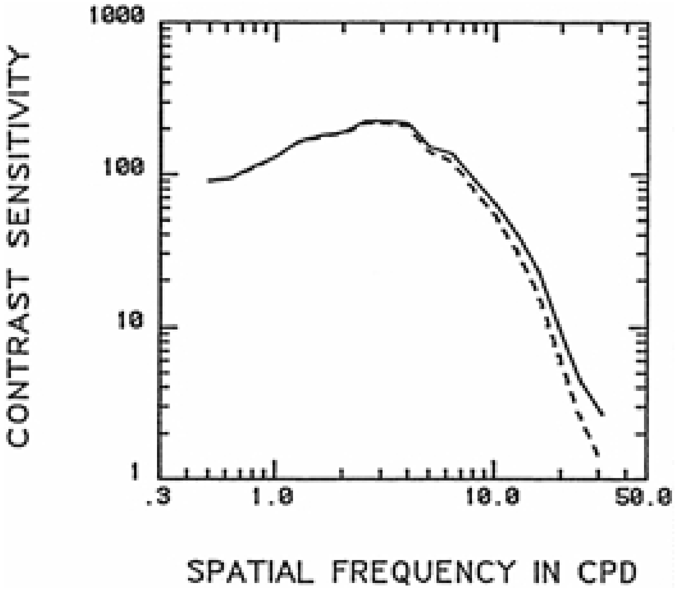


FIGURE 16 Contrast sensitivity function for vertical and oblique orientations. Note the lower sensitivity at oblique orientation.
SOURCE: Campbell et al., 1966. Reprinted with permission from F. W. Campbell. Copyright 1966 by The Physiological Society.

APPENDIX B: DETECTION SENSITIVITY AND RESPONSE BIAS

Classical psychophysical methods have as their goal the determination of a stimulus threshold. Thresholds measured can be detection, discrimination, recognition, and identification. The concept of threshold actually has two meanings, one empirical and one theoretical. Empirically a threshold is the stimulus energy that will allow the observer to perform a task (detection, discrimination, recognition, or identification) at some criterion level of performance (75 percent correct, for example). Sensitivity is defined as the reciprocal of the threshold value.

The classical concept of detection threshold, as represented in the high threshold model of detection, hypothesizes that there is a stimulus level below which the stimulus has no effect (as if the stimulus were not there) and above which the stimulus is perceived. The classical psychophysical methods (the method of limits, the method of adjustment, and the method of constant stimuli) developed by G.T. Fechner (1860) were deigned to infer the stimulus value corresponding to the theoretical threshold from the observed detection performance data. In this sense, the stimulus threshold is the stimulus energy that exceeds the theoretical threshold with a probability of 0.5. Until the 1950s the high threshold model of detection dominated conceptualization of the detection process and provided the theoretical basis for the psychophysical measurement of thresholds.

In the 1950s a major theoretical advance was made by combining detection theory with statistical decision theory. Actual detection performance was conceived to be based on two separate and independent processes: a sensory process and a decision process. The sensory process transforms the physical stimulus energy into some sort of internal representation, and the decision process makes a decision based on this representation to say “yes, the stimulus was present” or “no, the stimulus was not present” (in the simplest case). Each of these separate processes is characterized by at least one parameter: the sensory process by a sensitivity parameter and the decision process by a response criterion or response bias parameter. It was further realized that estimates of thresholds made using any of the three classical psychophysical methods confounded the sensitivity of the sensory process with the response criterion of the decision process. In order to measure these two separate characteristics, one needs two measures of detection performance. Not only must one measure the probability that the observer says “yes” when a stimulus is present (the hit rate: HR) but also one must measure the probability that the observer says “yes” when a stimulus is not present (the false alarm rate: FAR). Under certain assumptions, these two performance measures, the hit rate and the false alarm rate, may then be used to estimate detection sensitivity and decision criterion.

HIGH THRESHOLD MODEL OF DETECTION

The specific way in which the hit rate and the false alarm rate are used to derive detection sensitivity and response criterion depends on the specific model one adopts for the sensory process and the decision process. Some of these different models and how to distinguish among them are discussed by Krantz (1969). Assuming the high threshold model leads to the following measures of sensory process sensitivity and decision process response criterion:

$$p = \frac{(HR - FAR)}{(1 - FAR)} \qquad (1)$$

$$g = FAR \quad (2)$$

where p is the probability that the stimulus will exceed the hypothetical threshold and g is the response bias (called guessing rate in the high threshold model). Equation 1 is the widely used correction-for-guessing formula. Extensive research testing the validity of the prediction of the high threshold model has led to its rejection as an adequate description of the detection process and the conclusion that neither Equations 1 nor 2 succeeds in separating the effects of sensitivity and response bias (Swets, 1961; Swets et al., 1961; Krantz, 1969; Green and Swets, 1974).

One important characteristic of any detection model is its prediction of the relationship between the hit rate and the false alarm rate as the observer changes the response criterion. This plot of HR against FAR is called an ROC curve (receiver operating characteristic). By algebraic rearrangement of Equation 1, the high threshold model of detection predicts a linear relationship between HR and FAR in the ROC curve:

$$HR = p + (1-p) * FAR \quad (3)$$

where p is the sensitivity parameter of the high threshold sensory process. This predicted ROC curve is shown in Figure 17.

When one actually measures the HR and FAR pairs in a detection experiment using different degrees of response bias, one obtains a bowed-shaped ROC curve shown by the filled circles in Figure 17. This curve, which one actually obtains in experiments is quite different from the straight line relationship predicted by the high threshold model and is one of the bases for rejecting that model.

SIGNAL DETECTION THEORY

A widely accepted alternative to the high threshold model is the signal detection model. This model does not contain the concept of a sensory threshold (Swets, 1961). It assumes that the sensory process has a continuous output based on random Gaussian noise and that when a signal is present, it adds to that noise. The sensitivity of the sensory process is expressed as the difference between the mean output under no signal condition and that under signal condition: d• (d-prime). The decision process is assumed to hold a single decision criterion (in more elaborate versions of this model, multiple criteria are possible). This decision criterion is based on the output of the sensory process. If the output of the sensory process equals or exceeds the decision criterion, the observer says “yes, the signal was present.” If the output of the sensory process is less than this criterion, the observer says “no, the signal was not present.” The decision criterion may be expressed in several ways. One is beta, the ratio formed by the likelihood that the observed output of the sensory process was due to a signal being present divided by the likelihood that the output was due to the signal being absent. Another measure is x_c, the critical value of the sensory process output used as the decision criterion. If one assumes that the probability distributions describing the output of the sensory process are normal Gaussian distributions of equal variance, then d• and x_c are calculated from the HR and FAR in the following way:

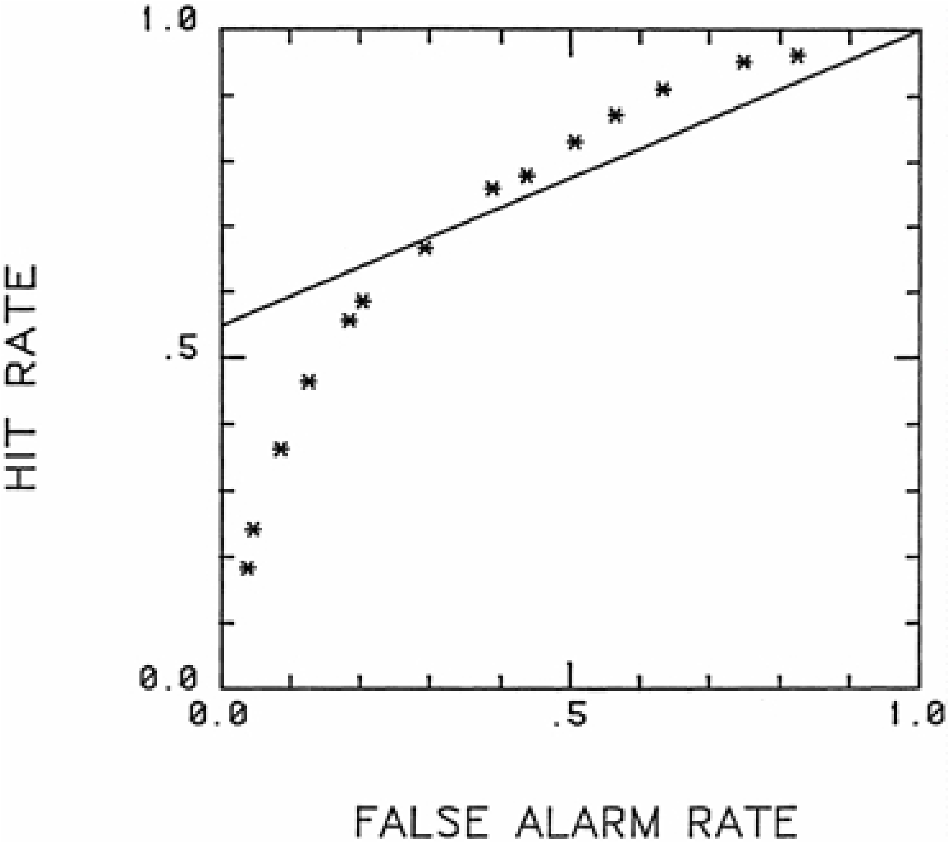


FIGURE 17 Hit rate as a function of false alarm rate. The filled circles are HR-FAR pairs from a detection experiment, forming a bowed-shaped ROC curve. The straight line is the ROC curve predicted by the high threshold model of detection.

$$d\bullet = Z_{HR} - Z_{FAR} \quad (4)$$

$$x_c = Z_{FAR} \quad (5)$$

where Z_{HR} and Z_{FAR} are the z-score transforms, based on the normal distribution, of the HR and FAR probabilities. The ROC curve predicted by the signal detection model is shown in Figure 18 along with the empirical data shown in the previous figure. The signal detection prediction is in accord with the observed data. The data shown in Figure 18 correspond to d• = 1.0. All ROC curves predicted by this model are anchored at the 0,0 and 1,1 points on the graphs. Each different value of d• generates a different ROC curve. For d• = 0, the ROC curve is the positive diagonal extending from 0,0 to 1,1. For d• greater than 0, the ROC curves are bowed. As d• increases, so does the bowing of the corresponding ROC curve.

An algebraic rearrangement of Equation 4 leads to this relationship between HR and FAR:

$$Z_{HR} = d\bullet + Z_{FAR} \quad (6)$$

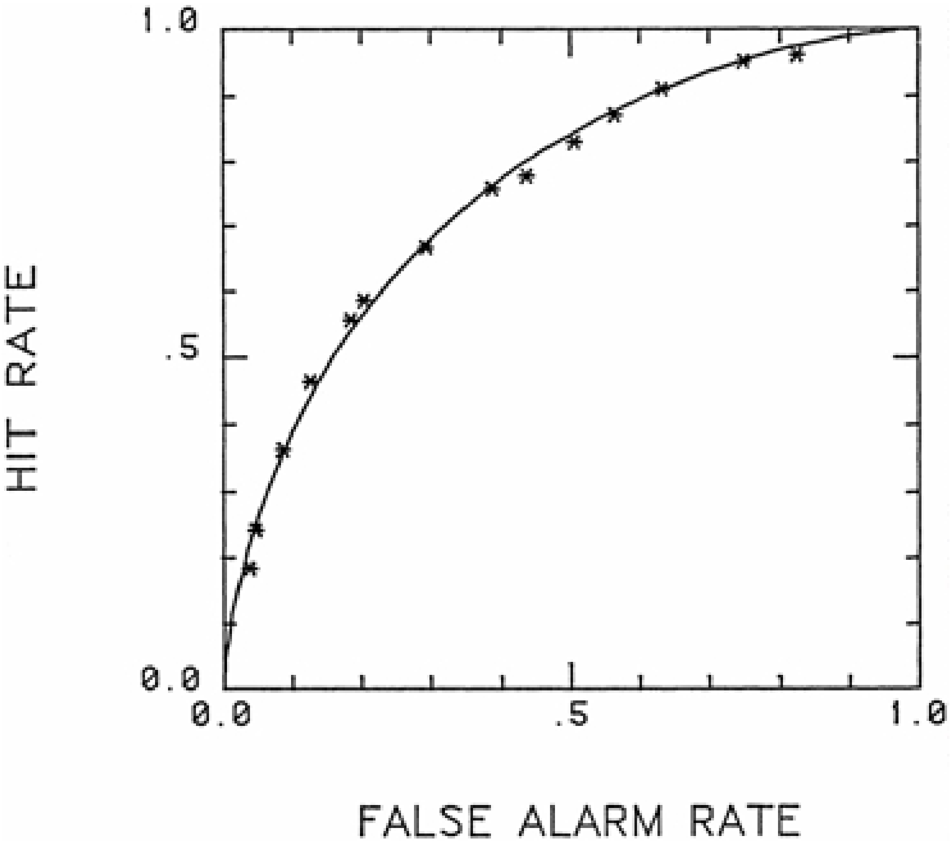


FIGURE 18 Hit rate as a function of false alarm rate. The filled circles are the same data as in Figure 18. The smooth curve is the ROC curve predicted by the equal-variance Gaussian signal detection theory.

Equation 6 predicts that when HR and FAR are plotted as z-scores instead of probabilities, the bowed-shaped ROC curve shown in Figure 18 will be a straight line, because equation 6 is in the form of a linear equation. This predicted ROC curve is shown in Figure 19, along with the data from the previous figures.

Sensitivity is generally a relatively stable property of the sensory process, but the decision criterion used by an observer can vary widely from task to task and from time to time. The decision criterion used is influenced by three factors: (1) the instructions to the observer; (2) the relative frequency of signal and no-signal trails (the a priori probabilities); and (3) the payoff matrix, the relative cost of making the two types of errors (false alarms and misses) and the relative benefit of making the two types of correct responses (hits and correct rejections). These three factors can cause the observer to use quite different decision criteria at different times, and, if the proper index of sensitivity is not used, changes in decision criteria will be incorrectly interpreted as changes in sensitivity. Figure 20 shows the high threshold sensitivity index, p, for different values of decision criteria, for an observer having constant sensitivity. The detection

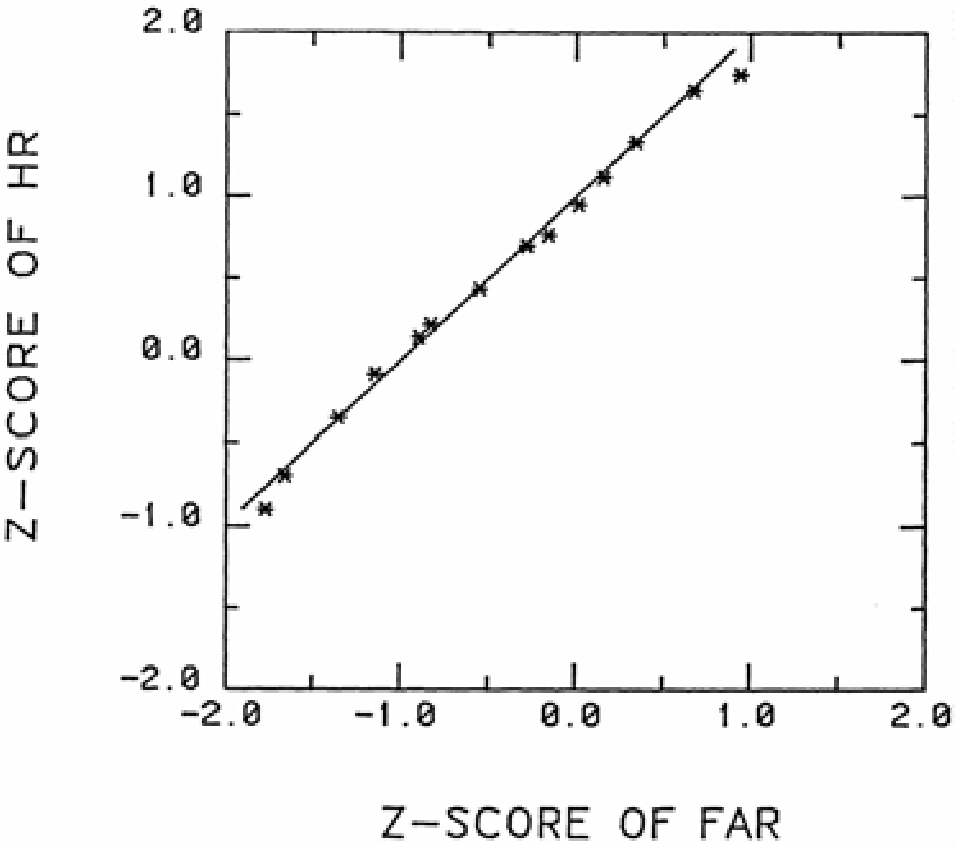


FIGURE 19 Z-score of the hit rate as a function of the Z-score of the false alarm rate. The same data from Figure 19 replotted in Z-score coordinates. The predicted ROC curve and the data form a straight line.

sensitivity, p, calculated from Equation 1, is not constant but changes as a function of decision criteria.

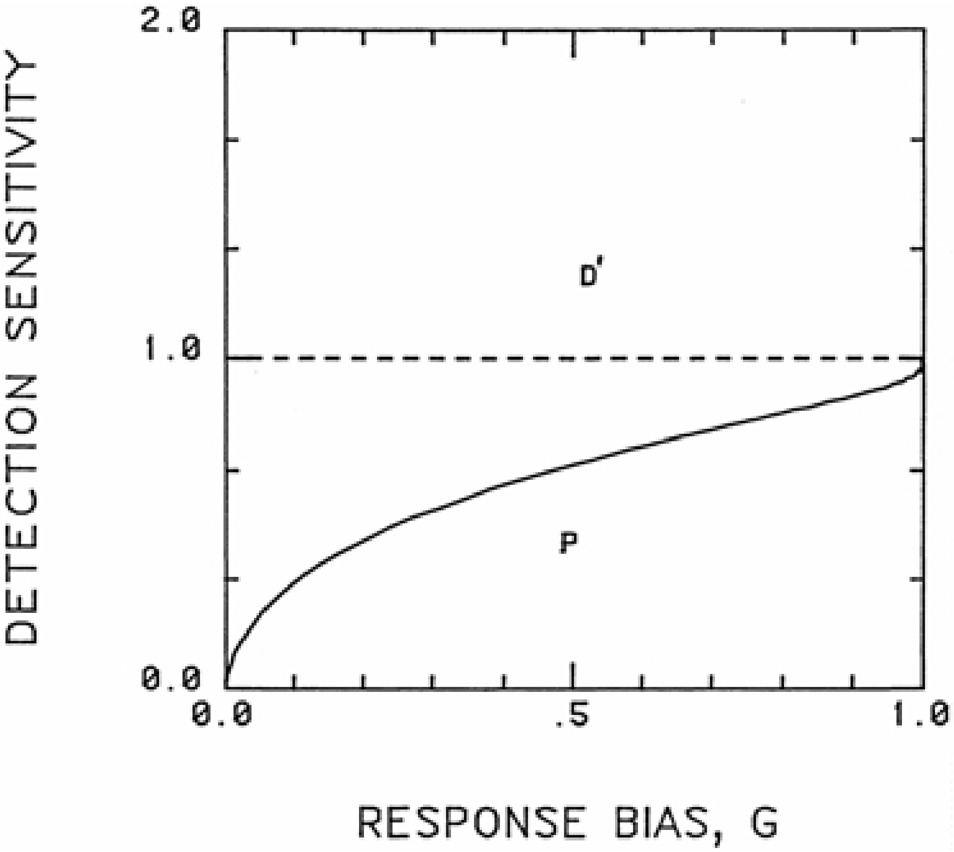


FIGURE 20 Detection sensitivity, p, calculated under the assumptions of the high threshold model (equation 1), as a function of response bias, g (equation 2). Note that p is not independent of g, contrary to the assumption of the high threshold model of detection. Also plotted is d′ (equation 4) as a function of response bias. Note that it is unaffected by shifts in response bias.

A widely used psychophysical procedure is the forced-choice paradigm, especially the two-alternative, forced-choice (2AFC) paradigm. Because only one performance index is obtained from this paradigm, the percentage correct, it is not possible to calculate both a detection sensitivity index and a response criterion index. It is now understood, however, that detection performance in the 2AFC paradigm is equivalent to an observer using an unbiased decision criterion and that the percentage correct performance can be predicted from signal detection theory. Specifically, the percentage correct in a 2AFC detection experiment corresponds to the area under the ROC curve obtained if the same stimulus were used in the yes-no signal detection paradigm (Green and Swets, 1974; Egan, 1975). Calculation of d• from the 2AFC percent correct is also straightforward:

$$d\bullet = 2.0^{0.5} * Z_{p}c \quad (7)$$

where Z_{pc} is the z-score transform of the 2AFC percentage correct (Simpson and Fitter, 1973). The area under the ROC curve for d• = 1.0, illustrated above, is 0.76 (the maximum area of the whole graph is 1.0).

SUMMARY

The classical psychophysical methods of limits, of adjustment, and of constant stimuli provide procedures for estimating sensory thresholds. These methods, however, are not able to separate the independent factors of sensitivity and decision criterion. Furthermore, there is no evidence to support the existence of sensory thresholds, at least in the form these methods were designed to measure.

There are today two methods that allow one to measure an observer's detection sensitivity relatively uninfluenced by changes in decision criteria. One method is the forced-choice paradigm, which forces all observers to adopt the same decision criterion. The second method is based on signal detection theory and requires that there be two types of detection trials: some containing the signal and some containing no signal. Both detection sensitivity and response criterion may be calculated from the hit rates and false alarm rates resulting from the performance in these experiments. Either of these methods may be used to measure the contrast sensitivity function. “Threshold” contrast corresponds to the stimulus contrast giving rise to a certain level of detection performance. A d• of 1.0 or a 2AFC detection of 0.76 is often used to define threshold, but other values may be chosen as long as they are made explicit.

A comparison of contrast sensitivity functions measured by means of the method of adjustment and the two-alternative, forced-choice method is reported by Higgins et al. (1984). The variability of the 2AFC measurements is less than half of those made with the adjustment method. This reduction of measurement variability will increase the reliability of the threshold measures and increase its predictive validity.

Although there are clear benefits of reducing the variability due to differences in decision criterions, the cost effectiveness of these benefits must be evaluated on a case by case basis. Factors such as testing time, ease of administration, ease of scoring, and cost must be carefully considered in relation to the desired reliability, accuracy, and ultimate use to which the measurements will be put. Finally, it must be recognized that no psychophysical method is perfect. Observers may make decisions in irrational ways; some may try to fake a loss of sensory capacity. Care must be taken, regardless of the psychophysical method used to measure capacity, to detect such behavior. A properly administered, conceptually rigorous psychophysical procedure will ensure the maximum predictive validity of the measured sensory capacity.

APPENDIX C: BASIC CONCEPTS IN FOURIER ANALYSIS

STIMULUS SPECIFICATION

A visual stimulus has its beginning as a retinal image and exists as a function of both space and time. One of the core questions in vision research is “What is the best way to specify the visual stimulus?” Usually “best” means the stimulus measure that has the simplest relationship with the performance of some visual task and one that accounts for as much of the variance in performance as possible.

Two broad approaches to answering this question have been taken. Historically, specifications of the visual stimulus have been based on the distribution of luminance across a two-dimensional plane whose coordinates are expressed in degrees of visual angle. Spatial measures derived from the luminance specification range from contrast with the background to amount of contour and number of line and edge features in the stimulus. The empirical basis of visual science until the 1960s was based on relationships between performance on one hand (detection, discrimination, recognition, and identification) and some expressed characteristic of the stimulus on the other (contrast, mean luminance, or angular size). Often, in order to give a simpler relationship between a stimulus specification and performance, the stimulus specification is subjected to a mathematical transformation. The most widely used stimulus transform is the logarithm; for example, the logarithm of stimulus luminance or contrast often has a linear relationship with the z-score of percentage correct in the psychometric function.

The second approach to stimulus specification developed in the past 15 years and is based on a rather complicated mathematical transformation of the luminance distribution of the stimulus: the two-dimensional Fourier transform. The basis of this transform is Fourier's theorem, and in this application the theorem states that any two-dimensional image can be expressed as a harmonic series of sinusoidal grating components of the appropriate spatial frequency, amplitude, phase, and orientation. Each image has a unique series of sinusoidal components that, when added together, will recreate the original image.

In general, the Fourier transform of real numbers (e.g., luminance values in space) is composed of complex numbers, having a real and an imaginary component. These complex numbers are more usually represented as having an amplitude and a phase component. When the two-dimensional luminance plane of a visual stimulus is subjected to Fourier transformation, two planes are therefore created. In both planes the coordinate axes are measured in spatial frequency (cycles per degree), not spatial distance (in degrees). The first plane contains the amplitude information as a function of spatial frequency and is called the amplitude spectrum of the stimulus. The second plane contains phase information as a function of spatial frequency and is called the phase spectrum of the stimulus. Each point in the spatial frequency space represents a sinusoidal grating, of a particular spatial frequency, orientation, contrast, and phase. The Fourier transform is reversible: given the amplitude and phase spectrum of a stimulus, it is possible to reconstruct the original spatial stimulus by means of the inverse Fourier transform. Thus no information is lost or gained in going from the spatial to the spatial frequency specification of a stimulus. Two examples of two-dimensional Fourier transforms are shown in Figure 21. In the upper part of the figure are shown the luminance distributions of the letters "B" and "H" (white letters on a black background. Distance above the plane represents luminance. Below the spatial representation

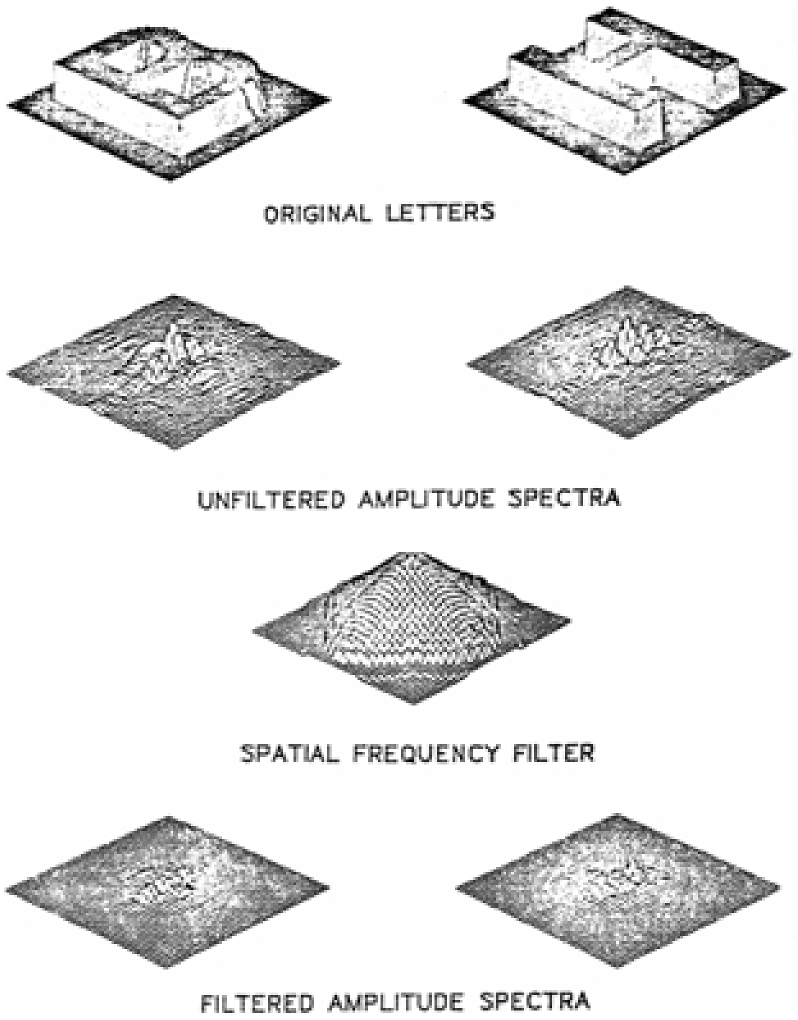


FIGURE 21 Spatial and spatial frequency representations of the letters B and H. Top row: The luminance distribution over space--for ease of viewing, they are shown as white letters against a dark background. Second row: The two-dimensional spatial frequency amplitude spectra. Third row: a two-dimensional spatial frequency filter based on the two-dimensional contrast sensitivity function. Bottom row: The amplitude spectra after being filtered by the contrast sensitivity function. Note the severe loss of high spatial frequency information.

SOURCE: Gervais et al., 1984. Reprinted with permission from L. O. Harvey, Jr. Copyright 1984 by the American Psychological Association.

of the letters are the two-dimensional amplitude spectra of the letters, calculated by means of the fast Fourier transform. In these spectra, zero spatial frequency is in the center of each plane, with spatial frequency increasing outward from the center in all directions. Contrast is represented by distance above the plane.

LINEAR SYSTEMS ANALYSIS

One advantage of describing stimuli in the spatial frequency domain rather then in the space domain is that principles of linear systems analysis may be applied. The basic tenet is that if the response of a linear system is known for each of a series of elementary signals, then the response of the system for any stimulus, no matter how complex, can be predicted. In the case of Fourier analysis, the elementary signals are sinusoidal gratings. We can measure how a system responds when presented with individual sinusoidal gratings. Typically, it will respond better to some frequencies (usually low frequencies) and respond progressively less as frequency is increased. The response is measured by how much of the grating modulation present at the input is transferred to the output. This transfer ratio is measured as a function of spatial frequency and is called the modulation transfer function (MTF). The MTF of a system predicts how any stimulus will be transferred through the system because the stimulus can be described as a series of simple sinusoidal gratings, each of which is transferred with some specific transfer ratio.

There are many assumptions necessary to apply linear systems analysis to the human visual system, many of them not valid. Nevertheless, often the consequences of violating these assumptions are not serious and allow a first-order approximation to predicting how the visual system will respond to a stimulus. Since the final response of the visual system is a subjective experience, the MTF of the system cannot be measured directly. The contrast sensitivity function can be used as an approximation to the MTF. A two-dimensional contrast sensitivity function is shown in the third row of Figure 21. It is typically shaped like a volcano: we are more sensitive to intermediate spatial frequencies than to either lower or higher ones. The amplitude spectra of the letters B and H after passing though a system having a MTF shaped like the human contrast sensitivity function are shown in the fourth row of Figure 21. Notice how much high spatial frequency information is removed from the spectra as a consequence of this filtering.

The basis for the use of sinusoidal gratings as test stimuli in the measurement of the contrast sensitivity function is rooted in the desire to apply linear systems analysis in order to understand the functioning of the visual system. Since the elementary signals of Fourier analysis are sinusoidal gratings, they are the stimuli of choice, since it is necessary to know how the visual system responds to these elementary signals if predictions concerning complex stimuli are to be made. Much controversy still exists about the application of Fourier analysis to human vision, but this controversy is largely theoretical in nature. If the visual system were a linear system, than we could predict the appearance of any visual stimuli simply by filtering its two-dimensional Fourier spectrum with a filter shaped like the contrast sensitivity function. Indeed a few investigators have sought to show what the world looks like to a person with amblyopia (Lundh et al., 1981) or other ocular pathology (Ginsburg, 1984a).

GABOR FUNCTIONS

There are sets of elementary signals other than sinusoidal gratings that can be used to measure the sensitivity of the visual system for the purpose of linear systems analysis. One such stimulus is a sinusoidal grating that has been multiplied by a Gaussian function. Several such stimuli are shown in Figure 22. These stimuli are being called Gabor functions, after Dennis Gabor, who in 1946 proposed that they could be used as a set of elementary signals for linear systems analysis (Gabor, 1946). Gabor showed that there is a trade-off between localizing a stimulus in space and localizing it in frequency. For example, a point in space is perfectly localized in space but completely unlocalized in frequency because its frequency spectrum contains all frequencies. An infinitely large sinusoidal grating is perfectly localized in frequency, because it contains only one frequency, but it is completely unlocalized in space because it extends to infinity. Gabor proved that the stimuli shown in Figure 23 maximize the joint localization in both space and frequency simultaneously.

Marcelja (1980) first suggested that cells in the visual cortex have receptive field sensitivity profiles that are of the form of Gabor functions, and further electrophysiological measurements in the visual cortex of monkies support this idea (Kulikowski et al., 1982; Pollen and Ronner, 1982; Pollen et al., 1984). Psychophysical evidence suggests that the human visual system may also contain mechanisms having characteristics of Gabor functions (Daugman, 1980; MacKay, 1981; Watson et al., 1983; Pollen et al., 1984). These developments may have consequences for the way in which the human contrast sensitivity function is measured, but it is too early to know with any certainty what they are.

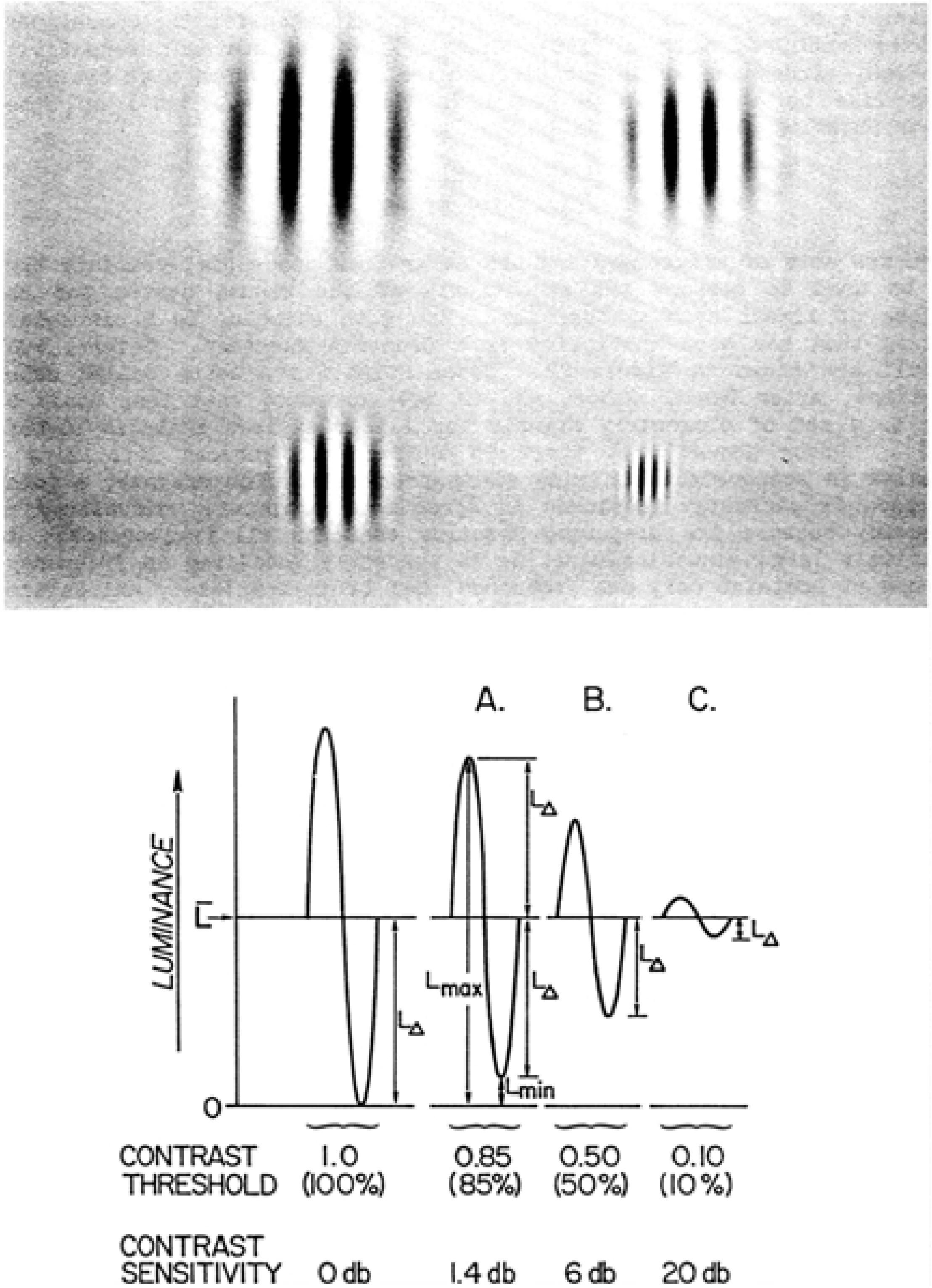


FIGURE 22 Sinusoidal gratings that have been windowed by a Gaussian function, called Gabor signals or Gabor functions. These stimuli are optimally localized both in space and in spatial frequency.

APPENDIX D: THE USE OF TESTS FOR SCREENING AND SELECTION

One use of tests of vision, and one realm in which the working group believes that the emerging techniques can make a considerable contribution, is in the screening and selection of personnel. There are several important and independent issues that must be taken into account when tests are used for these purposes. These issues are often discussed in the context of statistical decision theory (e.g., Einhorn and Hogarth, 1981) and measurement theory (e.g., Stevens, 1951; Townsend and Ashby, 1984). Any test giving a quantitative score, whether visual acuity, grating resolution, or I.Q., has three fundamental characteristics that determine its worthiness: reliability, accuracy, and validity.

RELIABILITY

Reliability is the degree to which a test score is repeatable. It is usually measured by the correlation coefficient, R, calculated between either two separate administrations of the same test or two separate versions of the same test given simultaneously. With a reliable test, persons scoring high on the first administration will score high on the second, while those scoring low on the first will score low on the second. For a perfectly reliable test, $R = 1$; in a completely unreliable test, $R = 0$.

ACCURACY

Accuracy (or precision) is a concept related to reliability. A measurement can be considered to be composed of two components: the true value and some random error. It is not possible to know how much random error is in a specific measurement, but it is possible, using statistical methods, to estimate the average size of the error component. We can therefore specify the accuracy of a particular measurement in terms of a statistical confidence interval. The standard error of the mean is the most commonly used measure of statistical accuracy. Take, for example, a measured threshold value of −2.00 log contrast having a standard error of 0.05. Using the Gaussian probability distribution, one can estimate that the "true" threshold value lies within the range of values −2.05 to −1.95, with a statistical probability of 0.68 (i.e., the 68 percent confidence interval is −2.05 to −1.95). The commonly used 95 percent confidence interval corresponds to plus and minus 1.96 times the standard rror (in this example, −1.90 to −2.10). All other factors being equal, it is desirable to use tests having the highest reliability and giving the most accurate measurements. In any case, the reliability and the accuracy of any vision test used for screening or personnel selection should be known by its users.

VALIDITY

Being reliable is a necessary attribute of a test, but it is not sufficient to ensure that it is useful. A test measurement must also have validity. There are actually three main types of test validity (Nunnally, 1978; Wood, 1977): content validity, predictive validity, and construct validity. For the purpose of screening and selection, predictive validity is the most relevant of the three. Predictive validity is determined by assessing the ability of a test to accurately predict performance on some other test (the other test is called the criterion or standard test). Predictive validity is expressed in terms of R^2, the proportion of variance in the criterion test that is accounted for by the variance in the predicting test. A perfect test would give $R^2 = 1$ and would allow for no errors in screening or selection.

SCREENING AND SELECTION

The factors that must be taken into consideration when a test is used to screen or select personnel will be discussed using a hypothetical example. Flanagan (1947) presents a discussion of the application of these methods to the selection of pilots during World War II. Let us assume that we want to select pilots for their ability to detect distant targets, and that we would like to make this selection on the basis of a simple vision test (which is fast and easy to administer) rather than on the basis of actual target detection performance (which is time-consuming and expensive to measure). In order to use the vision test for selection, we must first measure its predictive validity. To measure its predictive validity, one first takes a randomly selected sample of people from the target population (Air Force pilots in this example), then administers both the vision test and the actual target detection test to all the subjects, then calculates the predictive validity of the vision test by calculating the ability of the vision test to predict each person's score on the target detection task. A set of hypothetical data based on this procedure is shown in Figure 23. Here pilots' target detection ability (criterion task) is plotted as a function of their score on the vision test (predictor score). The predictive validity of the vision test shown in the figure is 0.6, a reasonable value for actual tests. In screening and selection, it is necessary to establish a vision score above which a person will be accepted and below which he or she will be rejected. This cutoff score is illustrated in Figure 23 by the vertical line extending to the horizontal axis of the graph. There is a second cutoff score that also must be established: the performance level on the criterion task that defines the minimum acceptable level of performance. This cutoff is represented by the horizontal line extending to the vertical axis of the graph. Target detection performance above this level is defined as acceptable, while performance below it is unacceptable.

These two cutoffs divide the population of tested individuals into four groups or quadrants. Two quadrants represent correct decisions and the two others represent mistakes in the screening or selection process.

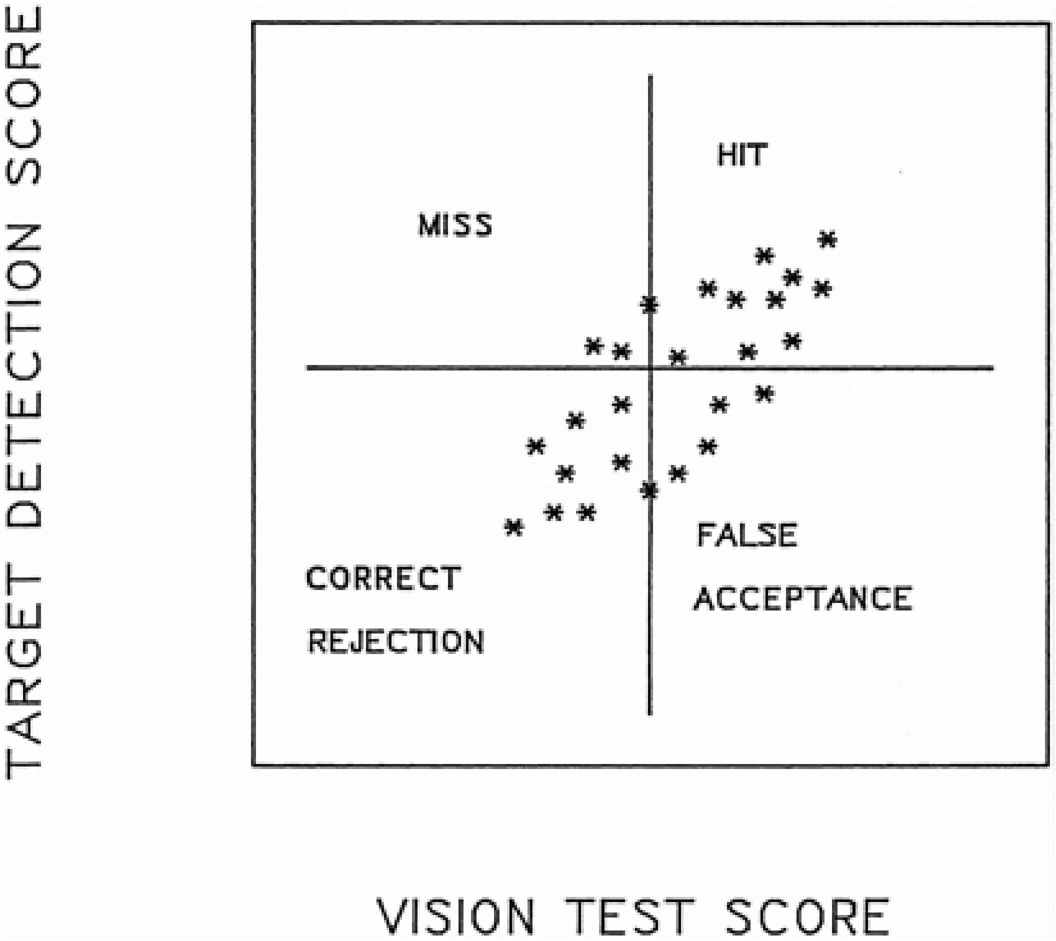


FIGURE 23 Selection of pilots based on hypothetical data.

The people in the upper right quadrant are those who are accepted on the basis of their vision test score and who have acceptable target detection ability: they are called hits. The other correct decisions are the people in the lower left quadrant who are rejected on the basis of their vision score and who indeed have unacceptable target detection ability: they are called correct rejections. There are two types of selection mistakes. The people in the upper left quadrant are those who are rejected on the basis of their low score on the vision test but who nevertheless have acceptable target detection ability: they are called misses. The other mistakes are in the lower right quadrant; those who, because of their high vision score, are accepted but have poor target detection performance: they are called false acceptances. Generally, it is desirable to maximize the hits and correct rejections, while minimizing the misses and false acceptances.

An interesting aspect of the screening or selection process is that it is only possible to have error-free decisions when using a predictive test with a predictive validity of 1. In the more usual screening situation illustrated in Figure 23, errors of selection will always occur; there is no way to achieve error-free selection. The two cutoffs can be adjusted as is appropriate for each specific circumstance. For example, requiring a higher vision score for acceptance (moving the cutoff score to the right) will decrease the number of false acceptances and increase the correction rejections, but at the cost of increasing the misses and decreasing the hits. In a similar manner, lowering the criterion level defining acceptable target performance will increase the number of hits and decrease the false acceptances but at the cost of reduced correct rejections and increased miss rate. Exactly where the two cutoffs are placed would usually depend on the relative costs of the two types of errors and the relative benefits of the two types of correct decisions. This approach to selection allows a rational basis for setting cutoff points to achieve the goals of the screening or selection process.

SUMMARY

In order for a test to be useful in screening or personnel selection it must first be reliable (a necessary but not sufficient condition) and it must have a reasonably high predictive validity on some relevant criterion task. Accuracy is also important because it contributes both to reliability and validity; lower accuracy lowers both test reliability and predictive validity. It is important when comparing two tests on their reliability and predictive validity that the measurements be taken with the same level of statistical accuracy. Otherwise the test with the higher statistical accuracy (smaller confidence interval) will have an artifactual advantage over the other. It is not possible to achieve error-free screening or selection using a test whose predictive validity is less than 1. Cutoff points can be adjusted, however, to allow an appropriate balance between hits, correct rejections, misses, and false acceptances. The costs, benefits, and goals of the screening or selection process will determine how the cutoffs are set.

REFERENCES

Appelle, S. (1972). Perception and discrimination as a function of stimulus orientation: The "oblique effect" in man and animals. Psychological Bulletin, 78, 266-278.

Banks, M. S., and Stephens, B. R. (1981). A Test of the Linear Systems Approach to Studying Infant Pattern Vision. Poster presented at the meeting of the Society for Research in Child Development, Boston, Mass.

Bentivegna, J., Owens, D. A., and Messner, K. (1981). Aging, cycloplegia, and the accuracy of accommodation. Investigative Ophthalmology and Visual Science, 20, 21.

Beverley, K. I., and Regan, D. (1975). The relation between discrimination and sensitivity in the perception of motion in depth. Journal of Physiology, 249, 387-398.

Beverley, K. I., and Regan, D. (1980). Temporal selectivity of changing-size channels. Journal of the Optical Society of America, 70, 1375-1377.

Beverley, K. I., and Regan, D. (1983). Texture changes versus size changes as stimuli for motion in depth. Vision Research, 23, 1387-1400.

Blackwell, H. R. (1946). Contrast thresholds of the human eye. Journal of the Optical Society of America, 36, 642-643.

Blakemore, C., and Campbell, F. W. (1969). On the existence of neurons in the human visual system selectively sensitive to the orientation and size of retinal images. Journal of Physiology, 203, 237-260.

Bodis-Wollner, I. (1972). Visual acuity and contrast sensitivity in patients with cerebral lesions. Science, 178, 769-771.

Bodis-Wollner, I., and Diamond, S. P. (1976). The measurement of spatial contrast sensitivity in cases of blurred vision associated with cerebral lesions. Brain, 99, 695-710.

Bodis-Wollner, I., Hendley, C. D., Mylin, L. H., and Thornton, J. (1979). Visual evoked potentials and the visuogram in multiple sclerosis. Annals of Neurology, 5, 40-47.

Bour, L. J. (1981). The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. Vision Research, 21, 1287-1296.

Brettel, H., Caelli, T., Hilz, R., and Rentschler, I. (1982). Modelling perceptual distortion: Amplitude and phase processing in the human visual system. Human Neurobiology, 1, 61-67.

Burg, A. (1966). Visual acuity as measured by dynamic and static tests: A comparative evaluation. Journal of Applied Psychology, 50, 460-466.

Burg, A. (1967). The Relationship Between Vision Test Scores and Driving Record: General Findings. Report no. 67-24. Los Angeles: University of California, Department of Engineering.

Burg, A. (1968). Vision Test Scores and Driving Record: Additional Findings. Report no. 68-27. Los Angeles: University of California, Department of Engineering.

Burg, A., and Hulbert, S. (1961). Dynamic visual acuity as related to age, sex, and static acuity. Journal of Applied Psychology, 45, 111-116.

Caelli, T., and Bevan, P. (1982). Visual sensitivity to two-dimensional spatial phase. Journal of the Optical Society of America, 72, 1375-1381.

Campbell, F. W., and Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings. Journal of Physiology, 197, 551-566.

Campbell, F. W., Kulikowski, J. J., and Levinson, J. (1966). The effect of orientation on the visual resolution of gratings. Journal of Physiology, 187, 427-436.

Cannon, M. W., Jr. (1979). Contrast sensation: A linear function of stimulus contrast. Vision Research, 19, 1245-1252.

Crawford, W. A. (1960a). The Perception of Moving Objects. I. Ability and Visual Acuity. Report FPRC/Memo 150a. Farnborough, England: Royal Air Force Air Ministry Flying Personnel Research Committee.

Crawford, W. A. (1960b). The Perception of Moving Objects. II. Eye Movements. Report FPRC/Memo 150b. Farnborough, England: Royal Air Force Air Ministry Flying Personnel Research Committee.

Crawford, W. A. (1960c). The Perception of Moving Objects. IV. The Aaccuracy of Fixation Required in the Perception of Detail in Moving Objects. Report FPRC/Memo 150d. Farnborough, England: Royal Air Force Air Ministry Flying Personnel Research Committee.

Daniel, M., and Whitteridge, D. (1961). The representation of the visual field on the cerebral cortex in monkeys. Journal of Physiology, 159, 203-221.

Daugman, J. G. (1980). Two-dimensional spectral analysis of cortical receptive field profiles. Vision Research, 20, 847-856.

Davis, H., and Silverman, S. R. (1960). Hearing and Deafness. Revised edition. New York: Holt, Rinehart, and Winston.

DeKlerk, L. F. W., Eernest, J. Th., and Hoogerheide, J. (1964). The dynamic visual acuity of 30 selected pilots. Aeromedica Acta, 9, 129-136.

DePalma, J. J., and Lowry, E. M. (1962). Sine-wave response of the visual system. II. Sine-wave and square wave contrast sensitivity. Journal of the Optical Society of America, 52, 328-335.

Dichgans, J., and Brandt, Th. (1978). Visual-vestibular interaction: Effects on self-motion and postural control. In R. Held, H. W. Leibowitz, and H. L. Teuber, Eds., Handbook of Sensory Physiology. Vol. VIII. Heidelberg: Springer.

Ebenholtz, S. M., (1981). Hysteresis effects in the vergence contol system: Perceptual implications. In D. F. Fisher, R. A. Monty, and J. W. Senders, Eds., Eye Movements: Cognition and Visual Perception. Hillsdale, N.J.: Lawrence Erlbaum Associates.

Ebenholtz, S. M. (1983). Accommodative hysteresis: A precursor for induced myopia? Investigative Ophthalmology and Visual Science, 24, 513-515.

Ebenholtz, S. M. (1984). Hysteresis magnitude as a function of fixation target distance from the dark focus. Proceedings of the International Society for Eye Research, 3, L-6, 133.

Ebenholtz, S. M., and Fisher, S. K. (1982). Distance adaptation depends upon plasticity in the oculomotor system. Perception and Psychophysics, 31, 551-560.

Egan, J. P. (1975). Signal Detection Theory and ROC Analysis. New York: Academic Press.

Einhorn, H. J., and Hogarth, R. M. (1981). Behavioral decision theory: Processes of judgment and choice. Annual Review of Psychology, 32, 53-88.

Elkin, E. H. (1962). Target velocity, exposure time and anticipatory tracking time as determinants of dynamic visual acuity (DVA). Journal of Engineering Psychology, 1, 26-33.

Epstein, D., Ingelstam, E., Jansson, K., and Tengroth, B. (1981). Low-luminance myopia as measured with a laser optometer. Acta Ophthalmologica 59, 928-943.

Fechner, G. T. (1860). Elemente der Psychophysik. Vol. I. Leipzig: Breitkopf und Hertel.

Flanagan, J. C. (1947). Scientific development of the use of human resources: Progress in the Army Air Forces. Science, 105, 57-60.

Gabor, D. (1946). Theory of communication. Journal of IEE (London), 93, 429-457.

Gayl, I. E., Roberts, J. O., and Werner, J. S. (1983). Linear systems analysis of infant visual pattern preferences. Journal of Experimental Child Psychology, 35, 30-45.

Georgeson, M. A., and Sullivan, G. D. (1975). Contrast constancy: Deblurring in human vision by spatial frequency channels. Journal of Physiology, 252, 627-656.

Gervais, M. J. (1978). Spatial Frequency and Letter Cconfusions: A Test of Fourier Analysis as a Metric and a Model for Form Perception. Master's thesis, Department of Psychology, University of Colorado.

Gervais, M. J., Harvey, L. O., Jr., and Roberts, J. O. (1984). Identification confusions among letters of the alphabet. Journal of Experimental Psychology: Human Perception and Performance, 10, 655-666.

Ginsburg, A. P. (1981a). Spatial filtering and vision: Implications for normal and abnormal vision. Pp. 70-106 in L. Proenza, J. Enoch, and A. Jampolsky, Eds., Clinical Applications of Visual Psychophysics. Proceedings of a Symposium held in San Francisco, October 1978. Cambridge, England: Cambridge University Press.

Ginsburg, A. P. (1981b). Proposed New Vision Standards for the 1980's and Beyond: Contrast Sensitivity. Air Force Aerospace Medical Research Laboratory, Report AFARML-TR-80-121. Wright-Patterson Air Force Base, Dayton, Ohio.

Ginsburg, A. P. (1983). Contrast sensitivity: Relating visual capability to performance. USAF Medical Service Digest (Summer): 15-19.

Ginsburg, A. P. (1984a). Visual form perception based on biological filtering. Pp. 53-72 in L. Spillmann and B. R. Wooten, Eds., Sensory Experience, Adaptation, and Perception. Hillsdale, N.J.: Erlbaum.

Ginsburg, A. P. (1984b). A new contrast sensitivity vision test chart. American Journal of Optometry and Physiological Optics, 61, 403-407.

Ginsburg, A. P., Cannon, M. W., Jr., and Nelson, M. (1980). Suprathreshold processing of complex visual stimuli: Evidence for linearity in contrast perception. Science, 208, 619-621.

Ginsburg, A. P., Easterly, J., and Evans, D. W. (1983). Contrast sensitivity predicts target detection field performance of pilots. Proceedings of the Human Factors Society. (27th Annual Meeting): 269-273.

Ginsburg, A. P., Evans, D., Cannon, M. W., Owsley, C., and Mulvanny, P. (1984). Large-sample norms for contrast sensitivity. American Journal of Optometry and Physiological Optics, 61, 80-84.

Ginsburg, A. P., Evans, D., Sekuler, R., and Harp, S. (1982). Contrast sensitivity predicts pilots' performance in aircraft simulators. American Journal of Optometry and Physiological Optics, 59, 105-109.

Gogel, W. C. (1977). The metric of visual space. In W. Epstein, Ed., Stability and Constancy in Visual Perception: Mechanisms and Processes. New York: Wiley.

Goodson, J. E., and Miller, J. W. (1959). Dynamic visual acuity in an applied setting. Aerospace Medicine, 30, 755-763.

Graham, C. H., and Margaria, R. (1935). Area and the intensity-time relation in the peripheral retina. American Journal of Physiology, 113, 299-305.

Graham, N., and Nachmias, J. (1971). Detection of grating patterns containing two spatial frequencies: A comparison of single and multi-channel models. Vision Research, 11, 251-259.

Green, D. M., and Swets, J. A. (1974). Signal Detection Theory and Psychophysics. Huntington, N.Y.: Robert E. Krieger.

Guth, S. K., and McNelis, J. F. (1969). Threshold contrast as a function of complexity. American Journal of Optometry and Archives of American Academy of Optometry, 46, 98-103.

Harvey, L. O., Jr., and Gervais, M. J. (1978). Visual texture perception and Fourier analysis. Perception and Psychophysics, 24, 534-542.

Harvey, L. O., Jr., and Gervais, M. J. (1981). Internal representation of visual texture as the basis for the judgment of similarity. Journal of Experimental Psychology: Human Perception and Performance, 7, 741-753.

Head, H. (1918). The Sense of Stability and Balance in the Air. Report no. 28 of the Air Medical Investigation Committee, Medical Research Committee, November 14th, 1918 .

Hecht, S., Hendley, C. D., Frank, S., and Shlaer, S. (1949). Contrast discrimination charts for demonstrating the effect of anorexia on vision. Journal of the Optical Society of America, 11, 922-923.

Held, R. (1968). Dissociation of visual functions by deprivation and rearrangement. Psychologische Forschung, 31, 338-348.

Held, R. (1970). Two modes of processing spatially distributed visual stimulation. In F. O. Schmidt, Ed., The Neurosciences: Second Study Program. New York: Rockefeller University Press.

Henderson, R. L., and Burg, A. (1973). The Role of Vision and Audition in Truck and Bus Driving. TM-(L)-5260/000/00. Santa Monica, Calif.: Systems Development Corp.

Hennessy, R. T. (1975). Instrument myopia. Journal of the Optical Society of America, 65, 1114-1120.

Hennessy, R. T., and Leibowitz, H. W. (1972). Laser optometer incorporating the Badal principle. Behavioral Research Methods and Instrumentation, 4, 237-239.

Hennessy, R. T., Iida, T., Shiina, K., and Leibowitz, H. W. (1976). The effect of pupil size on accommodation. Vision Research, 16, 587-590.

Hess, R. (1984). Uses and abuses of assessing contrast threshold functions for anomalous vision. Pp. 633-650 in L. Spillmann and B. R. Wooten, Eds., Sensory Experience, Adaptation, and Perception. Hillsdale, N. J.: Lawrence Erlbaum Associates.

Higgins, K. E., Jaffe, M. J., Coletta, N. J., Caruso, R. C., and de Monasterio, F. M. (1984). Spatial contrast sensitivity: Importance of controlling the patient's visibility criterion. Archives of Ophthalmology, 102, 1035-1041.

Ingle, D. (1967). Two visual mechanisms underlying the behaviour of fish. Psychologische Forschung, 31, 44-51.

Johnson, C. A. (1976). Effects of luminance and stimulus distance on accommodation and visual resolution. Journal of the Optical Society of America, 66, 138-142.

Karmel, B. Z. (1969). The effect of age, complexity, and amount of contour on pattern preferences in human infants. Journal of Experimental Child Psychology, 7, 339-354.

Kelly, D. H. (1979). Motion and vision. II. Stabilized spatio-temporal threshold surface. Journal of the Optical Society of America 69, 1340-1349.

Kintz, R. T., and Bowker, D. O. (1982). Accommodation response during a prolonged visual search task. Applied Ergonomics, 13, 55-59.

Krantz, D. H. (1969). Threshold theories of signal detection. Psychological Review, 76, 308-324.

Kruk, R., and Regan, D. (1983). Visual test results compared with flying performance in telemetry-tracked aircraft. Aviation, Space, and Environmental Medicine, 54, 906-911.

Kruk, R., Regan, D., Beverley, K. I., and Longridge, T. (1981). Correlations between visual test results and flying performance on the Advanced Simulator for Pilot Training (ASPT). Aviation, Space, and Environmental Medicine, 52, 455-460.

Kulikowski, J. J., Marcelja, S., and Bishop, P. O. (1982). Theory of spatial position and spatial frequency relations in the receptive fields of simple cells in the visual cortex. Biological Cybernetics, 43, 187-198.

Leibowitz, H. W. (1976). Visual perception and stress. In G. Borg, Ed., Physical Work and Effort. New York: Pergamon Press.

Leibowitz, H. W., and Dichgans, J. (1980). The ambient visual system and spatial disorientation. In AGARD Conference Proceedings No. 287: Spatial Disorientation in Flight, Current Problems . Bodo, Norway.

Leibowitz, H. W., and Owens, D. A. (1977). Nighttime accidents and selective visual degradation. Science, 189, 646-648.

Leibowitz, H. W., and Owens, D. A. (1978). New evidence for the intermediate position of relaxed accommodation. Documenta Ophthalmologica, 46, 133-147.

Leibowitz, H. W., and Post, R. B. (1982). The two modes of processing concept and some implications. In J. Beck, Ed., Organization and Representation in Perception. Hillsdale, N.J.: Lawrence Erlbaum Associates.

Leibowitz, H. W., and Post, R. B. (in press). Some implications of gaze stability mechanisms for vision in aviation. In Conference Proceedings, Vision as a Factor in Military Aviation, School of Aviation Medicine, Brooks Air Force Base, Tex.

Leibowitz, H. W., Post, R., and Ginsburg, A. P. (1980). The role of fine detail in visually controlled behavior. Investigative Ophthalmology, 19, 846-848.

Leibowitz, H. W., Post, R. B., Brandt, Th., and Dichgans, J. (1982). Implications of recent developments in dynamic spatial orientation and visual resolution for vehicle guidance. In A. Wertheim, W. A. Wagenaar, and H. W. Leibowitz, Eds., Tutorials on Motion Perception. New York: Plenum Press.

Levine, J. R. (1965). Nevil Maskelyne, F.R.S., and the Discovery of Night Myopia. Notes and Reports, 20, 100-108, Royal Society of London.

Luckiesh, M., and Moss, F. K. (1940). Functional adaptation to near vision. Journal of Experimental Psychology, 26, 352-356.

Ludvigh, E. J. (1949). Visual acuity while one is viewing a moving object. Archives of Ophthalmology, 42, 14-22.

Ludvigh, E., and Miller, J. W. (1953). A Study of Dynamic Visual Acuity. NSAM-562. Naval School of Aviation Medicine, Pensacola, Fla.

Ludvigh, E., and Miller, J. W. (1954). An Analysis of Dynamic Visual Acuity in a Population of 200 Naval Aviation Cadets. NSAM-568. Naval School of Aviation Medicine, Pensacola, Fla.

Ludvigh, E., and Miller, J. W. (1958). Study of visual acuity during the ocular pursuit of moving test objects. I. Introduction. Journal of the Optical Society of America, 48, 799-802.

Lundh, B. L., and Arlinger, S. (1984). Three dB-scales for the standardized visuogram. Vision Research, 24, 889-890.

Lundh, B. L., Derefeldt, G., Nyberg, S., and Lennerstrand, G. (1981). Picture stimulation of contrast sensitivity in organic and functional amblyopia. Acta Ophthalmologica, 59, 777-783.

Luria, S. M. (1980). Target size and correction for empty-field myopia. Journal of the Optical Society of America, 70, 1153-1154.

MacKay, D. M. (1981). Strife over visual cortical function. Nature, 289, 117-118.

Mackworth, N. H., and Kaplan, I. T. (1962). Visual acuity when the eyes are pursuing moving targets. Science, 136, 387-388.

Maddock, R. J., Millodot, M., Leaf, S., and Johnson, C. A. (1981). Accommodation responses and refractive error. Investigative Ophthalmology and Visual Science 20, 387-391.

Malcolm, R., Money, K. E., and Anderson, P. (1975). Peripheral vision and artificial display. In AGARD Conference Proceedings No. 145 on Vibration and Combined Stress in Advanced Systems.

Mandelbaum, J. (1960). An accommodation phenomenon. Archives of Ophthalmology, 63, 923-926.

Marcelja, S. (1980). Mathematical description of the responses of simple cortical cells. Journal of the Optical Society of America, 70, 1297-1300.

Mayyasi, A. M., Beals, R. P., Templeton, A. E., and Hale, P. N., Jr. (1971). The effects of ambient illumination and contrast on dynamic visual acuity. American Journal of Optometry and Archives of the American Academy of Optometry, 48, 844-848.

McCann, J. J., Savoy, R. L., and Hall, J. A., Jr. (1978). Visibility of low frequency sine-wave targets: Dependence on number of cycles and surround parameters. Vision Research, 18, 891-894.

Mershon, D. H., and Amerson, T. L. (1980). Stability of measures of the dark focus of accommodation. Investigative Ophthalmology and Visual Science, 19, 217-221.

Miller, E. F., II. (1959). Effect of Exposure Time Upon Ability to Pperceive a Moving Target. NSAM-518. Naval School of Aviation Medicine, Pensacola, Fla.

Miller, J. W. (1956). The Effect of Altered Illumination on Visual Acuity Measured During Ocular Pursuit. NSAM-573. Naval School of Aviation Medicine, Pensacola, Fla.

Miller, J. W. (1958). Study of visual acuity during the ocular pursuit of moving test objects. II. Effects of direction of movement, relative movement, and illumination. Journal of the Optical Society of America, 48, 803-808.

Miller, J. W. and Ludvigh, E. (1953). Dynamic Visual Acuity When the Required Pursuit Movement of the Eye is in a Vertical Plane. NSAM-563. Naval School of Aviation Medicine, Pensacola, Fla.

Miller, J. W., and Ludvigh, E. (1962). The effect of relative motion on visual acuity. Survey of Ophthalmology, 7, 83-115.

Miller, R. J. (1978a). Temporal stability of the dark focus of accommodation. American Journal of Optometry and Physiological Optics, 55, 447-450.

Miller, R. J. (1978b). Mood changes and the dark focus of accommodation. Perception and Psychophysics, 24, 437-443.

Miller, R. J. (1980). Ocular vergence-induced accommodation and its relation to dark-focus. Perception and Psychophysics, 28, 125-132.

Miller, R. J., and LeBeau, R. C. (1982). Induced stress, situationally-specific trait anxiety, and dark focus. Psychophysiology, 19, 260-265.

Morgan, M. J., Watt, R. and McKee, S. (1983). Exposure duration affects the sensitivity of vernier acuity to target motion. Vision Research, 23, 541-546.

Morrison, T. R. (1980). A Review of Dynamic Visual Acuity. NAMRL Monograph No. 28. Naval Aerospace Medical Research Laboratory, Pensacola, Fla.

Murch, G. (1982). How visible is your display? Electro-Optical System Design (March): 43-49.

Murphy, B. J. (1978). Pattern thresholds for moving and stationary gratings during smooth eye movements. Vision Research, 18, 521-530.

National Research Council. (1980). Standards for testing visual fields and visual acuity. Recommended standard procedures for the clinical measurement and specification of visual acuity. Working Group 39, Committee on Vision . Advances in Ophthalmology, 41, 103-148.

Nunnally, J.C. (1978). Psychometric Theory. 2nd ed. New York: McGraw-Hill.

Ostberg, O. (1980). Accommodation and visual fatigue in display work. Pp. 41-52 in E. Grandjean and E. Vigliani, Eds., Ergonomic Aspects of Visual Display Terminals. London: Taylor and Francis.

Owens, D. A. (1979). The Mandelbaum effect: Evidence for an accommodative bias toward intermediate viewing distances. Journal of the Optical Society of America, 69, 646-652.

Owens, D. A. (1980). A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. Vision Research, 20, 159-167.

Owens, D. A. (1984). The resting state of the eyes. American Scientist , 72, 378-387.

Owens, D. A. (in press). The resting states of accommodation and vergence: Individual differences and their perceptual consequences. In Proceedings of the Conference on Vision as a Factor in Military Aircraft Mishaps, United States Air Force School of Aerospace Medicine, Brooks Air Force Base, Tex.

Owens, R. L. and Higgins, K. E. (1983). Long-term stability of the dark-focus of accommodation. American Journal of Optometry and Physiological Optics, 60, 32-38.

Owens, D. A., and Leibowitz, H. W. (1976). Night myopia: Cause and a possible basis for amelioration. American Journal of Optometry, 53, 709-717.

Owens, D. A., and Leibowitz, H. W. (1980). Accommodation, convergence, and distance perception in low illumination. American Journal of Optometry and Physiological Optics, 57, 540-550.

Owens, D. A., and Leibowitz, H. W. (1983). Perceptual and motor consequences of tonic vergence. In C. Schor and K. Ciufredda, Eds., Vergence Eye Movements: Basic and Clinical Aspects. Boston: Butterworth Publishers.

Owens, D. A., and Wolf, K. S. (1983). Accommodation, binocular vergence, and visual fatigue. Investigative Ophthalmology and Visual Science, 24, 23.

Owens, D. A., Mohindra, I., and Held, R. (1980). The effectiveness of a retinoscope beam as an accommodative stimulus. Investigative Ophthalmology and Visual Science, 19, 942-949.

Owens, R. L., Sterling, R. H., and Owens, D. A. (1982). The Clinical Determination of Night Driving Corrections. Presentation at the Annual Meeting of the American Academy of Optometry, Philadelphia.

Owsley, C., Sekuler, R., and Siemsen, D. (1983). Contrast sensitivity throughout adulthood. Vision Research, 23, 689-699.

Pollen, D. A., and Ronner, S. F. (1982). Spatial computation performed by simple and complex cells in the visual cortex of the cat. Vision Research, 22, 101-118.

Pollen, D. A., Nagler, M., Daugman, J., Kronauer, R., and Cavanagh, P. (1984). Use of Gabor elementary functions to probe receptive field substructure of posterior inferotemporal neurons in the owl monkey. Vision Research, 24, 233-241.

Post, R. B., and Leibowitz, H. W. (1982). The effect of convergence on the vestibulo-ocular reflex and implications for perceived movement. Vision Research, 22, 461-465.

Post, R. B., Owens, R. L., Owens, D. A., and Leibowitz, H. W. (1979). Correction of empty-field myopia on the basis of the dark focus of accommodation. Journal of the Optical Society of America, 69, 89-91.

Proenza, L. M., Enoch, J. M., and Jampolsky, A., Eds. (1981). Clinical Applications of Visual Psychophysics. Cambridge, England: Cambridge University Press.

Raymond J. E., Lindblad, I. M., and Leibowitz, H. W. (1984a). The effect of contrast on sustained detection. Vision Research 24, 183-188.

Raymond, J. E., Lindblad, I. M., and Leibowitz, H. W. (1984b). Contrast sensitivity function of the accommodative system. Investigative Ophthalmology and Visual Science (Suppl.), 22, 126.

Reading, V. M. (1972a). Visual resolution as measured by dynamic and static tests. Pflugers Archiv, 333, 17-26.

Reading, V. M. (1972b). Analysis of eye movement responses and dynamic visual acuity. Pflugers Archiv, 333, 27-34.

Reason, J. R., and Brand, J. J. (1975). Motion Sickness. New York: Academic Press.

Regan, D., and Beverley, K. I. (1983). Spatial-frequency discrimination and detection: Comparison of postadaptation thresholds. Journal of the Optical Society of America, 73, 1684-1690.

Regan, D., and Cynader, M. (1982). Neurons in cat visual cortex tuned to direction of motion in depth: Effect of stimulus speed. Investigative Ophthalmology and Visual Science, 22, 535-550.

Regan, D., and Neima, D. (1983). Low-contrast letter charts as a test of visual function. Ophthalmology, 90, 1192-1200.

Regan, D., and Neima, D. (1984). Low-contrast letter charts in early diabetic retinopathy, ocular hypertension, glaucoma, and Parkinson's disease. British Journal of Ophthalmalogy, 68, 555-559.

Regan, D., Bartol, S., Murray, T. J., and Beverley, K. I. (1982). Spatial frequency discrimination in normal vision and in patients with multiple sclerosis. Brain, 105, 735-754.

Regan, D., Raymond, J., Ginsburg, A.P., and Murray, T.J. (1981). Contrast sensitivity, visual acuity and the discrimination of Snellen letters in multiple sclerosis. Brain, 104, 333-350.

Roscoe, S.N. (1982). Landing airplanes, detecting traffic, and the dark focus. Aviation, Space, and Environmental Medicine, 53, 970-976.

Roscoe, S.N., and Hull, J.C. (1982). Cockpit visibility and contrail detection. Human Factors, 24, 659-672.

Rovamo, J., and Virsu, V. (1979). An estimation and application of the human cortical magnification factor. Experimental Brain Research, 37, 495-510.

Schade, O.H. (1956). Optical and photoelectric analog of the eye. Journal of the Optical Society of America, 46, 721-739.

Schneider, G. E. (1967). Contrasting visuomotor functions of tectum and cortex in the golden hamster. Psychologische Forschung, 31, 52-62.

Schober, H.A.W. (1954). Uber die Akkommodationsruhelage. Optik, 11, 282-290.

Schor, C.M., Johnson, C.A., and Post, R.B. (1984). Adaptation of tonic accommodation. Ophthalmic and Physiological Optics, 4, 133-137.

Schwartz, E. L. (1980). Computational anatomy and functional architecture of striate cortex: A spatial mapping approach to perceptual coding. Vision Research, 20, 645-669.

Sekuler, R., Wilson, H. R., and Owsley, C. (1984). Structural modeling of spatial vision. Vision Research, 24, 689-700.

Shebilske, W. (1981). Visual direction illusions in everyday situations: Implications for sensorimotor and ecological theories. In D. F. Fisher, R. A. Monty, and J. W. Senders, eds., Eye Movements; Cognition and Visual Perception. Hillsdale, N.Y.: Lawrence Erlbaum Associates.

Simonelli, N. M. (1983). The dark focus of the human eye and its relation to age and visual defect. Human Factors, 25, 85-92.

Stevens, S. S. (1951). Mathematical measurements and psychophysics. Pp. 1-49 in S. S. Stevens, Ed., Handbook of Experimental Psychology. New York: John Wiley.

Stromeyer, C. F., III, and Julesz, B. (1972). Spatial frequency masking in vision: Critical bands and spread of masking. Journal of the Optical Society of America, 62, 1221-1232.

Swets, J. A. (1961). Is there a sensory threshold? Science, 134, 168-177.

Swets, J. A., Tanner, W. P., Jr., and Birdsall, T. G. (1961). Decision processes in perception. Psychological Review, 68, 301-340.

Townsend, J. T., and Ashby, F. G. (1984). Measurement scales and statistics: The misconception misconceived. Psychological Bulletin, 96, 394-401.

Trevarthen, C. (1968). Two mechanisms of vision in primates. Psychologische Forschung, 31, 299-337.

Virsu, V., and Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. Experimental Brain Research, 37, 475-494.

Wald, G., and Griffin, D. R. (1947). The change in refractive power of the human eye in dim and bright light. Journal of the Optical Society of America, 37, 321-336.

Watson, A. B., Barlow, H. B., and Robson, J. G. (1983). What does the eye see best? Nature, 302, 419-422.

Weiskrantz, L., Warrington, E. K., Sanders, M. D., and Marshall, J. (1974). Visual capacity in the hemianopic field following a restricted occipital ablation. Brain, 97, 709-728.

Weissman, S., and Freeburne, C. M. (1965). Relationship between static and dynamic visual acuity. Journal of Experimental Psychology, 70, 141-146.

Weisz, C. L. (1980). The accommodative resting state: Theoretical implications of lens prescriptions. Review of Optometry, 117, 60-70.

Westheimer, G. (1957). Accommodation measurements in empty visual fields. Journal of the Optical Society of America, 47, 714-718.

Westheimer, G. (1960). Modulation thresholds for sinusoidal light distributions on the retina. Journal of Physiology, 152, 67-74.

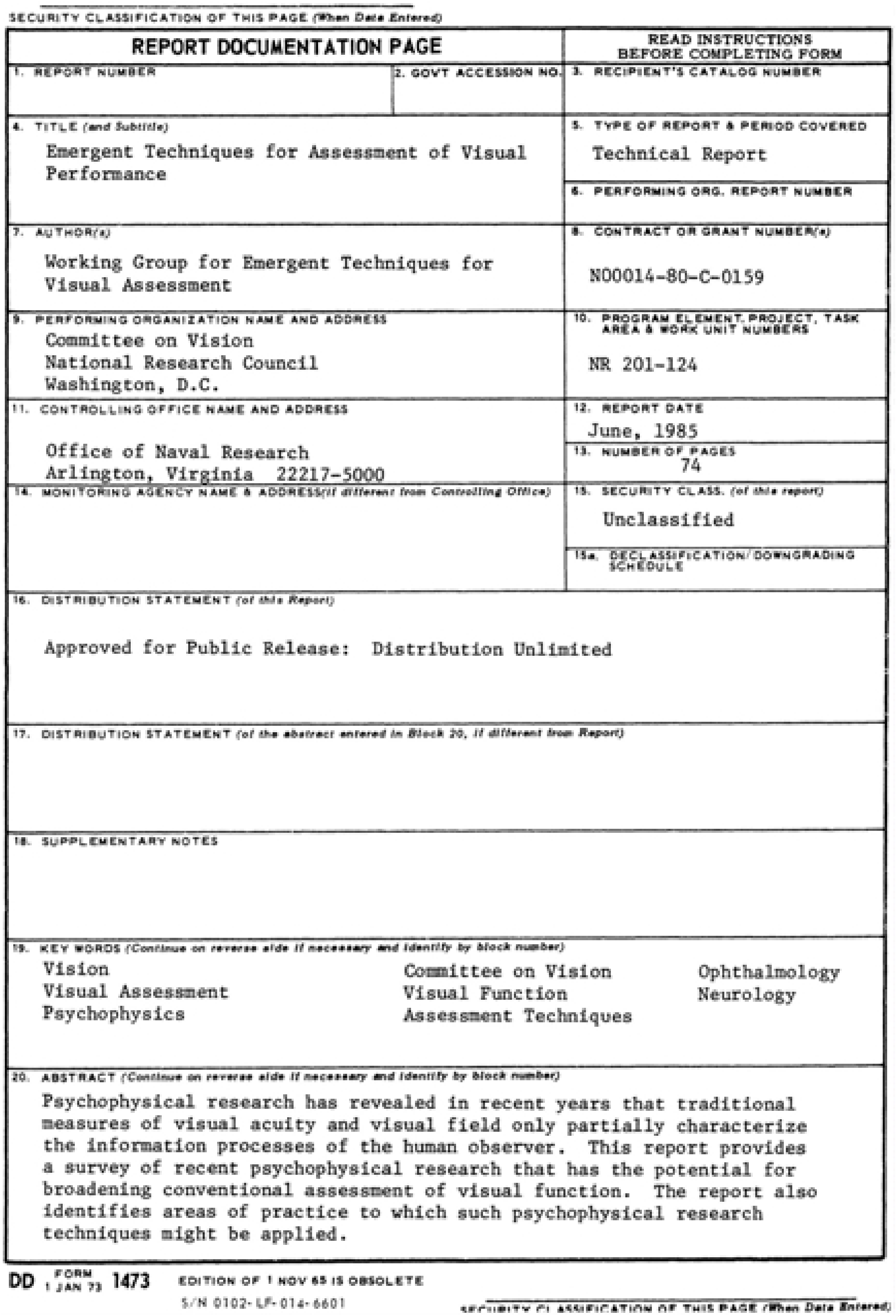
Westheimer, G., and McKee, S. P. (1975). Visual acuity in the presence of retinal-image motion. Journal of the Optical Society of America, 65, 847-850.

Whiteside, T. C. D. (1952). Accommodation of the human eye in a bright and empty visual field. Journal of Physiology (London), 118, 65.

Whiteside, T. C. D. (1957). The Problem of Vision in Flight at High Altitude. AGARD/NATO. London: Butterworths.

Wolkstein, M., Atkin, A., and Bodis-Wollner, I. (1980). Contrast sensitivity in retinal disease. Ophthalmology, 87, 1140-1149.

Wood, G. (1977). Fundamentals of Psychological Research. 2nd ed. Boston: Little, Brown.



SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Emergent Techniques for Assessment of Visual Performance

5. TYPE OF REPORT & PERIOD COVERED
Technical Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Working Group for Emergent Techniques for Visual Assessment

8. CONTRACT OR GRANT NUMBER(s)
N00014-80-C-0159

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Committee on Vision
National Research Council
Washington, D.C.

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NR 201-124

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Arlington, Virginia 22217-5000

12. REPORT DATE
June, 1985

13. NUMBER OF PAGES
74

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Vision	Committee on Vision	Ophthalmology
Visual Assessment	Visual Function	Neurology
Psychophysics	Assessment Techniques	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Psychophysical research has revealed in recent years that traditional measures of visual acuity and visual field only partially characterize the information processes of the human observer. This report provides a survey of recent psychophysical research that has the potential for broadening conventional assessment of visual function. The report also identifies areas of practice to which such psychophysical research techniques might be applied.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)