LEVEL II

Technical Report 540

SOURCEBOOK OF TEMPORAL FACTORS AFFECTING INFORMATION TRANSFER FROM VISUAL DISPLAYS

R. Sekuler and P. D. Tynan
Northwestern University

R. S. Kennedy
Canyon Research Group

SYSTEMS RESEARCH LABORATORY

U. S. Army
Research Institute for the Behavioral and Social Sciences

June 1981

U. S. ARMY RESEARCH INSTITUTE

FOR THE BEHAVIORAL AND SOCIAL SCIENCES

A Field Operating Agency under the Jurisdiction of the

Deputy Chief of Staff for Personnel

L. NEALE COSBY
Colonel, IN
Commander

JOSEPH ZEIDNER
Technical Director

Research accomplished under contract
to the Department of the Army

Northwestern University

NOTICES

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report 540	2. GOVT ACCESSION NO. AD-A109 907	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SOURCEBOOK OF TEMPORAL FACTORS AFFECTING INFORMATION TRANSFER FROM VISUAL DISPLAYS		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. Sekuler & P. D. Tynan Ed. R. S. Kennedy		8. CONTRACT OR GRANT NUMBER(s) N61756-76-M-5961
9. PERFORMING ORGANIZATION NAME AND ADDRESS Psychology Department Northwestern University Evanston, Illinois Canyon Research Group Westlake Village, CA		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2Q162722A777
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Institute 5001 Eisenhower Avenue Alexandria, VA 22333		12. REPORT DATE 1 June 1981 13. NUMBER OF PAGES 177
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

This report was funded as a collaborative effort by the U.S. Army Research Institute with the U.S. Naval Pacific Missile Test Center, Point Mugu, California and U.S. Naval Biodynamics Laboratory, New Orleans, Louisiana.

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

Temporal factors	Vision	Illusions
Human Engineering Design Criteria	Vection	Dynamic Visual Acuity
Visual Displays	Motion Perception	Display Design
Military Standards	Flicker	Spatio Temporal Interactions
Contrast Sensitivity	Brightness Enhancement	

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

This report collects in one document the important research literature on temporal factors in vision. Over 350 scientific articles are cited herein and this reporesents approximately 10 percent of the data base which was consulted. The literature searched was comprised of the following: 1) several thousand articles (under the general rubric temporal factors and information processing) from existing reprint files of the authors and others; 2) Ergonomics Abstracts,

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (continued)

Psychological Bulletins, Psychological Reviews and Human Factors for the last 12 years; 3) a listing from two automated look-up systems (Psychological Abstracts 1967-present and National Technical Information System 1964-present). An integrative review of the literature is provided and three chapters are included which deal with application of these findings to display design. The subject matter is preception of temporal events--specifically motion perception (real and apparent) and flicker/flash sensitivity. A small chapter covers some temporally based phenomena which distort or degrade perception. Features of these phenomena may be observed in visual displays. Only studies which report findings which are robust enough to be expected to be important outside the laboratory are included. Where suggicient data were available, equations are provided to the engineer for the calculation of design criteria (e.g., peripheral motion threshold, contrast thresholds, contrast thresholds and age, etc.). Where gaps exist in our scientific knowledge, recommendations are provided for applied research. General guidelines are offered for incorporating design criteria into Military Standard 1472 for perceptions due to temporal events.

Technical Report 540

SOURCEBOOK OF TEMPORAL FACTORS AFFECTING INFORMATION TRANSFER FROM VISUAL DISPLAYS

R. Sekuler and P. D. Tynan
Northwestern University

R. S. Kennedy
Canyon Research Group

Submitted by:
Milton S. Katz, Chief
TRAINING TECHNICAL AREA

Approved by:
Edgar M. Johnson, Director
SYSTEMS RESEARCH LABORATORY

U.S. ARMY RESEARCH INSTITUTE FOR THE BEHAVIORAL AND SOCIAL SCIENCES
5001 Eisenhower Avenue, Alexandria, Virginia 22333

Office, Deputy Chief of Staff for Personnel
Department of the Army

U.S. NAVAL PACIFIC MISSILE TEST CENTER
Point Mugu, California

U.S.NAVAL BIODYNAMICS LABORATORY
New Orleans, Louisiana

June 1981

Army Project Number
2Q162722A777

Individual Training Technology

ARI Research Reports and Technical Reports are intended for sponsors of R&D tasks and for other research and military agencies. Any findings ready for implementation at the time of publication are presented in the last part of the Brief. Upon completion of a major phase of the task, formal recommendations for official action normally are conveyed to appropriate military agencies by briefing or Disposition Form.

FOREWORD

This Technical Report, "Sourcebook of Temporal Factors Affecting Information Transfer from Visual Displays," is the result of a cumulative effort made between Naval Air Systems Command, Northwestern University and the Army Research Institute for the Behavioral and Social Sciences (ARI).

In this technical report, the basic and applied science literature are surveyed for data to aid human factors engineers in understanding temporal events and how these events may affect the visual response to displayed information.

Through the main efforts of Dr. Robert Sekuler and Dr. Paul Tynan from Northwestern University, IL, this research was completed under Army Project Number 2Q162722A777.

JOSEPH ZEIDNER
Technical Director

Authors' Preface

When one compares vision and audition as input pathways for processing information one is impressed with the spatial sensitivity of the eye and with the temporal sensitivity of the ear. In military workplaces vision is the predominant display mode. Thus, it is not surprising that the framers of Military Standard 1472, (including A and B versions) emphasized this fact by concentrating almost exclusively on the spatial coding mechanisms of the visual system (size, location, contrast, etc.) and ignored temporal cues (e.g., motion). Indeed, except for "...flashing lights..."virtually no mention is made in Military Standard 1472 of how one could code information temporally in order to improve the extraction of information from displays. However, starting with Boynton's (1961) seminal paper calling attention to the temporal capacities of the visual system, a large literature has evolved. Prior to that time little work was performed except for studies of motion perception, flicker, and curiosities in vision (e.g., Mach bands, brightness enhancement, Crawford effect, etc.) Since then symposia have been held and books of readings have been compiled. Thus, we believed that the time was right to acquire in one place all the research data associated with temporal factors in vision, particularly with reference to how these data impact on display design.

However, the task was obviously too ambitious because, as we progressed, more and more phenomena were discovered which qualified for the denomination "temporal factors" in vision. Therefore, it became necessary to delimit what we meant by "temporal factors". We have chosen to report only on motion perception, flicker, flash acuity, and a representative collection of phenomena that distort perception. An attempt was made in the report to avoid studies that were more closely related to throughput than to input, but this approach has resulted in omissions. We feel that the literature is sufficiently large and growing fast enough so that a sequel could update the existing area, and add a few items. Specifically, the distortion chapter could be amplified to include all "factors which inhibit seeing" (under which Mach bands, masking, metacontrast, and the Crawford effect might fall). Issues such as "sensory and environmental interactions", "eye movement versus image movement", "simultaneity and numerosity", are also candidates for a future revision. Additionally, specific subtopics could most likely include reports concerning effects named for: Pulfrich, Parks, Troxler, Bezold-Brücke, Sherrington, and others. Plus, saccadic and blink suppression, binocular rivalry, alphanumeric recognition, stabilized retinal images, phantom images, vection, and directional specificity in scanning, could be included. Moreover, future documentaries should attempt to divide the literature into the separate and critical issues of enhancement (or degradation) criteria for training equipment versus design criteria for equipment which is to be operated by skilled persons. (Only the latter is implied in Military Standard 1472B.)

The present sourcebook is a self-conscious attempt to address the difficult issue of Technology Transfer and is a first step in the temporal factors content area. To the extent that it is found useful to the design engineer, it will have fulfilled its purpose. To the extent that it does not, it should be improved in future revisions. The best places for the design engineer to look are in the first three chapters, "Applications and Recommendations for Applied Research", "Extrapolations from Laboratory Data", and "Toward a Military Standard."

TABLE OF CONTENTS

Introduction

In this report the basic and applied science literatures are surveyed for data to aid human factors engineers in understanding temporal events and how temporal events may affect the visual response to displayed information. By this means, we hope to provide information which will aid design engineers in improving display design. To our knowledge there has been no attempt to review these literatures on a broad enough scale to produce a document that would be generally useful to anyone involved in display design. However, the topic of "temporal factors" is sufficiently broad in scope that one document can hardly provide complete, encyclopedic coverage. We have therefore concentrated on factors that we felt may impact on the design of visual displays with the hope that in many cases a human factors engineer will be able to use the information presented in this text directly to guide display design. In other cases, the information may not be presented in sufficient detail, and either original sources will have to be consulted by the engineer and/or integration may be required.

The usefulness of this report depends on the task that the designer faces. In many cases, the information he needs is simply not available. The reason for this is two-fold. First, most scientists engaged in "pure" research are primarily concerned with testing theories about how the visual system interacts with a set of display variables. Most researchers are more interested in the changes in observers' responses with changes in display parameters than in the quantitative description of the responses themselves. The researcher is often not interested in the variation of the response from observer to observer. The second part of the problem arises because applied researchers generally focus only on rather specific, applied problems. For instance, a researcher interested in the perception of television systems may only use displays of about the same size, luminance, number of lines on the raster, and flicker rate as are possible with a particular television system. Thus, the research would not be very useful to a designer trying to optimize the visibility of warning beacons, or even other television systems.

This report combines many data sources in an effort to develop general rules of perception that may be useful to human factors engineers. To accomplish this, only certain types of articles were considered. If a paper did not directly study the temporal variable or its effect, but only used temporal variation to examine some other dimension of perception, the paper was not used as a reference. For example, in many studies the stimulus is presented for a brief duration only to produce errors in identifying the stimulus. The error level can then be the dependent variable used to measure some other variable, such as a drug effect. Some effects have inspired so great a volume of literature that not even a majority can be directly included in this survey. An example of this is the motion aftereffect. In such cases, only those articles which provide a good description of the basic phenomenon, or may be directly of interest to the human factors engineer, have been included.

In order to be included in this report, a scientific finding had to satisfy three criteria. First, the effect had to be "robust", that is, strong enough that it would be noticed in an industrial or military setting. If an effect could only be teased out statistically under the best of laboratory conditions, it was not included. Second, the effect had to be observable in "normal" (non-pathological) conditions. Finally, we insisted that the stimulus conditions producing the effect not be so exotic that they would never be seen outside the laboratory. These criteria were selected to maximize the report's interest to the human factors engineer.

Because it is hoped that this book will be used by design engineers seeking solutions to problems, the solution section appears first. However, students will probably prefer to read the literature review sections first. The report consists of three basic parts: The first part is on the application of data to practical problems. The second part is on the perception of temporal events. Half of this part is concerned with the perception of motion, the other half with the perception of flashes and flickering. The third part includes the effects of temporal events on distortions, illusions, and degradations of displays. The relative size of each part reflects the amount of information available for each. Most of the report is concerned with the second part, simply because so much work has been done in these areas that is important in display design. The first part, on applications, was the least adequately treated in the literature. These three parts of the report are described in more detail as follows:

1) Application. Articles in this part show the application of temporal effects information to industrial and military problems, whether to avoid distortions in a display, to improve visibility and detection, or to code information. Examples include temporal cues for radar displays, flashing indicators of all kinds, the perception of CRT displays, and the design of aviation instruments. In addition, there is a summary of important instances which have been mentioned in the other two sections. Also included is a summary of the important "bare spots" in the literature and comments on what additional research would be most useful for the design engineer. The authors also suggest changes in the section of Military Standard 1472 regarding the uses of visual indicators, as well as speculate upon the possibility of using temporal events as a medium for conveying information to the operator.

2) The perception of temporal events. One goal of this report is to suggest ways temporal events could be used to convey information from machine to man. The first step is to understand the factors influencing the perception of temporal events themselves. Articles in this category delineate the conditions under which motion, flicker and other transients are perceived and the discriminability of changes along these dimensions. Examples of variables included in this category are the spatial characteristics of the stimulus, eye movements, adaptation, and factors influencing the after effects to temporal stimuli.

3) Distortions, illusions, enhancement and degradation due to temporal events. If a temporal event causes a misperception or illu-

sion in some stimulus dimension, other than its clarity or visibility, that effect is included in this category. Hue shifts, spatial distortions such as changes in perceived curvature, line length, and spatial frequency are examples. Also included are the effects of temporal events on the clarity, visibility and recognizability of a stimulus. Examples include dynamic visual acuity, brightness enhancement, masking, and sequential blanking effects.

CHAPTER 1

Applications and Recommendations for Applied Research

In each chapter of this report, comments will be made on the display application of specific perceptual phenomena, when it seems appropriate. An attempt will be made to integrate some of these suggestions into more general recommendations on how the interface between man and machine may be improved and expanded. Because of data gaps in both the pure and applied literatures, some of these recommendations are admittedly speculative. The authors have enough confidence in other recommendations, however, to suggest changes in the Military Standard. These will be reiterated at the end of this section. In addition to the summary and analysis of the review, a chapter on how laboratory data may generally be interpreted for use in applied settings has been included.

This review covers the basic phenomena and psychophysical data on motion perception (absolute motion threshold, differential motion thresholds, perceived velocity, etc.). Perhaps the most important parameter for the human factors engineer to consider when applying these data is the amount of time the operator will spend looking at any one display element. For instance, the perception of motion as measured by absolute motion thresholds follows different empirical rules depending on whether the exposure duration of the display is greater than or less than 1 sec ("inferred" and "directly sensed" motion). Ford, White and Lichtenstein (1954) and White and Ford (1960) found that the average amount of time an operator observes any particular area of a display is about .25 to .33 sec. This puts absolute motion thresholds in the "directly sensed" range, where reference lines have little effect and motion thresholds are greatly dependent on the luminance of the target. If the human factors engineer demands the utmost performance from the operator on this task, and thus the advantages of "inferred" motion perception, he would have to rearrange his entire display configuration so that the operator would not have to constantly take his eyes off the motion display to monitor other instruments. These changes in fixation are called "switching" by Valerie (1960), who felt that it hindered performance on certain types of delicate tracking tasks. His solution was to provide extra information in the peripheral field of vision coded by the luminance of LED's. Indeed, this approach reduced "switching" and improved tracking performance.

Another problem is taking too short a "glance" at a moving target. As shown by Runeson (1974, 1975) and others, short exposure durations lead to various misperceptions in perceived velocity. In Runeson's case, the perceived velocity of an object was overestimated, reducing an observer's ability to predict the collision of two moving objects.

An even more severe problem is one of providing information about the acceleration of some element in the observer's environment. While an observer can detect as little as a 14% change in the velocity of an object if this change occurs suddenly, with a gradual acceleration, an object must change position 200% before motion is detectable.

The solution to this problem may require re-thinking how an instrument should code the state of the world. When considering television or other CRT systems, for instance, one usually thinks that the more resolution, either spatial (number of raster lines), or temporal (frames per second), the better. The problem of representing acceleration, however, may require a reduction in temporal resolution. In this case, acceleration may be easier to detect if it is quantized in units of approximately .5 sec. The target would move at a constant velocity for the next .5 sec. Therefore, if each jump were greater than 14%, acceleration would be detected. On the other hand, if presented more faithfully (updated many times per second), motion may not be detected. Schmerler (1976) found that acceleration detection improved when he "blanked" the target for part of its path. However, quantizing the motion may be preferable to intermittent presentation of the target, because flashing the target would degrade visual prediction of collision and other psycho-motor tasks. Of course, whether quantizing motion produces similar problems remains to be investigated.

The classic motion "illusions" are reviewed for the clues as to how they might help or hinder the man-machine interface. For instance, the motion aftereffect (MAE) could produce a problem in displays like one of the aviation displays described by Kitchel and Jenney (1968) as shown in Figure 1. Part of this display is a moving dashed line; upward movement of the line indicates that airspeed is less than that commanded by the pilot, while downward movement indicates that airspeed is greater than desired. The "ideal" state is a stationary line. If air speed were consistently less than that commanded (upward moving) then, when airspeed is finally correct, and the line is stationary, the motion aftereffect may actually make it appear to move downward, creating the false impression that aircraft had "overshot" the target speed. A slight change in fixation could eliminate the illusion, or the MAE might be eliminated entirely by adjusting the line's motion.

Another chapter section of the report deals with apparent motion itself (i.e., the movement of one object between two positions). The most important finding of our review is that the data of the "classic" apparent motion literature does not allow one to predict the perception of other apparent motion displays. Notably, these other displays involve: (1) the motion of a cluster of many objects between two positions, like the simultaneous motion of a swarm of insects, and (2) perhaps more importantly, the movement of one object across many positions, as in the simulation of continuous motion by motion pictures, television, and computer driven displays. Unfortunately, the information about the latter situation is sparse and contradictory at present. Yet, precisely this sort of information will be invaluable to future display designers.

To summarize and perhaps oversimplify the literature on induced and relative motion: (1) when judging the movement of objects, it is important to have a large stable frame of reference; and (2) when more than one object moves, the objects may interact if they are close to one another. The display in Figure 1, for instance, has many other contours besides the moving dashed line. However, the addition of other moving dashed lines (perhaps to indicate relative airspeed of

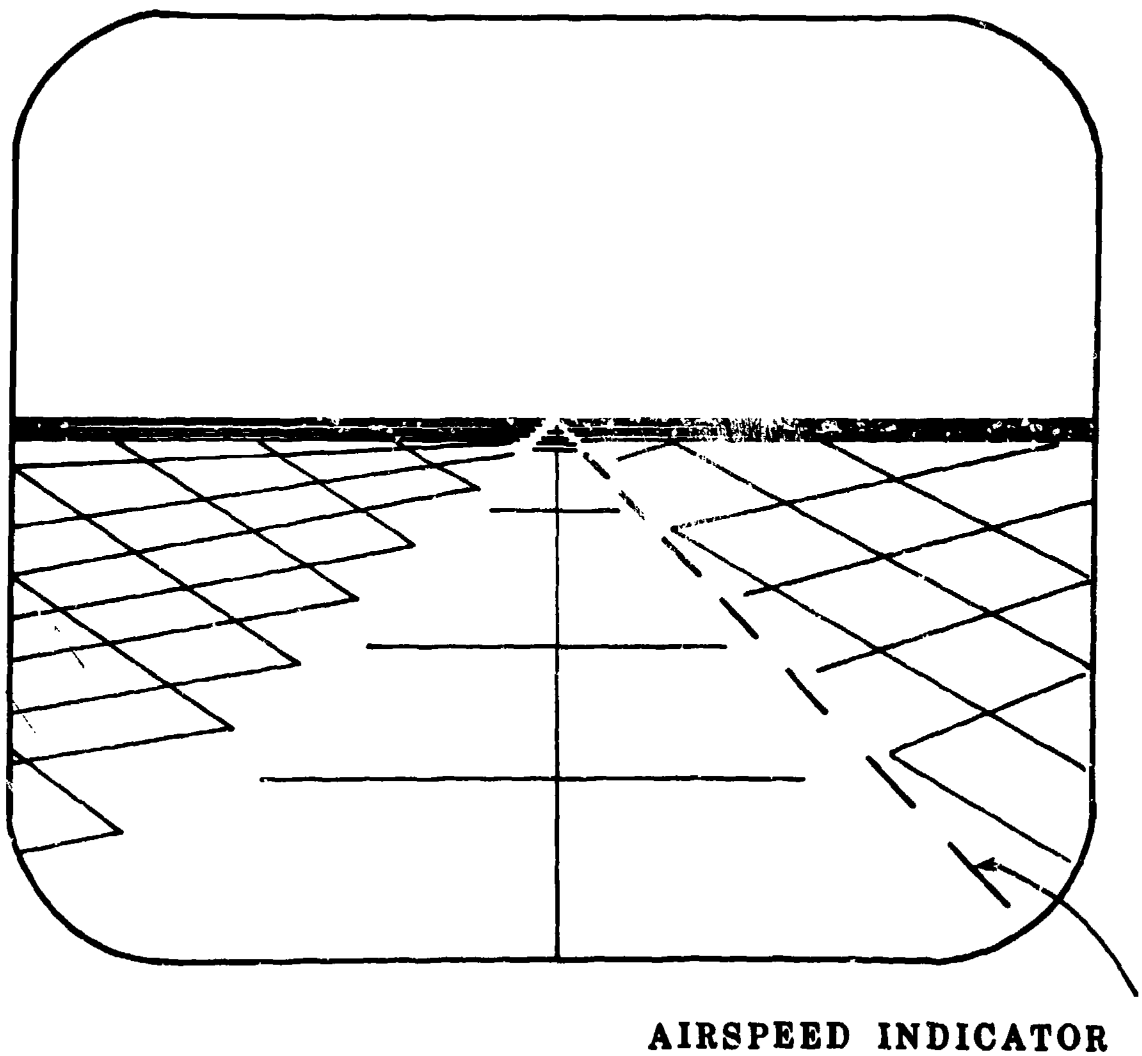

Figure 1. CRT aviation display (from Kitchel & Jenney, 1968)

enemy aircraft) would not be advisable; one of the lines might induce movement into its otherwise stationary mate.

One chapter of this report is devoted entirely to peripheral motion perception, and in the chapters on flash and flicker perception, information on perception in the peripheral field of vision was included whenever possible. We have already alluded to one reason for using this part of the visual field: to reduce the number of separate fixations the operator must make in the course of monitoring his environment. Reducing the number of fixations also improves performance when the operator must search for a target embedded in a complex pattern such as the noise on a radar screen, or in a pictorial representation of terrain, as might be the case when using a television monitoring system.

When compared on most tasks the peripheral field of vision seems inferior to central vision. One exception to this is the detection of temporal events. In fact, at low and moderate levels of luminance, the periphery is sometimes more sensitive than the fovea (for instance Welde and Cream's (1972) observation that television monitors may flicker when viewed peripherally). Even at high levels of luminance, the observer is able to respond to fast moving peripheral objects as quickly as to those in central vision. In one way, however, the periphery is <u>too</u> sensitive to movement. Movement of even one object over an extended distance may cause linearvection, an illusion in which the observer feels that he and his immediate environment are moving. Such an illusion could cause considerable disorientation to the pilot of an aircraft who must rely on visual sensations to assist in flying the plane. For this reason, it might be preferable to include information to the periphery via flashing lights, or spatially localized motion such as the rotation of a small contour.

The chapters on flash and flicker sensitivity, provide guidelines on how to decide if a flashing or flickering signal will be detected. Two important points are: (1) one flash will interfere with the detection of a second flash at certain inter-flash intervals, that is, a double flash could be less effective than two widely spaced single flashes, and (2) flicker is often avoided in display systems by modulating the display at rates above CFF, yet amplitude or modulation of frequencies up to 1000 Hz can produce "sideband" frequencies that fall in the range of visual sensitivity, and cause transient flashes or flickering. These could be most distracting and confusing when produced in a system that isn't supposed to flash or flicker.

This report comments on the use of flashes and flickering as a coding mechanism - a way to provide information to the operator of a machine. Kitchel and Jenney (1968) have reviewed the applied work on using flicker as a coding mechanism and conclude that the medium is only suitable as an attention-getting device, or for simple types of loading (for successful applications of these principles, see Goldstein & Lamb, 1967; Smith & Goodwin 1971). There are many reasons to agree with Kitchel and Jenney. Flash durations seem identical when less than 70 msec, and this range probably is greater at lower levels of luminance. Also there is confusion in the literature on perceived "numerosity" when compared with observations on "perceived rate". More information is needed to determine exactly what the observer is responding to under these different tasks.

Studies by Mowbray and Gebhard (1955, 1960) show that the visual system is acutely sensitive to differences in the flicker rate of two stimuli. This suggests that perhaps the key to using flicker as a coding mechanism is to always provide at least two adjacent flickering patches; information would then be coded in terms of the size of the easily recognized difference between the two rates of flicker.

The literature on brightness enhancement of flicker shows that the parameters that optimize the effect are similar to those that optimize the threshold detection of flicker. Thus brightness enhancement is an effect that could be taken advantage of when one is concerned with the detection of a flickering target. Detectability will be maximized under conditions that produce brightness enhancement. However, if the task is not detection, but based on spatial acuity, then the conditions that produce brightness enhancement are the <u>worst</u> conditions to choose. In this case, one should be careful about following Kitchel and Jenney's advice that flicker should be used as an attention getting device. In fact, flickering contours might get the observer's attention, but leave him unable to interpret information represented in the contours.

The possible degradation of visibility by flicker is strongly dependent on the spatial frequency content of the display and the range of spatial frequencies is most critical for the observer's task. Both flicker and movement may enhance the visibility of low/medium frequencies, even though both types of temporal modulation degrade the visibility of very high spatial frequencies. It will be pointed out in the chapter on "Dynamic Visual Acuity", that the observer's <u>task</u> is very important. A task such as recognizing letters or symbols may require the analysis of medium spatial frequencies. This may or may not be affected by temporal modulation. On the other hand, a task that is clearly an acuity task will really always suffer from temporal modulation. It is suggested that tasks could be analyzed in terms of <u>relevant</u> spatial frequencies, so that the display designer would be able to tell whether temporal modulation will help or hinder the operation.

In reviewing the literature on visual distortions, the authors enumerated a list of phenomena to be avoided in the design of visual displays. In addition, speculations as to how some distortions could be put to good use are also considered.

One major class of distortions arising from the movement of a target is the misperception of the path of a moving target. In every case, the distortion is an underestimation of the object's path caused by the failure of the observer's eye to "keep-up" with the target being pursued. As a result, a straight-line path seems shorter than it would be, a circlular path of smaller diameter than it should, and a square path seems "bowed" inward. One effective cure for this distortion is to keep the observer from pursuing the target by having him fixate on some stationary point on the screen. However, another kind of distortion, the Ansbacher effect, might occur under conditions of fixation, since its cause is probably masking rather than pursuit error. However, both kinds of distortion are eliminated when the target moves in a discrete, "jerky" type of apparent movement.

Another problem associated with pursuit eye movements is the multiple images that may occur with certain types of motion pictures, computer driven CRTs, or LED displays.

Some of the distortions associated with flicker are even more bizzare and inexplicable. Flicker may produce the illusion of contours and colors in large homogeneous fields, or increase the perceived fineness of contours and reduce the length of lines in contoured displays. Flicker can also produce color in a more predictable way in small achromatic fields, or alter the perceived color of chromatic targets. These latter effects, however, are probably not great enough to affect discrimination in "gross" color coding schemes, like traffic lights.

A few of the illusions we treat might find application as coding media themselves. For instance the "phantom" gratings discussed in the chapter on distortion (Tynan & Sekuler, 1975a), do not seem to interfere with the visibility of real contours, and could therefore, be used as "overlay" information on another display readout. Also, if flicker-induced subjective colors could be produced reliably in the observer population, the subjective colors might be used to convey information on a temporal variable and do so with temporal resolution of better than one msec.

CHAPTER 2

Extrapolation from Laboratory Data

Most of the perceptual data in this report were collected in laboratories dedicated to "pure" research on visual processes; a considerable number were collected in laboratories interested in perception in the "real" world, especially the interfacing of information between man and machine. Few data were collected outside of the laboratory, in the environment similar to which the application of the data would occur. But wherever the data were collected and for whatever reason, they all have several things in common: (1) many variables were intentionally excluded to make the experiment manageable, and (2) when thresholds were measured, they almost invariably may be based on a criterion of seeing, detecting or identifying the signal of interest 50% of the time.

For the human factors engineer, detecting the the signal 50% of the time may not be good enough - the observer should be detecting it all the time, or as close to 100% as is possible. In addition. the observer in the laboratory usually knows where and when to look for the signal; this may not be true in the applied setting. Other variables such as heat stress and oxygen deprivation are also likely to affect perceptual performance in the field.

To produce acceptable performance levels in the field, signal levels must be greater than those suggested by basic vision research. Although not much work has been done concerning the method for "correcting" laboratory data for extrapolation to likely field conditions, enough research has been completed to provide some rough guidelines. The rest of this chapter attempts to summarize these attempts to develop correction factors for field conditions.

Table 1 is from Johnston, Cole, Jacobs and Gibson (1976), and summarizes correction factors collected by Taylor (1964b) for contrast threshold of small targets. The first set of factors is called "probability conversion factors" and is to be used as follows. Suppose that data have been collected for the 50% probability of seeing criterion. After determining the energy or contrast level that permits the target to be detected 50% of the time, one merely multiplie this energy or contrast value by 1.91 to produce a stimulus that the observer would see 99% of the time or by 1.50 to produce a stimulus that would be visible 90% of the time. Teichner and Krebs (1972) found that the same correction could be made for luminance thresholds of targets presented against a dark background. In fact, this type of correction may be made for many types of threshold data.

But these constants are only a portion of the total correction that may be necessary to assure adequate performance by the observer in the situation of interest. The second part of Table 1 lists factors that correct for the observer's knowledge or certainty about some target properties. It could be used for example, to extrapolate from an experiment in which there is no uncertainty about where the target

TABLE 1

A.

Contrast Threshold Correction Factors

Probability (Detection) Desired	Multiply laboratory Threshold Value by
0.50	1.00
0.90	1.50
0.95	1.64
0.99	1.99

B.

Corrections for Various Sources of Target Uncertainty

Factors to be applied when the observer does (+) or does not (-) have knowledge of various target properties.

Source of Uncertainty

Location	Onset time	Size	Duration	Correction Factor
+	+	+	+	1.00
+	-	+	+	1.40
+	-	+	-	1.60
+	-	-	+	1.50
+	-	-	-	1.45
-	+	+	+	1.31

Note: If observer vigilance is required outside the laboratory, multiply laboratory threshold values by 1.19

If observers outside the laboratory are naive rather than trained, multiply laboratory threshold values by 1.90

(after Johnston et al., 1976)

would appear, to predict performance in a field situation in which the observer only knows the location of potential signals to within 4 deg. In order to correct for the spatial uncertainty, one should multiply the experimentally determined contrast or target energy by 1.31. Other multipliers are used if: (1) the observer only knows to within a few seconds when the target will occur, or, (2) if several sizes may appear but the observer does not know which, or, (3) if the target may appear for one of several durations, and this information is unknown. Taylor warns that these factors are based on rather incomplete data and that this is why correction factors are not available for all possible combinations of these four variables. Unfortunately, at present, these are the best available data.

Taylor also adds a few important correction factors. "Vigilance required" (derived from Jerison & Pickett, 1963) is a correction factor to be applied if, in the field setting, the target will appear only once or twice during a period of 20 min. The use of the "practice effects" factor (from Taylor, 1964b) depends on whether the observer is naive or well-trained. An example from Taylor's paper (1964b) illustrates how these factors may be combined.

> At this point, it is well to give an example of how a field factor is determined for a real case, and how it may be used to arrive at a realistic estimate of observer performance under field conditions. Let it be assumed that an observer must confidently detect the occurrence of a stimulus of known duration and size but of unknown location within a circular display area with a diameter of 8 deg. The target will be present at infrequent intervals, say once every 15 min or so; and he can be allowed to miss only 5% of the occurrences. He is new to the task, and our problem is to arrange the contrast of the target so that this 95% criterion will be met. We begin by consulting the laboratory data, which tell us that, for our target size and duration and for the prevailing adapting luminance, the required contrast for 50% correct discrimination by practiced observers in a forced-choice experiment was found to be 0.0061. To correct, respectively, for confidence level, unknown location, vigilance, and lack of training we multiply this contrast value by 1.64, 1.31, 1.19, and 2.00, i.e. by 5.12. The needed target contrast, therefore, is 0.031 for our problem.

More recently, Sekuler and Ball (1977) and Ball (1977) found that uncertainty about the direction and speed of moving targets affected both the luminance threshold for detecting the targets, and reaction time to the same targets at suprathreshold luminances. The observer requires twice as much luminance to attain the same detection performance when he is uncertain about which of two directions (90 deg apart) the target could move, than when he was certain of the direction. This condition also caused a 15% increase in reaction time to suprathreshold targets. For a moving target of about 4 deg/sec, an 8 fold difference in speed between the two alternative speeds under conditions of uncertainty caused a 40 msec increase in reaction time over reaction time when speed was known. A 16 fold difference in speed produced a reduction in detection performance that would require a doubling of luminance to correct.

Besides these factors, an almost infinite number of difficulties peculiar to the specific man-machine system may arise. For instance, several factors affect the functional extent of the visual field. The excessive gravitational forces resulting from the acceleration of aircraft reduces a pilot's vision in the peripheral field; an increase from 1 to 4 G's reduces the functional diameter of the visual field by 50% (Gillingham & McNaughton, 1977). Also "loading" the center of vision with a difficult task reduces the size of the functional visual field (Webster & Haselrud, 1964; Ikeda & Takeuchi, 1975). Moreover, the magnitude of this visual field shrinkage increases with age (Layton, 1975). Unfortunately since clinical, perimetric measurements of the visual field are made without concomitant stress or attention demands on the observer, such measurements may be poorly correlated with the size of the field actually useable by an observer in some non-clinical setting. As a result, clinical tests of the extent of the observer's visual field may bear little relation to an observer's ability to use peripheral vision in some applied setting.

The last problem to consider is variability within a population of observers. Johnston, et al. (1976) do an excellent job of reviewing problems associated with distributions of both color and acuity deficiencies among observers, and how a display designer may take these into account. Table 2 shows the CIE's recommended correction factors for acuity as a function of age. Given that a particular target is seen by 50% of 20-year-olds, contrast would have to be increased by 1.6 so that it could be seen by 70% of 40-year-olds. Variability of visual capabilities is much less among some populations than among others. For example, commercial airline pilots are pre-screened for visual capabilities much more carefully than automobile drivers. Yet, each screening procedure must allow some degree of leeway, and Figure 2 shows that even a slight visual deficiency may require a substantial correction factor.

It is important to repeat and emphasize the fact that these correction factors and the rules for using them are very rough procedures and the data are very sketchy and incomplete. The correction for probability assumes that every procedure used in the laboratory measures the 50% frequency of seeing, however, this is not true. The method of adjustment, for instance, (the observer controls the strength of the signal and adjusts it until it is just barely detectable) most certainly measures a frequency of seeing much higher than 50%. Thus, the procedures presented here may be overly conservative. Also, Taylor's technique of serially multiplying correction factors is purely arbitrary. Ball (1977) provides evidence that the effects of two sources of uncertainty in her experiments should not be combined in this manner. If there are few rules for applying detection data in the field, there are none at all for reaction time. Parametric experiments will have to be conducted to find appropriate correction factors for both measures. Certainly, much more emphasis needs to be placed on finding and testing rules for applying laboratory data to field situations.

TABLE 2

Contrast Threshold Correction Factors for Age and Variability Between Observers

	Percentage of the Population to be Included					
Average age	50	60	70	80	90	95
20	1.00	1.09	1.20	1.34	1.56	1.76
25	1.00	1.09	1.20	1.34	1.56	1.76
30	1.03	1.12	1.24	1.38	1.61	1.81
35	1.09	1.19	1.31	1.46	1.70	1.92
40	1.17	1.28	1.40	1.57	1.82	2.06
45	1.33	1.45	1.60	1.78	2.08	2.34
50	1.58	1.72	1.90	2.12	2.46	2.78
55	1.94	2.12	2.32	2.60	3.02	3.42
60	2.30	2.51	2.76	3.08	3.58	4.05
65	2.66	2.90	3.19	3.56	4.15	4.68

(after Johnston et al., 1976)

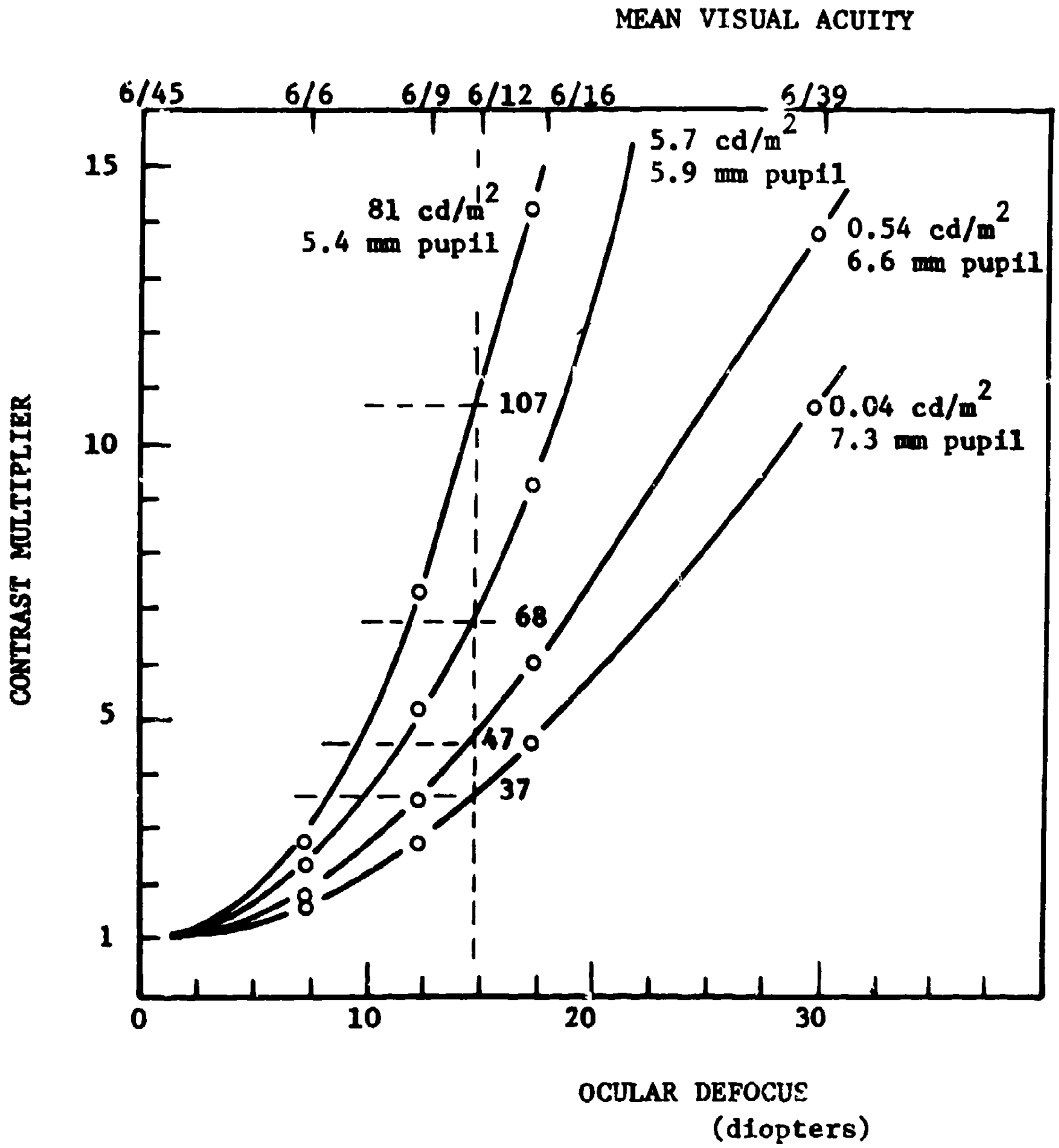

Figure 2. Contrast multipliers plotted against defocus for four levels of background luminance. Visual acuity was recorded for p = 0.5, using a Landolt C target presented at a low photopic level of illuminance (from Johnston, et al., 1976).

CHAPTER 3

Toward A Military Standard

Military Standard 1472B provides guidelines for designing equipment so that military personnel can use it effectively. The motto of the standard regarding visual displays seems to be "keep it simple", that is, do not create a display that is any more complicated than is necessary. Few could argue with such an approach. Yet, as military systems become more complex, and computers are needed to integrate the information generated by these systems, it will become increasingly difficult for human operators to "keep up" with the actions of their machines. The resulting visual displays may be radically different from the concept of a panel of indicators, the concept on which much of the Military Standard is based.

For instance, the Military Standard assumes that the operator is looking directly at a display when extracting information from it, except for a flashing indicator which may direct his attention to a different display. Thus, the Standard is not much help to a display designer interested in providing the operator with information from several displays without necessitating his changing fixation.

Even assuming that an operator looks directly at each display, the Standard neglects much important information on temporal parameters. For instance, it may be important for an operator to determine whether the pointer on an indicator is changing position, yet the Standard provides no criteria for rate of movement that would insure motion detection. A guideline similar to Table 1 of this report should be added. In addition, the Standard should make mention of thresholds for detecting a change in the velocity of an object moving on a display. These motion guidelines and others apply to CRT displays as well.

Also, information on flicker is almost completely lacking from the Standard. Paragraph 5.2.2.1.19 suggests that flickering lights only be used as an attention-getting device, and that a flickering indicator should only flicker at a rate between 3 and 5 Hz. The data presented in this report, however, show that desirable flicker rate depends on the task. If the operator is to detect the flicker, then a rate between 8 and 10 Hz would probably be more effective depending on other conditions. If the operator must read or perform some acuity task and the contour information is on the flickering indicator, then a much lower, or higher rate would be prefered.

There are also a few "don'ts" that should be considered for inclusion in the Standard. One of these concerns linearvection. This illusion of self-movement is quite powerful and dangerous, and the designer should be cautioned against producing motion in the operator's peripheral field of vision. Another highly reliable effect is the perception of flashes or transients when the flicker rate of a display, well above CFF, is suddenly changed either in frequency or amplitude. Such a situation is quite possible if the flicker rate of a CRT is dependent on the amount of information presented, which may happen with computer driven displays.

Many of the data reported in this report, however, are not suitable for immediate use as the basis for a Military Standard for two reasons: (1) many of these visual phenomena have not been tested for their applicability to field situations, and (2) many of these data are not very relevant to the general design of displays, yet may be very important to the designer trying to solve some specific display problem. For instance, the information on observers' ability to make fine discriminations between two sources of flicker is only useful to someone experimenting with new design ideas. Similarly, the chapter on distortions may be useful for a designer whose new display "looks funny". However, it is impractical to list all these possible sources of distortion directly in the Standard.

CHAPTER 4

The Absolute Threshold for Motion Perception

An object's "absolute motion threshold" is the minimum speed with which an object must move in order for its motion to be detectable. Although the definition is straightforward, a number of subtleties attend its measurements. The most important of these subtleties involves the allowable inspection time. For example, even glacial movement could be detected if observed over a long enough period of time. Obviously, the width of the temporal window used to define the absolute motion threshold is of practical interest; a pilot has only limited time to spend observing any one object or instrument waiting to see motion. As shall be noted, other subtleties of measurement involve effects of the size of the test object, its luminance, and the presence and character of possible reference marks in the visual field.

Reviewing the effect of limited observation time upon the perception of motion, Bonnet (1975) supported the conclusion of earlier investigators: there are at least two types of motion perception, viz., "inferred" motion and "directly sensed" motion. In the first case, the motion of an object is inferred by noting that the object's position, sampled at two or more separate times, has changed. In the second case, if the exposure is brief and the speed of motion rapid enough, motion may be sensed directly in a manner analogous to sensing a flash of light. This distinction will be made from time to time throughout this section.

First, how does one know when one is dealing with inferred motion? If the observer has unlimited time to view the moving object, then the motion at threshold will be inferred. However, what is the shortest observation time for which motion perception can be considered inferred? Leibowitz (1955b) varied the luminance and exposure duration (1/8, 1/4, 1, 2, and 16 sec) of a moving stimulus and found that for all, except the longest exposure (16 sec), variations in luminance had a strong effect on motion threshold. At 16 sec, however, it had almost no effect and the threshold varied only slightly around a value of 0.4 min of arc/sec. Leibowitz argued that the luminance-sensitive thresholds reflected the "directly sensed" type of detection but that at long durations, the observer merely noted changes in the position of the stimulus with time, and as long as the object was visible, its luminance was not important. Johnson and Leibowitz (1976), using many more stimulus exposure values, concluded that the critical duration between "sensed" and "inferred" motion was 1 sec. All durations greater than 1 sec had the same threshold for motion: 1.5 min of arc/sec. Below 1 sec, threshold velocity increased with decreased exposure duration such that the object had to move a constant distance in order to be detected.

The great range of values in the literature for the threshold for motion is probably in large part the result of the presence and character of reference marks. As far back as 1886, Aubert (as related in Graham, 1965) found a ten-fold reduction in motion threshold when reference marks were added to the display. Mates (1969) found the same results, a gradual lowering of motion threshold occurred as the number of reference marks was increased from 0 to 16. Her target measured 7 min x 17 min and was located about 27 min from an edge in which reference lines were scribed. Leibowitz (1955a) examined the effect of reference marks while varying exposure duration (1/4, 1/2, 1, 2, and 16 sec) and found that the marks had little effect at the short durations, but lowered threshold at long durations. This suggests that reference marks will only help an observer in detecting "inferred" motion.

The exact spatial arrangement of the movement display varies from one study to another, but Kinchla and Allan (1969), and Kinchla (1971) suggest just how close the reference mark must be to the moving target to facilitate detection. In their work, a reference mark (a small spot) had little effect on motion thresholds of a small object if it was more than 10 deg away; the mark reached near optimal effectiveness in the 3 to 5 deg range.

Another important variable is the size of the test object. In this case, however, the results are not as intuitively obvious as for reference marks, since an increase in the size of an object actually raises its motion threshold. Brown (1965a) predicted this outcome because he had found that increasing the size of an object makes it look slower (although it is well above motion threshold; see the Suprathreshold Motion chapter). He correctly felt that this phenomenal slowing would simply extend to the threshold levels of velocity and that an increase in physical speed would be needed to offset the effect of increased size. For a square 27.5 min on a side, motion threshold was 6.6 min of arc/sec; for a 13.8 min square, threshold was 3.61 min of arc/sec, and for a 6.9 min square it was 1.89 min of arc/sec. For every one/half reduction in the stimulus dimensions the motion threshold dropped roughly by a factor of two. Mates and Graham (1970) came to a similar conclusion when they varied the length of a moving line. Shortening the line (6.9 min wide) from 58.4 min to 17.2 min lowered motion thresholds from 6.75 min of arc/sec to 2.3 min of arc/sec, a roughly proportionate change. On the other hand, Graham (1968) found that varying line length between 2.8 and 45 min had no effect on motion thresholds when exposure duration was less than one second.

So, for long exposure (greater than 1 second) durations and "inferred" motion, the basic findings are: (1) motion threshold is best described as the minimum rate of motion necessary for detection; (2) as long as the moving object is visible, luminance is not important; (3) the spatial characteristics of the stimulus (viz., reference marks and object size) are important. None of this holds for exposure durations of less than 1 sec.

Bonnet (1975) concludes that in the exposure range of about 0.1 to 1 sec, velocity threshold is not a constant, but varies with the duration of exposure. The critical event for motion perception in this case is the extent of the movement. Cohen and Bonnet (1972) found that they could "trade-off" exposure and velocity over an exposure range of 50 to 700 msec and still have a stimulus near threshold as long as it moved through a distance of 0.8 min of arc. Johnson and Leibowitz

(1976) found the same relationship holding over a range of 0.1 to 1 sec, although their constant displacement was 1.5 min of arc Leibowitz' (1955b) data suggest that this displacement value is sensitive to luminance. It varies roughly from 0.5 min of arc at his highest luminance of 1591 cd/m^2 to 5 min of arc at the lowest of .016 cd/m^2, although the "constant extent rule is not as clear at high luminances. Somewhat below 100 msec this constant distance relationship breaks down. Henderson (1971) claims that the distance-time relationship in the lower range now takes the form $dt^m=c$, where $\underline{d}$ is distance, $\underline{t}$ is time, $\underline{c}$ is a constant, and $\underline{m}$ is an exponent that varies between 1/2 and 1 depending on background luminance. In other words, for motion to be perceived, as exposure decreases, distance must increase. At very low target luminances, the task is really one of detecting anything at all (Bonnet, 1975, Henderson, 1973). At this level, a constant energy (dependent on luminance) is needed to detect the object, thus exposure is constant.

Johnson and Leibowitz (1976) found that for exposures below 100 msec, velocity threshold is constant at 18 min of arc/sec. This means that distance actually decreases as exposure decreases, the opposite of Henderson's findings. The authors do not dwell on these results, nor compare their findings to Henderson, but they do note that since their display was a stop-go-stop type of movement (that is, the object was clearly stationary before and after the movement), their observers saw nothing but the sudden acceleration or jerk of the stimulus. Johnson and Leibowitz think that this is qualitatively different from the experience of motion in the 0.1 to 1 sec range. In Henderson's experiment, however, the object was moving when it appeared and then disappeared so the observers' tasks (at very small exposures) were simply to detect a streak of light. These two types of displays evidently stimulate different perceptual mechanisms.

During the discussion of "inferred" motion detection it became clear that motion thresholds in the "directly sensed" range (less than 1 second) are not affected by either reference marks (Leibowitz 1955a) or the size of the object (Graham, 1968). However, it should be noted that the latter study only looked at the effect of the length of a thin line, not the size of square or round objects, and their longest line length was still less than 1 deg.

So far we have been considering foveal vision, but since motion thresholds invariably increase as the object is located more and more peripherally, the retinal location must also be taken into account. This and other effects of eccentricity on motion perception have been treated separately in another chapter (see Peripheral Motion Perception). An important point is that reference marks are not effective in the periphery (Tyler & Torres, 1972).

As a way of summarizing these data, we could consider the task of a display designer or human engineering specialist trying to decide whether an object's motion will be seen or not. Table 3 presents a model for determining changes in motion thresholds that would accompany changes in an object's peripheral location, size, and proximity to reference marks. The designer would start with a rough idea of how

TABLE 3

Calculation of Peripheral Motion Threshold

$$\text{Peripheral Threshold} = \text{Foveal Threshold} \times \frac{\text{Target Size}}{7.5} \left[.125 \sqrt{(1.45y)^2 + X^2}\right] \quad (1)$$

$$\text{Peri Thresh} = \text{Fov Thresh} \times \frac{\text{Target Size}}{7.5} \times d. \sqrt{(1.45(\sin\alpha)^2 + (\cos\alpha)^2} \quad (2)$$

Equation (1) is used to estimate the threhold for motion perce ion with a target presented at a retinal locus specified as (x,y) in degrees visual angle.

Equation (2) is used when target position is specified in terms of meridian, α, and distance, d, from fixation, in degrees.

Notes: In each equation, the first variable represents the foveal threshold. If unknown, an approximation might be 5'/sec for the motion of a small (5' to 10') target which is highly visible on a photopic background ($> .1$ cd/m^2) with exposure durations > 1 sec. Target size should be expressed in minutes of arc. If reference lines are present, the computed values should be reduced (see text). If exposure duration is between 0.1 and 1.0 sec, foveal threshold should be expressed in terms of the minimum distance the object must travel to be seen (1.5 min arc) rather than velocity required for detection of motion. Also, for durations in this range, the effect of object size and reference lines are reduced. Unfortunately, present data do not allow us to estimate by how much. The constant 1.45 in the above equations reflects the scale difference between horizontal and vertical axes of McColgin's (1960) iso-response contours; the contrast 1.25 reflects the rate of eccentricity.

much time the human operator could devote to looking at the object, for example, a radar operator may have several seconds. If he has a long time, (1 second or more) and the object is small but quite visible (5 to 10 min of arc), and no reference marks are present, threshold could be anywhere from 1 to 5 min of arc/sec. As the size of the object is increased, threshold should increase proportionately up to a limit of one degree (beyond this limit data are not available). If reference marks are added, threshold could be changed by a factor of 10, depending on the number, spacing and proximity of the points, they should be at least within 5 deg of the object. If the object is viewed peripherally, threshold should go up by at least a factor of 10 comparing the fovea to 80 deg in the periphery. In Table 3 is an attenuation factor based on the formula for elipses that we have fitted to McColgin's (1960) data. The upper model in the table uses the visual field coordinates in degrees as parameters (fovea is 0.0), the lower one the angle and distance of the object from the fovea.

Our rules cannot be as specific when the exposure duration of the movement puts it in the "directly sensed" range. If exposure duration is greater than 100 msec it is probably safe to calculate velocity based on the rule that the object must travel at least 1.5 min of arc for motion to be detected. Reference marks probably will not make any difference, nor will the object size, at least up to 1 deg. The data on luminance are sketchy, but from Leibowitz's (1955b) study we can infer that this displacement value increases by a factor of 10 as the target becomes dim; most of this change occurs for target luminances below 1.6 cd/m^2. It is probably safe to assume, at this time, that the effect of peripheral location is about the same for this exposure range as for inferred motion. Below 100 msec exposure, it is difficult to find a simple rule which will ensure that motion will be visible, except that below 6 msec it is very hard to produce a stimulus that appears to be anything more than a non-moving flashed line or streak (Henderson, 1973).

The previous conclusions are quite tentative since they assume that there are no unknown interactions among variables. These figures are based on careful laboratory measurements and therefore should only be considered the limit of the human visual system when trying to apply them to existing situations. For instance, an observer's uncertainty about which direction an object will move may hamper performance (cf. chapter on Extrapolations from Laboratory Data).

CHAPTER 5

Suprathreshold Motion Perception

Display-related aspects of motion perception in which both the target and its motion are highly visible are discussed in this chapter. Of particular interest are (1) how easily the movement's characteristics are recognized or discriminated, and (2) how a target's speed may appear to change with time and other variables (e.g., the spatial structure of the environment). In additon, we shall discuss the relationship of these findings to actual human performance on tasks which depend on visual information about velocity. Specifically, tracking performance and observers' abilities to predict the future position of a moving object will be discussed.

One of the most salient features of a target's motion is its velocity. The first question certainly should be concerned with how perceived velocity varies with physical velocity. If the velocity of an object is doubled will it <u>seem</u> like the velocity is doubled? It is well known that this is not true of many stimulus dimensions; for instance, doubling the amount of current of an electric shock stimulus will much more than double the sensation (Stevens, 1962). The relationship between the magnitude of the stimulus parameter and sensation is often expressed as a power function:

$$\text{sensation} = (\text{stimulus magnitude})^p$$

where p is an exponent. If p=1, then the relationship between sensation and stimulus magnitude will be linear; a doubling of magnitude would produce doubling of sensation. In the case of velocity, the power law has been found to be stable (Kennedy, Yessinow, & Wendt, 1972; Mashour, 1969; Walker, 1975), although estimates of this exponent vary between 0.7 - 1.0 (Rachlin, 1966). Unfortunately, these experiments have not used a large enough variety of stimulus conditions nor enough variety of stimulus conditions to permit easy generalization to arbitrarily chosen target sizes, contrasts, luminances, etc. But it can be assumed as a first approximation, non-linearities are minimal in the relationship between perceived and physical velocity.

The next question is, "How sensitive is an observer to differences in velocity?" The spatial relationship between two moving objects which are to be compared is one important determinant of velocity discrimination. Brown (1961a) in his review of nine papers on velocity discrimination, distinguishes among three stimulus configurations. The first is the "adjacent" in which the target moves for a while at one velocity, then suddenly changes to another. The second is the "separate" in which the targets whose velocities are to be compared are separated in time and/or space. For instance, an observer may see the motion of an object on one screen and then look to another screen for the comparison stimulus; or, if the targets appear on the <u>same</u> screen, they appear in succession with an appreciable interval between the two. In the third, "superimposed", configuration the two stimuli move through the same space at the same time. This allows one stimulus to actually "gain on" and pass the other. This is also called a motion parallax display, because it produces a monocular cue for depth (if the two objects are actually moving at the same speed but one were further from the observer, it would appear to move more slowly).

Comparing data from the three configurations, Brown (1961a) found the smallest velocity difference threshold in the superimposed configuration. This is probably because Vernier acuity cues are confounded with the difference in velocity. With even a small difference in velocity between two superimposed points, the gap between them will quickly change and be detected. Next, Brown found that the "separate" configuration permitted smaller differences to be detected than did the configuration with "adjacent" stimuli. The reason for Brown's finding is not clear and is not in agreement with findings on acceleration detection which will be reviewed. In fact, Brown apparently did not recognize that the "separation" condition would probably introduce a range of possible velocity discrimination performances as a function of the size of the temporal and spatial separations between stimuli.

This report will consider only the last two configurations, since the velocity difference threshold found with the superimposed configuration may depend more on acuity than on temporal sensitivity *per se*. The practical question is, "How does minimal velocity difference change, vary with the velocities of the objects?" For instance, could the "difference threshold" be proportional to velocity (Weber's law)? Brown concluded that Weber's law roughly holds over a limited range for test stimuli presented in either "adjacent" and "separate" configurations. For adjacent stimuli, $\frac{\Delta\omega}{\omega} = .138$, where $\Delta\omega$ is the change needed to detect a difference in velocities at speed ω. Stated differently, for a given velocity, ω times .138 is the just discriminably different velocity. In the "separate" configuration, $\frac{\Delta\omega}{\omega} = .0769$. The first equation holds over a range of 1 to 20°/sec. For the "separate" configuration, Weber's law only holds well in the range 1 - 10°/sec. Brown (1961b) found that Weber's law also held for field judgments of the speed of planes, he obtained a similar ratio of .085. Note that Brown's "adjacent" configuration actually allows the observer to respond to stimulus acceleration since, at some point along its movement, the stimulus undergoes instantaneous acceleration.

Other forms of acceleration have also been investigated. For instance, Gottsdanker (1961) noted that one could not predict difference thresholds for steadily accelerating objects from difference thresholds measured with instantaneously accelerating objects (such as those in Brown's "adjacent" configuration). Rather than the approximately 14% difference needed for instantaneous acceleration, more than a 200% change is necessary to discriminate a positively accelerating object from one of constant velocity; about half as much change is needed to recognize a negatively accelerating object. Gottsdanker concluded that steady acceleration was inferred rather than perceived instantly: observers compared the velocity at the beginning of the movement with velocity at the end. This relationship held for mean velocities ranging from .96 to 7.7 deg/sec. Exposure duration ranged from .45 to 3.6 sec. Schmerler (1976) came to the same conclusion from a very similar experiment.

What is the appearance of a moving object that does not move at a acceleration constant speed but accelerates or decelerates? Since the difference threshold for acceleration is so high, one would think that many accelerating or decelerating objects would appear to be moving at a constant velocity. Indeed, Gottsdanker, in his 1956 review, notes that observers almost always underestimate the speed of accelerating objects and overestimate the speed of decelerating ones. They have difficulty noting that the object is starting to move faster or slower, i.e., their perceptions do not keep up with the change in the stimulus. Schmerler (1976) offers additional demonstrations of this hysteresis in apparent velocity. Johansson (1950) also reports that sinuosidal movement appears to most observers to be of constant velocity. In other words, if the position of an object varies as a sinusoidal function of time, its velocity would illusorily appear constant.

The difficulty of discriminating between an accelerating motion and one of constant velocity can be eased by enriching the spatial structure of the field through which the object moves. Gottsdanker (1962) found a 10% increase in the apprehension of a target's acceleration when various reference marks were added to the stimulus field. Interestingly, it made little difference whether the reference mark was a single spot or a rather complex texture. Any single stationary object seemed to suffice. Similarily, Schmerler found that the detection of acceleration was improved by about 50% by "blanking" the object for some portion of the middle of its run (in this case the object entered and left a tunnel). An important question at this point is, "Does constant velocity movement continue to look constant if viewed over an extended period?" Runeson (1974) demonstrated that it does not. Figure 3 has been reproduced from this study. Runeson asked his observers to draw graphs depicting the perceived change in velocity of the moving objects. Stimulus P1 was of constant velocity (dotted line), yet it seemed to slow down considerably in the first 1 to 2 seconds. Runeson concludes that the stimulus which produces the sensation of constant velocity is one that accelerates quickly in the first few seconds of presentation and then asympotes to a constant velocity (see FA 35 of Figure 3). These results agree with other measures by Runeson in which observers had to select the constant velocity stimulus from various pairs of these moving stimuli.

In addition to this immediate change in perceived speed, several investigators have noted a longer term but very substantial change in the perceived speed of a moving object with time. Goldstein (1957) used a matching technique to measure the perceived speed of a moving grating (train of bars moving perpendicular to their orientation) at various times during the observer's inspection of it. He found no change up to 8 sec; but between 8 and 30 sec, the perceived speed of the grating dropped to 30%, beyond 30 sec there was little additional change. Using a similar technique, Thompson (1976) confirmed this finding although he did not measure speed until 15 sec of inspection had elapsed. Incidentally, Goldstein's data for 0 to 8 sec fail to show the short term effect reported by Runeson. We suspect that Goldstein's technique of measuring apparent speed (observers moved a hand-held stylus at a speed which supposedly matched the apparent speed of the object) would not be sensitive to such a transient effect.

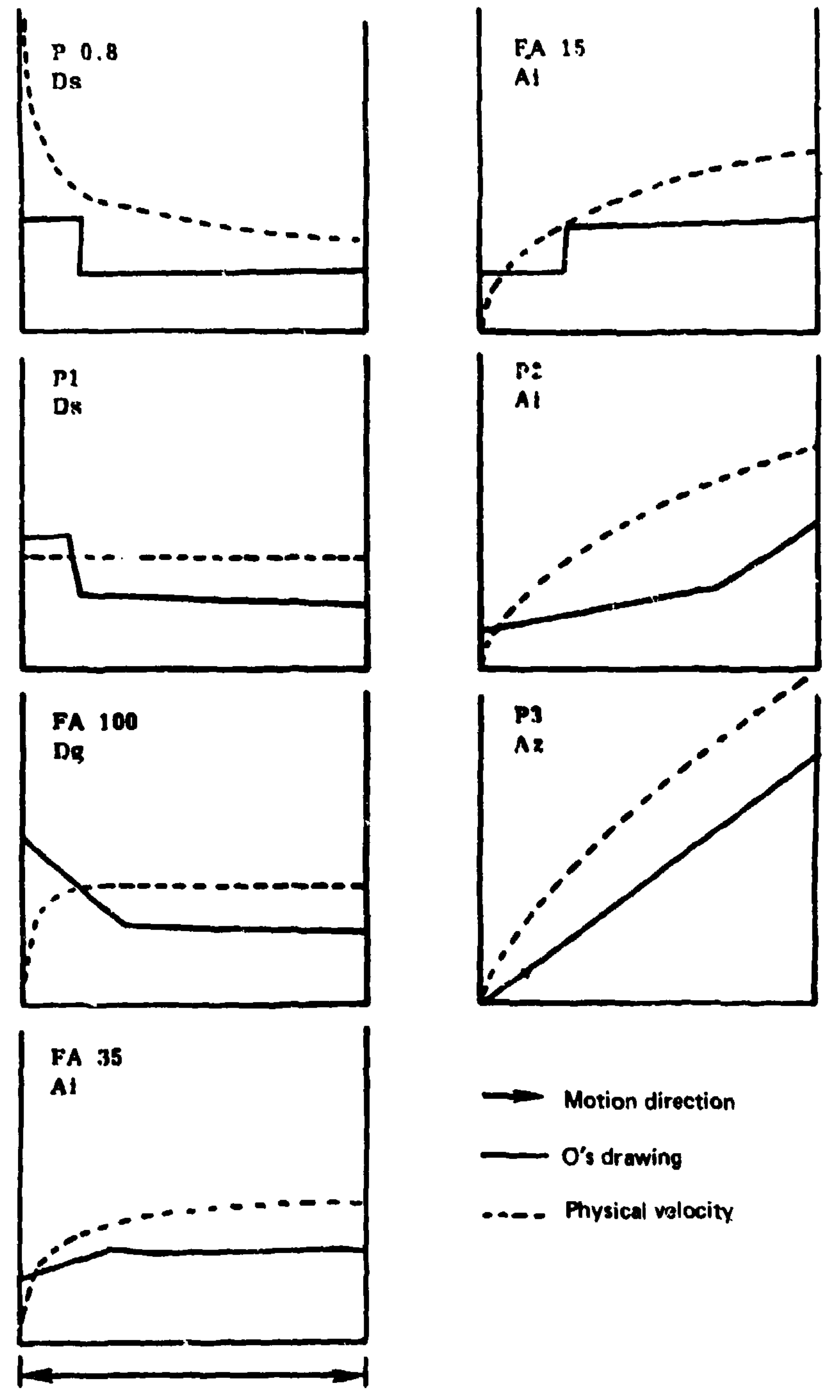

Figure 3. The graphs from one observer (AL) at 20°/sec average velocity. Horizontal axes represent position along the track (s) and vertical axes represent velocity (v). The corresponding physical motion functions drawn with v as a function of s have been added for comparison. Function names and results of classification are given in each graph. The graphs are typical, except for the very unusual stepwise increase at FA 15. (From Runeson, 1974).

This report has tried to describe the general response of the human visual system to suprathreshold moving stimuli without considering the complications of variation in spatial configuration, luminance, or contrast of the moving objects. Since these parameters influence perceived speed, and the choice of the parameters' values could account for differences among studies, these influences must be reviewed before proceeding to relate psychophysical data on movement to human performance in visio-motor tasks.

Results on the effect of spatial parameters on the perceived speed of objects have been conflicting. Walker (1975) measured the perceived speed of rotating disks using a matching technique, and found that an increase of the coarseness of the pattern on disks (increasing the size of the dots and their spacing) produced an increase in perceived speed. A tenfold magnification of the pattern produced a 25% increase in perceived speed. Diener, Wist, Dichgans, and Brandt (1976) found the opposite effect for grating stimuli; decreasing the spatial frequency, (making the bars wider and spaced further apart) decreased their perceived velocity. He also found that for a single moving bar, a wider bar seemed to move more slowly than a narrow one. These effects were, like Walker's, on the order of 25%. Although Diener et al.(1976) used a much larger display, (160 deg with 6 deg wide bars) their results agree at least qualitatively with those of Brown (1965a, 1965b) whose entire display of moving bars measured only about 7 deg across. There are so many differences between Walker's display and Diener's or Brown's (e.g., rotary versus linear motion; random dots versus bars; absence or presence of stationary contours) that it is difficult to speculate on what might cause these discrepant findings.

The effects of target contrast and luminance are also worth mentioning although their importance is just being recognized. Thompson (1976) has shown that the contrast of a moving grating dramatically alters its perceived velocity. The variations in apparent speed with contrast changes ranged from the marginal, to as large as 40%. For a two cycle/deg grating moving at four deg/sec, a reduction in contrast reduced its apparent speed; but when the same grating moved at speeds faster than four deg/sec, reduced contrast produced the opposite effect: increased speed. Reducing the luminance also may make an object appear to move more slowly (Brown, 1965a, 1965b), but no quantitative work has yet been done on this effect.

So far, the basics of suprathreshold motion perception, the ability of observers to discriminate among different speeds, and the appearance of the speed of moving objects have been considered. But the design engineer will also want to know how these perceptual processes would affect responses to motion information. For example, how would the perception of motion determine tracking behavior? How would it affect an observer's ability to predict the future position of a moving object and take appropriate action? Obviously, these behaviors are affected not only by motion perception but by memory and motor control as well. In this report we will only consider how the motion phenomena, already discussed, could affect these two performance measures.

Brown (1961a, 1961b) devotes a large part of his review of the literature on the velocity difference threshold to tracking and predictive behavior. His conclusion is that, in general, the two classes of measures agree. For instance, difference motion thresholds for tracking errors increase linearly with the average speed of a moving target. In addition, the average error in a tracking task is about the same as for the difference velocity threshold (14%). In a motion prediction task, Kimball (1970), Ellingstad and Heimstra (1969), and Gerhard (1959) found a linear relationship between mean velocity and random error. In the first two papers, the task was as follows: the observer saw an object moving over a limited path; for part of the path the object was occluded. The observer's task was to guess the moment at which the occluded object would reach some prespecified point.

In Gerhard's study the task was similar except that the object, a vertically moving point, intersected a horizontally moving one. The observer tried to adjust the speed of the horizontal point so that the two points would intersect. All three studies found a linear relationship between speed and error, although error was minimized in Gerhard's study because the observer could continuously adjust the speed of the horizontal point. Kimball, and Ellingstad and Heimstra both found standard deviations of about 3 deg/sec for an object moving at 7 deg/sec; but their data differ considerably for slow speeds. It is difficult to generalize much beyond qualitative statements, however, because many other variables in the prediction task affect error (Gerhard, 1959; Kimball, 1970): for example, the distance the target travels, the time for which the target is exposed, the distance and/or time over which the target is hidden, and whether the target intersects with a stationary or moving object.

It is even more difficult to relate the literature on the perceived speed of an object to that on tracking and prediction behavior. We will restrict ourselves to the relationship between an object's perceived speed and an observer's over- or under-estimations of that speed as reflected in his tracking or predicting behavior. For instance, Runeson (1974) claims that the perceived speed of a moving object decreases dramatically in the first few seconds it is seen. This implies that, in a prediction task, the length of time the observer is exposed to the moving object should drastically effect the constant error in his predictions of when the object will reach a target point. Also predicted is, that tracking and prediction will be affected by intermittently presenting the object as it is in motion (in a series of short exposures) rather than allowing it to be continuously seen. Weiner (1962) and Rosenbaum (1975) found that exposure duration had no effect on prediction performance: the latter using exposures as short as .25 sec. On the other hand, intermittently presented objects do appear to move faster than continuously presented ones (i.e., observers underestimate the time that it will take an object to reach a target if the object appears intermittently). Returning to Gerhard's (1959) study, he looked at the effect of occluding sections of the path taken by the vertical point on constant error. When the vertically moving object was not occluded along its path, the observer exhibited no constant error, but when an occluder was present, he underestimated the time that it would arrive at the point of intersection (it looked too fast). In accordance with the random error data in that study, so too this effect was small. Similarly, Morin (1956) using a radar display, found that observers underestimated the arrival time of intermittently presented moving objects, especially when the objects moved slowly (about .2 deg/sec). Observers in this case, had to make their predictions during the "fast" phase of their responses to the movement (see Figure 3). When the object appeared to be of constant velocity (physically it starts off fast, Figure 3), the time at which it was occluded made little difference. They also made the most accurate predictions during this condition. Knowledge about the motion illusion did not help them correct their errors.

Intermittent light can also severly disrupt motor tracking tasks. Ailslieger and Dick (1966) assessed the effect of intermittent illumination on a number of tasks related to aviation. The pursuit rotor task was the only one seriously effected; not only did the flashing light make tracking very difficult, but observers commented that the rotor was moving faster than under the steady light condition. Croft (1971) also noted that it is very difficult to catch a tossed beanbag under stroboscopic illumination. As with other phenomena in this section, ample research has been conducted to allow contradictions, but too few studies have been done to allow them to be resolved. In sum, it seems clear that many of the variables discussed in this section, spatial environment, luminance, contrast, etc., could affect the perceived speed of an object in a man-machine situation, which in turn could affect an operator's ability to perform his assigned task.

Another performance measure important to the design engineer is the speed with which an observer can react to motion. Since so much of this literature compares reaction time for foveally and peripherally viewed displays, the authors have reviewed this literature in the chapter titled Motion Perception on the Periphery.

CHAPTER 6

Illusions of Motion

This section will briefly review some of the basic illusions associated with motion perception: the motion aftereffect, apparent motion, and induced motion. The first and last of these are particularly important to the display-designer because they could influence an operator's motion thresholds and his judgments of an object's speed. Apparent motion, sometimes called "phi" or "beta" motion, is important for another reason. It is the illusion of smooth continuous motion produced when the observer only sees discrete pictures or "frames" of that motion. Thus this illusory effect is crucial if motion pictures, television, and computer driven displays are to successfully imitate real motion.

Motion Aftereffect

If after observing a moving pattern (a train of bars, a rotating spoke, a spiral pattern, or moving random dots) for 15 sec or more, the motion suddenly stops, the pattern will seem to move slowly in the opposite direction. This is the motion aftereffect (MAE). Usually, it is measured in one of three ways: (1) the time it takes for the illusion to fade away (i.e., the pattern finally appears to stop), (2) the velocity of the illusory motion, measured either by matching or magnitude estimation technique (Stevens, 1957), and (3) a nulling technique in which the pattern is not completely stopped but is moved slowly in the direction opposite to that of the MAE until the pattern appears to be stationary. Researchers who have measured more than one of these properties have usually found them to be highly correlated (Sekuler & Pantle, 1967).

The first question raised is "What characteristics of the moving stimulus are responsible for the motion aftereffect?" Although almost any patterned object that presents continuous motion to the same part of the retina will produce the effect, this chapter shall try to define the conditions which are most likely to produce illusory after-motion. Scott, Jordan, and Powell (1963) found that a velocity of 2 to 4 deg/sec was optimal for producing the effect with the Archimedes spiral stimulus (the speed is that of the contour of the spiral along any radial). Sekuler and Pantle (1967) found a decrease in the speed and duration of the aftereffect with increased speed during the inspection period using a disk of rotating radial lines. The linear speed of a point half-way between the center and the edge ranged from 3 to 24 deg/sec. Thus the low end of their range of speeds may already have been optimal, and their data do not disagree with that of Scott et al. (1963). They also show a slight increase in the duration and velocity of the MAE with increased inspection time; for 17 sec of inspection, the MAE lasted about 3.75 sec and for 60 sec of inspection, about 4.75 sec. Holland (1957) found that inspecting a rotating spiral display for as little as 5 sec produced an MAE of 5 to 8 sec in duration.

The absolute speed of the MAE movement itself cannot be known from Sekuler and Pantle's data because they measured relative speeds using the method of magnitude estimation. Scott et al. (1963), however, matched the apparent speed of the MAE to that of a stimulus that was actually moving, and found the MAE velocity to be about 5 to 6 min of arc/sec.

The question of how long the MAE lasts is not as easy to answer as might be expected. One problem is that all the variables so far mentioned have been found to influence the duration of the MAE. The reason the information on MAE duration is so complete is that duration is the easiest way to operationally define the "strength" of the MAE. The observer inspects the moving pattern, then views the stationary one, and in some way signals when the MAE has completely disappeared. Holland (1957) found the maximum duration of the MAE to be from 80 to 100 sec. However, if one retests the observer later (without an additional exposure to motion), he may see the MAE again, and again it will fade, perhaps more quickly.

The amount of time that can pass between the inspection period and the test, and without eliminating the MAE response from the observer, is another measure of the duration of the MAE (sometimes called the "long-term MAE"). Masland (1969) was the first to discover the strength f this effect. He had 121 naive observers inspect a spiral display for 15 minutes and found that he could measure MAEs from 20 to 26 hours later. These results have been replicated by Kaflin and Locke (1972), and Favreau, Emerson, and Corballis (1972). The latter report that after 24 hours the effect is weak and fades in 5 sec.

Those are the basic findings, however, spatial, luminance and contrast parameters that effect the strength or persistence of the illusory after-motion will be reviewed again. The most important spatial requirement for seeing the MAE is that the stationary pattern fall on the same area of the retina as the moving inspection pattern. As Sekuler and Pantle (1967) varied the amount of the spatial overlap between the inspection and stationary targets from 100% to 54%, they found a dramatic decrease in both perceived velocity and duration of the MAE. Masland (1969) found that he could not observe his "long-term" MAE unless the inspection and stationary patterns overlapped by at least 50%. Under these conditions, if the MAE is seen, even that portion of the test field that falls on a previously unstimulated retinal area will seem to move (Bonnet & Pouthas, 1972). In addition, though the inspection and stationary patterns need to be roughly proximate with respect to the visual field, they do not have to be alike. Grindley and Wilkinson (1953) asked observers to inspect a 60 deg rotating spiral (inward movement) using a plain white field as the stationary test stimulus. The plain field now appeared to be textured and expanding outward and moving closer to the observer although the borders did not appear to move. Also, the MAE is stronger if reference contours appear in the visual field. Day and Strelow (1971) found the MAE was seen less frequently when the area <u>surrounding</u> either the inspection or stationary pattern was itself patternless, and even less frequently when <u>both</u> stimuli had patternless surrounds.

Variation of luminance and contrast of the inspection and stationary patterns do not greatly affect the strength of the MAE (Holland, 1957). Day (1958) created a disk of colored sections to produce distinct radial contours with minimal brightness contrast. He found that with a 12% difference between the brightness of adjacent sectors, he was able to generate a motion aftereffect. Note, however, that a difference of 12% probably represented a brightness difference which was many times greater than threshold. Keck, Palella, and Pantle (1976) found that the contrast of the inspection pattern had little effect on MAE velocity and duration once it was above 3%. However, as the contrast of stationary pattern was increased from .9% to 10.5%, MAE velocity and duration decreased bv 50%. The strongest MAE, then, is generated by a high contrast inspection pattern in combination with a stationary pattern of very low contrast.

There are a few additional observations that may be important to the display designer. One is that an eccentrically viewed MAE appears faster and lasts longer than one produced in the center of the visual field (Sekuler & Pantle, 1967). This fact may play a role in the production of MAE in the third dimension following prolonged exposure to large-field moving optical flow patterns. Such flow patterns would exist if an on-board observer steadily gazed at the wake receding from a ship's bow or, possibly, at the display of a flight simulator.

Also, there is a difference in the strength of the MAE when the inspection motion is in a direction away from fixation (centrifugal) rather than toward it (centripetal); the MAE resulting from centrifugal motion is stronger. This difference increases with increasing eccentricity, reaching a twofold difference at 20 deg of eccentricity (Scott, Lavender, McWhirt, & Powell, 1966).

Lastly, the MAE is not as strong when the precipitating motion is a series of discrete displacements rather than continuous motion. Banks and Kane (1972) generated a MAE using motion picture images with various frame-like image displacements corresponding to the same constant velocity. The duration of the MAE decreased with an increase in displacement size; when the image displacement was 10' or greater, there was almost no MAE, even though Banks and Kane claim that picture quality was itself not much changed. Also Anstis, Gregory, Rudolph, and MacKay (1963) used continuous motion (spiral disk) for the inspection pattern, but stroboscopically illuminated the stationary one. Flashing the strobe at a rate of 4 to 30 Hz, completely abolished the spiral MAE and decreased the MAE produced with other types of movement.

The influence of the MAE is something that display designers should avoid if possible. That the illusion can affect the perception of slow real movements is evident from the fact that one of the ways psychologists measure the illusion is by "cancelling" it with real movement, so that a pattern that is actually moving seems stationary. Scott et al. (1963) showed that real and illusory after-motion added algebraically for very slow real-motion (less than 10' of arc/sec). However, the data suggest that a single moving target is not likely to produce a consequential motion aftereffect. A display of a large moving field viewed for 30 sec or more, could be a problem, but the literature reviewed in this report suggests that one could easily minimize illusory after-motion by varying gaze momentarily or stroboscopically illuminating either the inspection motion or the pattern affected by the illusion.

Apparent Motion

Apparent motion is the illusion of continuous movement resulting from the momentary presentation of an object at an orderly set of locations in the visual field. A typical stimulus used in research would be the following: a 1 deg square is presented for 10 msec; 100 msec after the square's offset, an identical square appears 4 degrees to the right of the first one, again for 10 msec. The observer will have the impression that the square moved continuously rightward through space (i.e., that the object at some time occupied every location between the motion's beginning and end). The two objects do not have to be identical; the illusion persists even when the objects have different shapes and/or colors (see Kolers, 1972; and Graham, 1965, for reviews). This chapter is restricted to the variables of the duration of the objects, and the space and time which separate them. In addition to the many variables manipulated in the course of investigating this effect, many _types_ of apparent movement have been discovered (Boring, 1942). However, the discussion will be primarily two types, _phi_ and _beta_ movements. Beta movement, sometimes known as "optimal apparent movement" is simply the illusion of an object moving through space, while _phi_ movement is the illusion of movement but without a clear impression of an object (Spigel, 1965; Graham, 1965; Aarons, 1964).

In his review, Graham relates Wertheimer's (1912) rule of thumb governing appearance of two sequentially flashing lights: (1) for intervals between lights of less than 30 msec, the lights will appear simultaneous, (2) for the range of 30 to 60 msec the illusion of movement between the lights is optimal, and (3) for intervals greater than 200 msec, the lights appear successive, with no motion between them. One will note, however, that this rule probably only holds for relatively brief flashes. Graham also relates Korte's famous "laws" of apparent motion formulated in 1915. They are a guide to the interplay between the four variables of: (1) the luminance of the target, (2) their duration, (3) distance between them, and (4) the time between the offset of the first and the onset of the second target (Interstimulus Interval or ISI). For optimal apparent movement to be seen:

1. As the luminance of the targets is increased, the space between them must be increased.

2. As the ISI is increased, luminance must be decreased.

3. As the ISI is increased, distance must be increased.

4. As the ISI is increased, duration of the target must be decreased.

Therefore, if the influence of apparent motion is to be avoided in a display rules 1 - 4 must be considered in display design.

Much research has been aimed at validating or refuting these rules in qualitative terms; rather than collecting parametric data that would allow the computation of optimal apparent movement for many display conditions. Data on luminance are especially lacking. This is true even in studies undertaken to provide results which would be used by display designers. Obviously, such an omission is quite a handicap. In the following paragraphs, the authors assume that display (background and target) luminance is constant, at an acceptable level (mid-photopic) for good visibility, and that the targets are of sufficiently greater luminance than their background to insure a contrast of more than 5 times threshold. Such assumptions make it more probable to concentrate on other, more thoroughly explored parameters of apparent motion.

Korte's laws imply that with all but one parameter fixed, the free parameter had to assume some particular value in order for the observer to see apparent movement. However, Neuhaus (1930, as related to Kolers, 1972) found that the free parameter could assume a wide range of values and apparent motion could still be seen. This fact is reflected in Figure 4. The lower set of three curves represents the boundary between the perception of simultaneity and the perception of good apparent motion. The upper curves represent the boundary between good apparent motion and the appearance of successively presented lights with no motion. Note the unusual label on the ordinate: the interval from the onset of first target to the onset of second target. This interval, commonly known as Stimulus Onset Asynchrony (SOA), is equivalent to the sum of the first target's duration plus the ISI. Korte's fourth law itself suggested the importance of SOA in determining whether apparent motion or successive flashes will be seen. As far as the design of display systems is concerned, the most significant aspect of Figure 4 is that for small spatial separations of the lights, a wide range of SOAs will produce the illusion of motion.

Two other investigators support the perceptual significance of a constant SOA. Sgro (1963) found a trade-off between duration and interstimulus interval (ISI) resulting in a constant SOA of about 100 msec. This was true so long as duration was less than 65 msec; above this duration value, optimal interval asymptoted at a small value. Similarly, Kahneman and Wolman (1970) found that apparent motion was optimal at SOAs of 120 msec, for durations less than 100 msec. For longer durations, apparent motion was optimal when the ISI was zero, that is, the second object appeared at the offset of the first (SOA = duration).

A perplexing question arises: "How do these general findings and rules derived from displays consisting of only two targets generalize to more complex displays?" A display used by Braddick (1973, 1974) and by Julesz (1970) provides some answers. They presented observers with two alternating but spatially overlapping fields of dense random dots; the fields were identical except that a square section in the center of one was displaced laterally relative to the corresponding section in

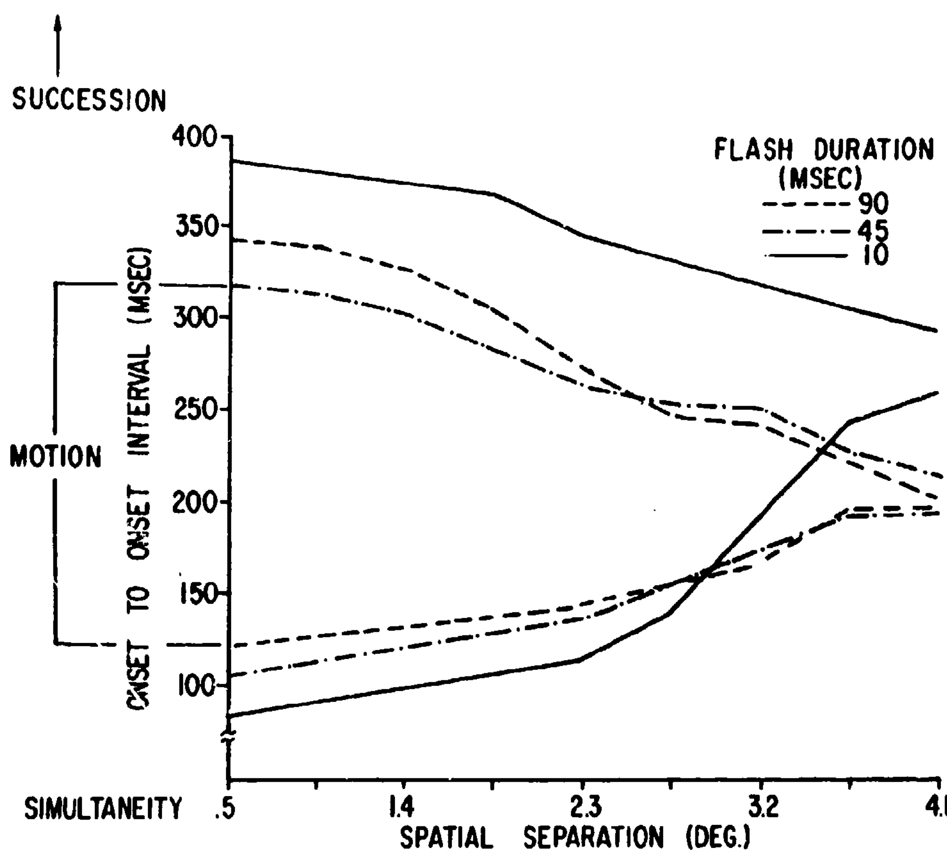

Figure 4. Abscissa: Spatial separation between targets. Ordinate: stimulus onset asynchrony for a pair of flashed targets. The parameter of the family of curves is target duration. For any target duration, the regon between upper and lower curves defines tne conditions of onset asynchrony and spatial separation which produce a good apparent motion, i.e., producing neither simultaneity nor successiveness in the percepts. (Kolers, 1972, based on data by Neuhaus, 1930).

the other field. Dots were removed or added at the borders of the shifted-area so that each display seen alone looked spatially random and insured that no contours outlined the displaced square. When the two frames were presented alternately to the observer at a rate that usually produces apparent movement, observers saw the square moving back and forth. But the range of displacements that produced apparent movement was much less than with the traditional two-object type of display (Braddick, 1974). The appearance of motion began to deteriorate when the displacement exceeded 5 min of arc, and was completely gone where it reached 20 min of arc. This is in comparison to the range Neuhaus used -- 30 minutes to 4 degrees. In addition, Braddick found no trade-off between displacement and ISI; Korte's third law did not hold. Braddick concluded that the type of apparent movement found with his random dot type display is not the same as that found with a simple two-object display.

What about the situation in which one object appears sequentially in many locations? Sperling (1976) has shown that this situation gives dramatically different results from the simple, two-position display. Using a computer generated display, he varied the number of points, their displacement, and duration. He had observers rate on a 10 point scale the quality of the movement on the displays, zero meaning no apparent movement and 10, meaning that the apparent motion looked just like continuous motion. Figure 5 shows his results. The left hand part of the figure shows Sperling's data for a two position display; the lines define the boundaries between combinations of displacement and duration that produced different qualities of motion. For the two position display, the quality of motion is given by the percent of the trials when the observer saw some sort of apparent motion. Thus the conditions enclosed by the line labeled "100" produced apparent motion on every trial; the conditions between this line and that labeled "50" produced apparent motion at least 50% of the time. The longest durations and largest displacements produced the best apparent motion. For the right hand figure, Sperling used the mean quality rating to draw these "iso-quality" contours. In this case, an intermediate duration and the smallest displacement produced the best motion. Sperling notes that the two-position data would not allow accurate prediction of the conditions that would produce the highest quality apparent motion with the multi-position case. Kolers (1972), also using a computer generated display, varied the number of positions across his 7.5 deg screen between 2 and 1024, by powers of 2. For each number of positions, he varied the duration of each object to try to optimize apparent motion. He could produce good motion with 2, and with 64 or more positions, but for intermediate values motion was poor. Motion quality in Kolers' display was not a monotonic function of the number of positions used. This finding is at odds with Sperling's claim of a monotonic improvement in apparent motion with increasing numbers of display positions. Unfortunately, neither researcher provided enough information about his display to allow us to resolve this conflict. This is unfortunate because these types of data would find wide application in display design. For example, many computer driven CRT displays use apparent movement to convey information about real or simulated movement of a target or targets. Systems designers will be interested in minimizing (1) the burden which the display places on the computer central proces-

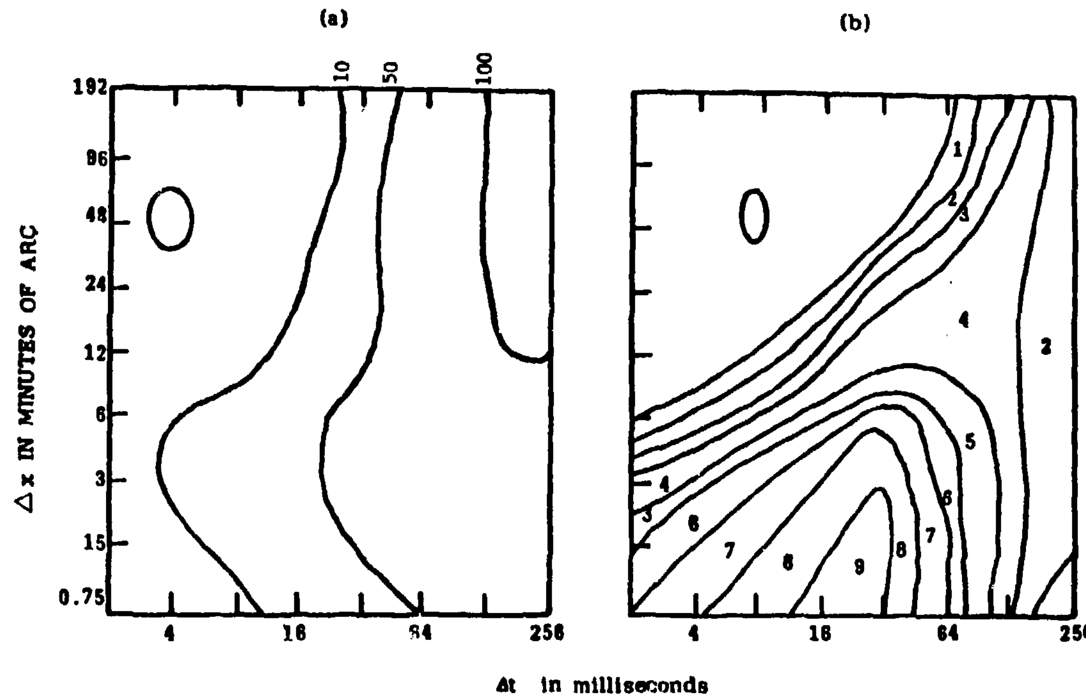

Figure 5. Judged quality of perceived movement as a function of the distance Δx and the time Δt between exposures of the points. Data of one subject: 10 judgments were made for each Δx and Δt combination. (a) Two-point experiment. The area designated zero indicates that generally no movement was perceived (i.e., less than 10% of quality judgments were greater than zero). The contours indicate boundaries of area in which 10% - 50%, 50% - 100%, and lastly, in which all quality judgments were greater than zero. (b) Multipoint data. The number in the areas designate the median value of the quality judgments for (Δx, Δt) within the area. The quality range is 0 (no perceived movement) to 10 (apparently continuous real movement). (From Sperling, 1976).

sor unit and (2) the bandwidth of the signal that drives the display. Such minimization, if it is to be consistent with compelling, high quality apparent motion on the CRT, requires that the display designer know in detail the correct interpretation of the Sperling/ Kolers data.

Induced Motion

Induced motion is defined as the effect which one set of moving objects exerts on the perceived velocity of another set of moving objects. Outside the laboratory, at any one time the visual field usually contains several objects moving relative to one another. As a result, the conditions which give rise to induced motion are quite common in everyday perceptional experience. Duncker (1929) was one of the first to study relative motion. He wondered how, given that there are just two objects in the visual field, their motions might interact. If just one of them were moving, would the observer be able to tell which one, or could the moving object induce motion into the non-moving one, producing a perception that was just the opposite of the physical situation? In this simple case, Duncker found that whichever object the observer fixated would appear to move, regardless of which one actually moved. Duncker believed that if the peripheral object provided the "frame of reference" defining the stable world, this caused all perceived movement to be imparted to the fixated one. But fixation is not always the dominating factor; if one object enclosed the other, like a picture frame, the visual system interpreted the frame as the stable reference and the enclosed object as moving, regardless of where the observer fixated. Duncker darkened the room so that the observer could only see the large frame with a small dot inside. When he moved the frame slowly but kept the dot still, the observer perceived the frame as still and the dot moving. One cannot make a stationary frame appear to move by moving the inner dot, however. If the room is well lighted so that other stationary objects are visible, the illusion is not so compelling; the frame appears to move, but movement is still induced into the dot. These observations were later replicated by Brosgole, Cristal, and Carpenter (1968), and others.

The available data on the magnitudes of these effects are merely adequate to demonstrate their strength but not much more of an analytical character. Duncker, using a display consisting of a disk surrounded by a rotating annulus, used a nulling technique to measure the amount of induced motion in the disk. In other words, he rotated the disk in a direction opposing the induced motion until the disc appeared stationary. The linear motion of the outer annulus between the border and the disk was about 18 deg/sec; the motion of the inner disk needed to cancel the induced motion was about 12 deg/sec. Brosgole, et al. (1968) using a [illegible] and frame arrangement, were able to induce a 2.5 deg movement on the stationary center dot, when the frame moved 10 deg. These values suggest that Duncker's motion induction was stronger than that by Brosgole, et al. (1968). Unfortunately, the two displays differ in many ways so that is is impossible to identify a single cause.

Other researchers have used more complex types of displays with many moving objects. Because these displays used large uniform fields of movement, usually dots, researchers have discussed them in terms of the motion "contrast" between one part of the visual display and another. This was also applied in the luminance domain. Indeed, an analogy between luminance and motion contrast effects has been drawn whereby an area of unvarying luminance may appear darker if the surrounding luminance is increased, or lighter if the surround luminance is darkened (Ratliff, 1965). Similarily, Loomis and Nakayama (1973) found that the perceived speed of an object is reduced if surrounded by faster moving object and is increased if surrounded by more slowly moving ones. Using a shadow-casting technique, they generated a field of moving dots that formed a velocity gradient; dots on the left of the screen moved more slowly than those on the right, with a gradient of velocity in between. Embedded in this field of dots, were two larger targets, one on the left and the other on the right; these moved at the same speed. Despite the fact that the spatial separation of the targets was fixed and should have provided a strong clue that they were indeed moving at the same speed, the left-side target (embedded in the slower moving dots) seemed to move faster than the right-side target (embedded in more rapidly moving dots).

Continuing with the analogy to luminance contrast effects, Holmgren (1973) found an enhancement of the perceived velocity difference at the border between moving and non-moving dots, similar to the contrast enhancement found at borders of luminance differences. These luminance effects are called Mach bands (Ratliff, 1965). Holmgren produced eight rows of dots on a CRT under computer control. The upper four rows moved horizontally. When a dot reached the end of the screen, it began again on the opposite side so the movement was endless. Subjects reported that the bottom-most row of the moving dots, the one bordering on the stationary rows, seemed to move faster than the other moving dots. Of the stationary dots, the row bordering on the moving ones appeared to be moving in the opposite direction. The perceived velocity of both moving and non-moving dots decreased with increased distance from the border between them. Walker and Powell (1974) report a similar result using six rows of moving dots. In this case all dots moved, the upper three rows at .3 deg/sec and the bottom three at .6 deg/sec. Walker and Powell measured the perceived velocities of each row of dots by a matching technique (see Figure 6). Again, the difference in velocity between the two halves of the display was enhanced at the border between them.

All these motion contrast studies, using complex displays, employed only one or a few display configurations. Tynan and Sekuler (1975b) measured one variation of this effect quantitatively, and found that the "motion contrast" rule was not as simple as it had seemed previously. They used a center-surround type of display; the motion in a 1.2 deg x 1.2 deg area was controlled independently of the motion surrounding it in a 10° x 9° field of moving random dots. Movement was of the endless type used by Holmgren, but dots in the center of the display were restricted to that area; surround dots were correspondingly confined to surround. Tynan and Sekuler varied the velocity of the surround dots and measured the perceived velocity of the center dots when they: (1) moved in the same; or (2) opposite direction from the surround, or (3) remained stationary. Figure 7 shows the results;

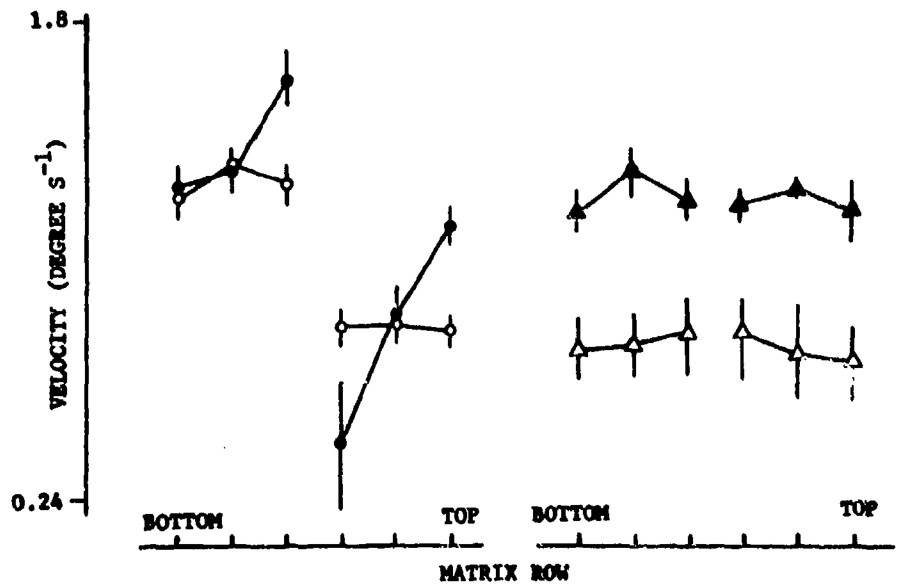

Figure 6. Perceived velocity of each of the six rows in the matrix of dots, with each point representing the average of three observations. The vertical bars delineate the range of values - spanned by the two extreme observations in each case. (a) o, The perceived velocity profile obtained when velocities of 0.30 deg/sec and 0.6 deg/sec were assigned, respectively, to the upper and lower rows in the matrix. The profile adds confirmation to the illusion reported by several observers; with fast and slow moving rows presented to separate eyes (the left and right respectively) simultaneous contrast does not occur. (b) Profiles obtained in control trials in which all six rows were assigned the same velocity, being in the one case 0.6 deg/sec (▲) and in the other, 0.3 deg/sec (Δ). (From Walker & Powell, 1974).

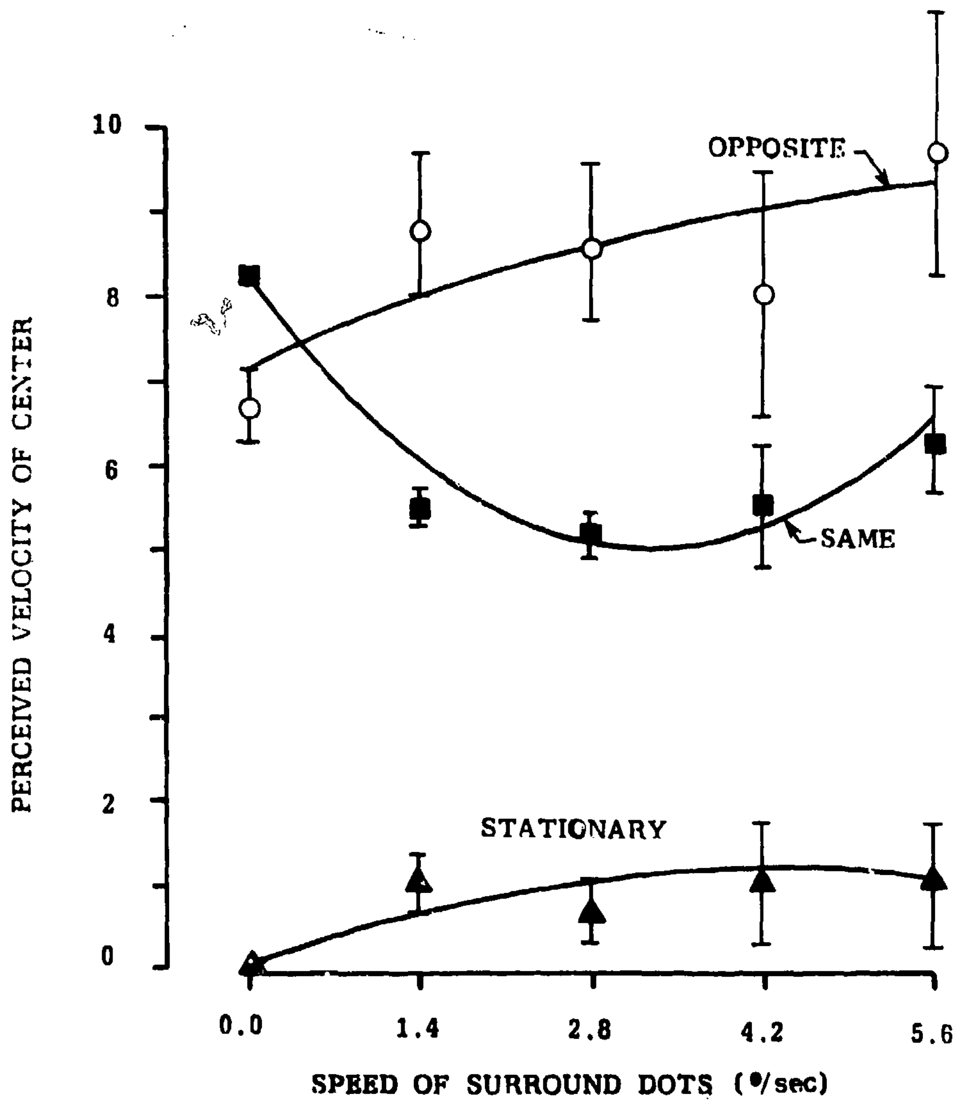

Figure 7. Magnitude estimate of center dots' speed as a function of the speed of surround dots. In all cases, when the center dots moved, their speed was 2.8 deg/sec. Except where the standard error is too small to be seen, ±1 S.E. has been plotted about each point. Curves drawn through the data points are the best fitting polynomial functions of the second degree. (From Tynan & Sekuler, 1975b).

for center dots moving in the opposite direction from the surround, perceived speed increased as the surround speed increased. Also; surround motion induced movement in the stationary dots. As expected, center dots that moved in the same direction as the surround were slowed relative to those that moved in the opposite direction. However, the maximum slowing occurred when the surround dots moved at the same speed as the center, not when they moved faster, as expected from the simple "contrast" rule. A more accurate rule would be a "similarity" law; the closer the surround speed is to the speed of the target, the slower the target appears, the less similar the speed, the faster the target appears. Changing the direction of the surround dots relative to the center is equivalent to changing the sign of a number when performing the arithmetic operations; now the disimilarity between the surround and the center speeds increases monotonically with the magnitude of the surround speed, hence the perceived velocity of the center increases monotonically.

CHAPTER 7

Motion Perception in the Periphery

According to most studies, peripheral motion perception, like that of form, is inferior to foveal perception. However, the literature on this topic is sparse and only a few types of measures have been used. It is noteworthy that in some cases the periphery is not inferior to central vision. Despite the sparseness of relevant data, a few established facts can be stated with confidence. First, motion thresholds always rise as the stimulus is placed further and further in the periphery. Gordon (1947), using rotating sectored disks, found that motion thresholds rose from 6'/sec at the center to 12'/sec at 40° into the periphery of vision. McColgin (1960), who was interested in aviation applications, used standard aircraft indicators as stimuli. The indicators either rotated or moved back and forth. He measured thresholds for movement along 12 meridia and with interpolation constructed iso-sensitivity contours. These are shown in Figure 8. For instance, the line labeled "2" in Figure 8 connects all points in the visual field for which movement thresholds would be 2 RPM. Based on the dimensions of his apparatus, (and assuming speed at the ends of his pointers) it is calculated that the threshold for rotary motion at 55° along the horizontal radial is about 22'/sec; for linear motion at 57° along the horizontal axis the threshhold is about 28'/sec. McColgin took no foveal measurements. The eliptical shape of these isograms will be discussed later.

More recently, Leibowitz, Johnson and Isabelle (1972) using a small, white square, measured a central threshold of 1'/sec and a threshold of about 8'/sec at an eccentricity of 80°. The effect of eccentricity was fairly linear between these two points. Later, Johnson and Leibowitz (1976), using a small dot target, found the central threshold to be about 1.5'/sec and the threshold at 60° to be about 5'/sec, but measured no points at other locations.

Finally, Tyler and Torres (1972) measured motion threshold using a sinusoidally oscillating line (1° in height). They varied the frequency, amplitude and position of this line. Their measurement was the just-detectable amplitude (extent) of oscillation. Tyler and Torres estimate motion thresholds at about 1'/sec in the fovea and 7'/sec at a point 20° in the periphery. The presence of stationary reference marks lowered motion in thresholds in the fovea, but not in the periphery of the visual field.

Except for the McColgin (1960) study, these findings are very much in agreement despite the fact that they used widely different stimuli. (See Absolute Motion Threshold section for a review of effects of spatial parameters on motion thresholds.) They all agree that the periphery is less sensitive than the center of vision for detecting very slow movement. But what of discriminative powers of the periphery at faster speeds? There is only one study that discussed difference thresholds in the periphery of vision. Link and Valerie (1969) found that the periphery is poorer than central vision at this task also.

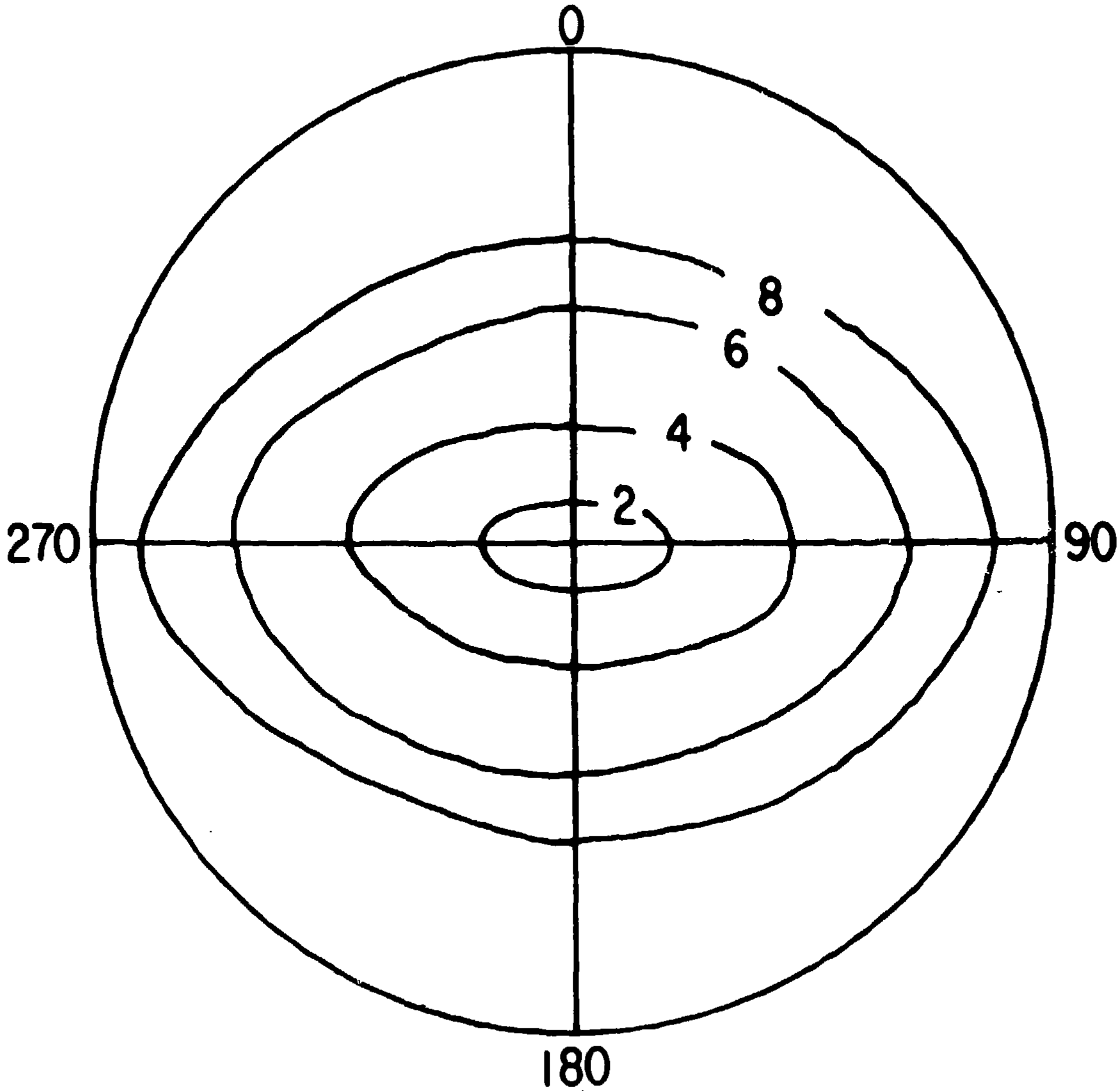

Figure 8. Perimetric chart showing the absolute threshold isograms (RPM) of rotary motion. (From McColgin, 1960).

Like McColgin, they were interested in the application of these data to aviation and used aircraft instrument indicators as their stimuli. The difference threshold measured ($\Delta V/V$) increases linearly with eccentricity. Like McColgin, they interpolated between their data points so that they could construct isograms. The isograms for linear and rotary motion are reproduced (Figure 9) for these slowest reference speed of 6.34°/sec. The .200 line means that any motion along this line (24° out along horizontal axis) would have to change from the reference speed to a speed of 7.6°/sec (i.e., 6.34 + 0.2 x 6.34°/sec) or greater in order for the change to be detected.

Although McColgin, Link, and Valerie used different measures or peripheral motion sensitivity, they agree on several points. First, all authors found that the decrease in motion sensitivity with increased eccentricity was linear. Thus, they felt justified in linear interpolation between data points. Secondly, both sets of isosensitivity contours were ellipcical, that is, the periphery is more sensitive to motion along the horizontal axis than along the vertical axis.* Finally, although it is not mentioned above, neither demonstrated a consistent difference in sensitivity to rotary or linear motion. Both studies however, found that observers preferred to be tested with the rotary motion because it seemed more "salient" to them.

Although the center of vision is more sensitive to certain kinds of motion than is the periphery, both Tyler and Torres, and Leibowitz agree that as stimulation is delivered to an increasingly peripheral retinal location, the response to moving targets declines less rapidly than responses to stationary targets involving spatial information (e.g., acuity). Leibowitz, et al. (1972) point out that "in the periphery, all visual functions are degraded, but motion suffers the least".

A striking example of the superiority of motion perception over acuity in the periphery is a phenomenon called" extended motion" much studied by Thorson, Lange, and Biederman-Thorson (1969) and Biederman-Thorson, Thorson, and Lange (1971). This was also noted many years before by Basler (1906/1975). The basic paradigm is as follows: two dots are flashed in the periphery so close together that they cannot be distinguished as two dots (less than 30' separation at 20° of eccentricity). If these dots are flashed sequentially (phi movement) or one dot is moved through this distance, the observer sees movement extending over a much greater distance than the separation of the dots. They report <u>apparent</u> movements of up to 3 deg at a location 10° in the periphery.

*A similar finding occurs in connection with induced vestibular stimulation and may have a common cause (cf. Benson & Guedry, 1971) for a discussion of the latter effects). A review of vertical/horizontal difference in information processing would have profound importance for display design.

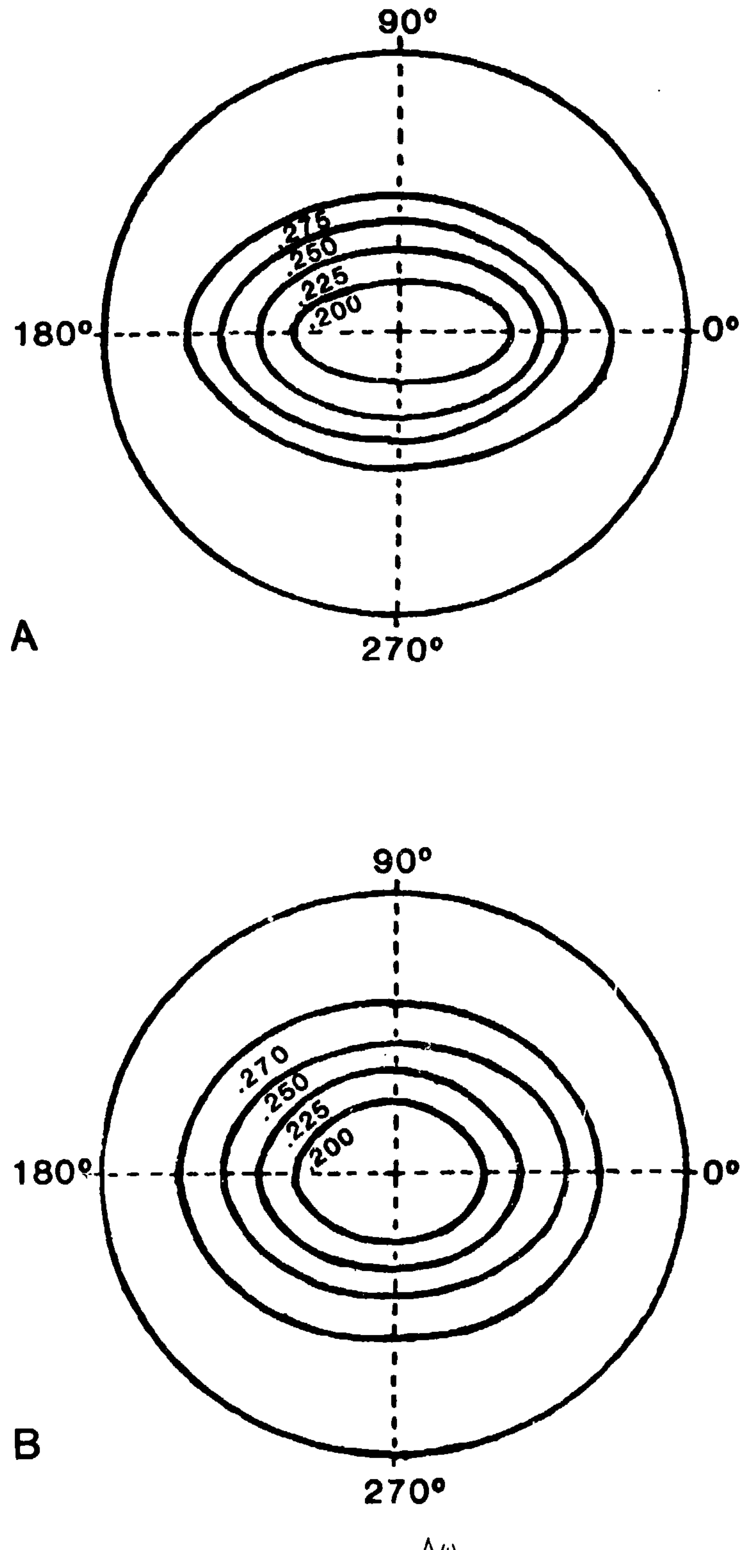

Figure 9. Differential threshold ($\frac{\Delta\omega}{\omega}$) isograms for (a) linear and (b) rotary motion at the slow reference velocity (16.34°/sec). (From Link and Valerie, 1969).

It should be noted that there are much greater differences among individuals when measuring motion thresholds in the periphery than when making similar measurements at the center of vision (Johnson & Leibowitz, 1976). Leibowitz, et al. (1972) showed that although central refractive error may be fully corrected, this does not guarantee that the periphery is not suffering from optical error -- error that affects motion threshold. In one case an observer with perfect central refraction had an 8 diopter error 80° in the periphery. When they corrected the refractive error among their observers for a peripheral location, and measured motion thresholds, the great individual differences they noted without correction had disappeared.

It has been established that the periphery of vision is less sensitive than the center to: (1) slowly moving targets, and (2) small differences in velocity. Another question emerges: for a given peripheral location, which is more effective, a moving or non-moving stimulus? Fankhauser and Schmidt (1960) using a luminance threshold measure rather than motion threshold, found that at the center of vision, a stationary target had a lower threshold than a moving one, but this reversed in the periphery (i.e., a moving target could be seen at a lower luminance than a stationary one). Rogers (1972), and Sekuler and Tynan (unpublished) also have evidence that suggests that the peripheral retina may be responsible for detecting low contrast moving targets, while stationary targets are detected by central-vision.

Different measures of peripheral capabilities have provided different results. One important but neglected measure is reaction time. One of the few studies on this subject was conducted by Borkenhagen (1974). He found that reaction to a small line moving at 1°/sec was 400 msec slower at 60° in the periphery than at central vision. However, when he increased the speed of the line to 12°/sec. this difference dropped to only 50 msec. Preliminary experiments by the authors using isotropic moving dots suggest that this difference can drop to zero, at least at up to 8° in the periphery. Also, Hamerman (1979) found choice reaction time to acceleration of a dot to be a function of degree of acceleration and eccentricity (see Figure 10).

The authors have collected reaction time data specifically to close this large gap in the literature (Tynan & Sekuler, unpublished). We were concerned with the variation in simple reaction time to motion onset with position of the motion in the field. Observers were the authors and a naive volunteer. Targets were random dot patterns produced by a computer on a cathode ray tube. Some 560 dots appeared with a 9.4° diameter circular apperture (constant luminance equals 0.75 cd/m^2); incremental luminance of the dots equals 5 cd/m^2. Viewing was binocular. On any trial, dots first appeared as a stationery pattern for a random foreperiod of 1.3 to 1.7 sec. The dots then instantly accelerated and continued to move upward until the subject depressed a telegraph key signalling that he had seen the moton. The dependent measure was reaction time; the interval from motion onset to key press. Speeds tested were 0.25°, 1°, 4°, and 16°/sec (with speed constant in each block of 125 trials). A specially designed electronic, blanking circuit was used to control the region of the cathode ray tube over

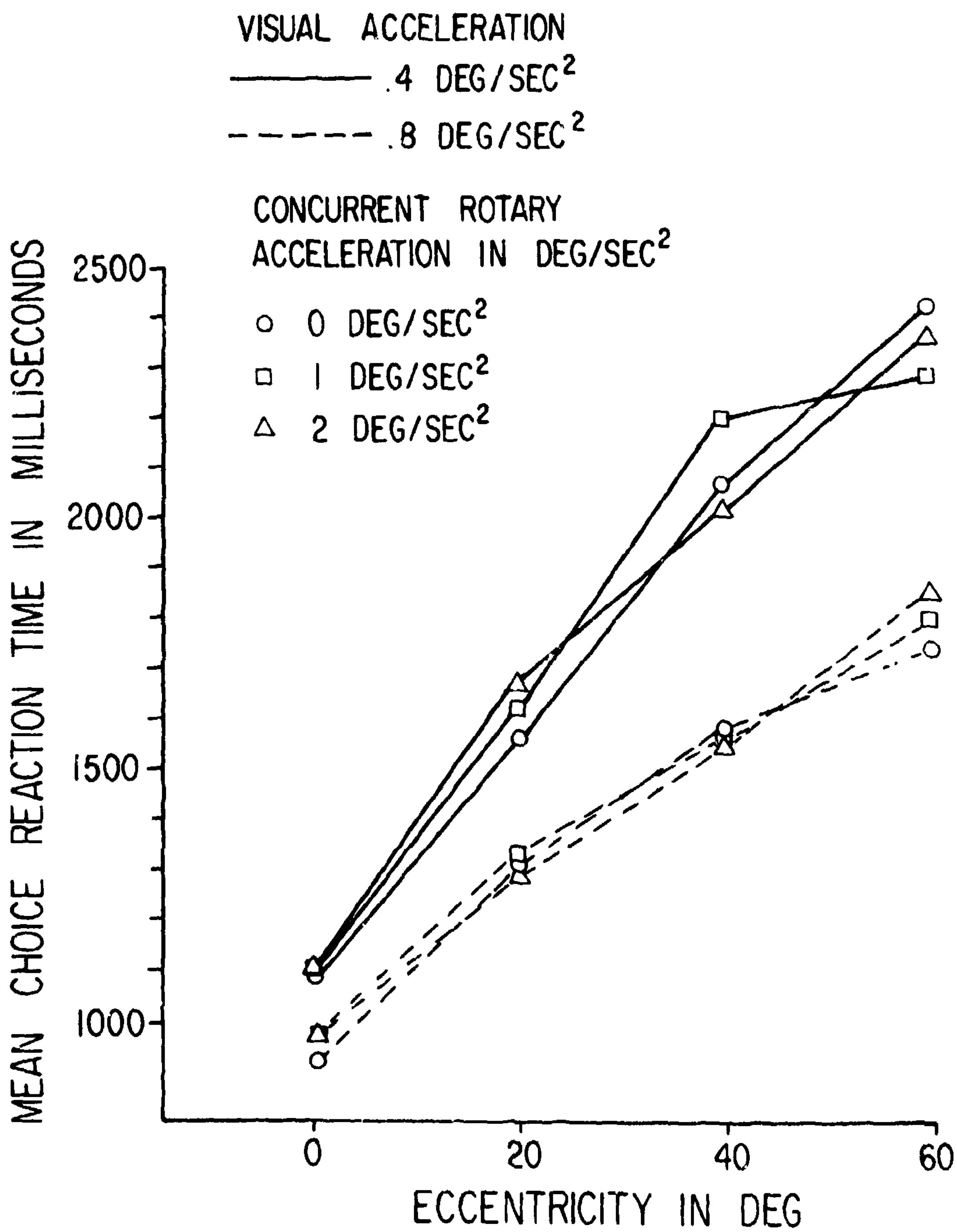

Figure 10. Mean choice reaction time for vertical dot movement at four eccentricities for 11 pilots. (From Hamerman, 1979).

which dots could be seen. The circuit blanked out dots over the remaining sections of the screen. The authors used three major configurations. Dots could be shown across the entire screen (hereafter "full field"), only within a center region of variable diameter (hereafter "patch"), or only within an annular region of variable inner diameter but fixed outer diameter of 9.4° (hereafter "hole" refers to the inner diameter of this annulus). Data for one observer are shown in Figure 11; average data for all observers are given in Figure 12. For all observers, reaction time to onset of the slowest motion increased with increasing hole size; but for the three higher velocities the hole size is without effect. In other words, only for the slowest speed is reaction time effective as more and more of the central portion of the stimulus is eliminated. As the three lower, dashed lines in Figure 12 show, so long as the speed is high enough, even eliminating more than 50% of the center dots fails to increase the reaction time. One may conclude from these results that as far as the potential for initiating reactions to motion onset is concerned, the near periphery of the field (that is up to 8° or 9° of eccentricity) is every bit as good as the center of vision. One may also conclude that the center of vision is more important than the periphery when it comes to initiating reactions to slowly moving targets. A different trend occurs in the patch condition, in which only the central region of the field is stimulated. As dots are eliminated from the periphery and smaller and smaller patches are tested, reaction time decreases for the slowest speed, but is unchanged for higher speeds. Note that for the three higher speeds (1°, 4°, and 16°/sec) stimulation of the central field and the periphery of the field are equally effective in producing reactions to motion onset. As Figure 12 indicates (lower 3 pairs of curves), for any of these speeds hole (peripheral stimulation) and patch (central stimulation) configurations of comparable area and therefore comparable number of dots produce equivalent reaction times. This suggests a form of equipotentially of retinal regions that is not found with the slowest speed (upper two curves in Figure 12).

There is also preliminary evidence to suggest that peripheral viewing affects the perceived speed of an object. As part of a study in 1942, Klein reviewed the literature on this problem and found it conflicting. Some studies claim the stimulus appears to move more slowly; others claim the opposite. Some investigators, (Von Bruecke, 1907; Stevens, 1908 as reported by Klein 1942) found that objects looked faster in the periphery than in central vision. Others, like Brown (1965a, 1965b) say the target looks slower. Preliminary evidence by the authors suggests the reason for these conflicts is: presented eccentrically, targets near the threshold for motion look slower than foveal targets of the same speed but the apparent speed of faster moving targets is unaffected by degree of eccentricity.

Using three naive observers, Tynan and Sekuler (unpublished) measured the preceived speed of moving random dots presented at several eccentricities. Dots appeared within a 1° wide strip some 8° in height. The dots were 7 times the luminance of a weak constant background (0.75 cd/m^2) against which they were presented. Duration of the movement varied randomly from 1.5 to 2.5 sec; motion was always upward. Within a strip some 500 dots were constantly present. The strip of

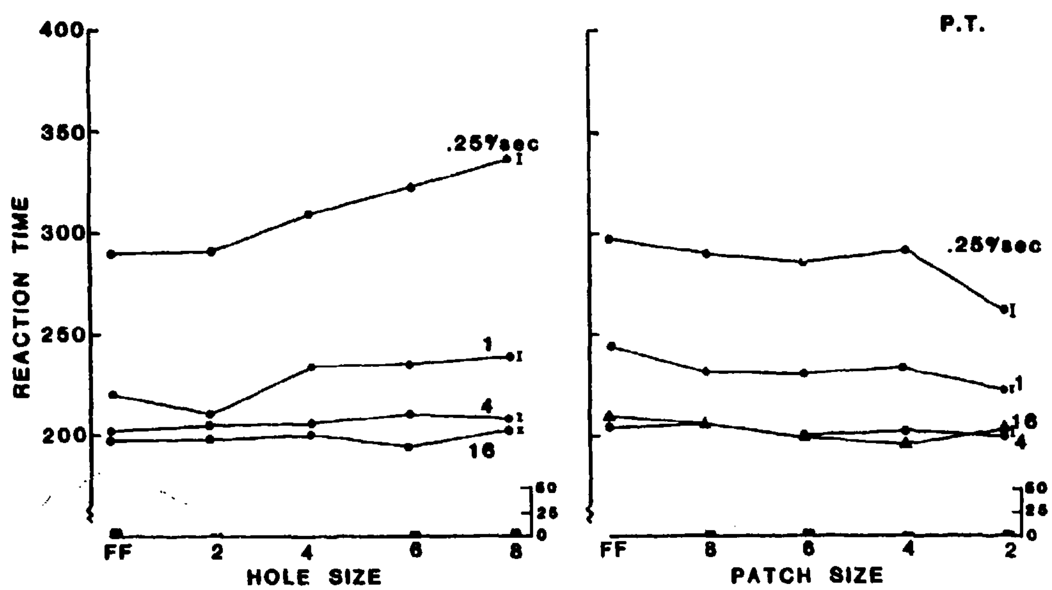

Figure 11. Reaction time to a sudden velocity increment from zero velocity (Observer P.T.). The abscissa is the diameter of the hole (left-hand figure) or patch (right-hand figure) in degrees of visual angle. FF represents full field, i.e., no patch or hole in the dot pattern. The parameter of the lines is velocity increment in deg/sec. Marks to the right of each line show the average standard error for each point along the line. Histograms at the bottom of the figures show the percent of trials on which the observer failed to detect the motion or responded prematurely for the .25 deg/sec. increment conditions (Tynan & Sekuler, unpublished).

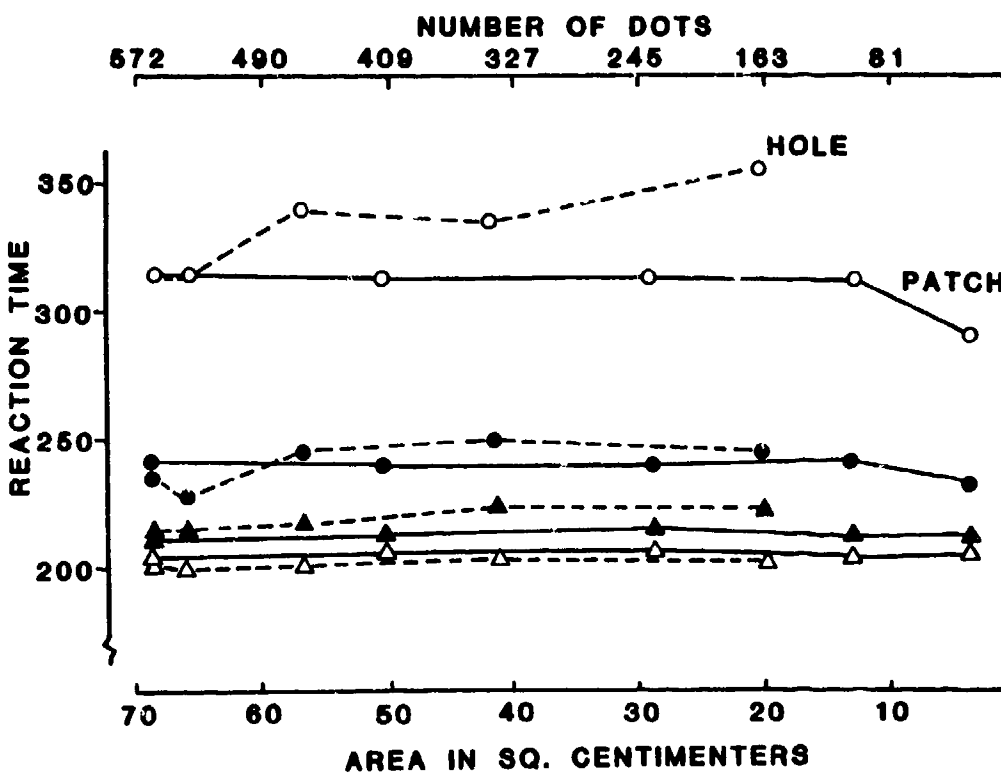

Figure 12. Reacton time as a function of amount of retina stimulated, for three observers. The solid lines are data for the "patch" configuration; dashed lines for the "hole" configuration (see text). o =.25 deg/ sec; o = 1 deg/sec; Δ = 4 deg/sec; Δ = 16 deg/sec. (Tynan & Sekuler, unpublished).

moving dots could be presented at various retinal positions separated by some 7½°, beginning at the fovea and going out to 30° of eccentricity. One-half second after determination of one of these strips, a similar strip appeared, always in the center of the field. The observer used a potentiometer to adjust the speed of this center motion until that speed seemed to match the speed of the other test motion that had been presented in one of five positons: center or 7½°, 15°, 22°, 30° eccentric. The test strip and the adjustable center strip alternated until the observer was satisfied with the match. At that point the matching speed was recorded. Test motion was either at 0.25°, 1°, 4°, or 16° sec. Eight measures were collected from each observer in each of the 20 conditions. For all observers, when presented at the largest eccentricities, the slowest speed (0.25°/sec) could almost never be matched by the motion of the central strip; on most trials the eccentrically presented slow motion appeared to be completely stationary. The remaining data are shown in Figure 13 averaged across all three observers. The ordinate shows the ratio between (1) central speed needed to match the test stimulus, and (2) the actual test stimulus. The parameter of the curves is the speed of test movement. Note that the perceived speed of rapidly moving targets (for example, 16°/sec) does not change with eccentricity but that the perceived speed of slowly moving targets (1°/sec) drops by more than 60% as eccentricity increases. An analysis of variance confirmed the significance of this interaction between velocity and eccentricity ($p < .01$).

One measure of visual perception in which the visual phenomenon is completely dominated by the response of the peripheral areas of the visual field is linearvection. This is the sensation of self-induced movement in the visual environment. Our vestibular apparatus can provide us with information about our bodily acceleration, but not about constant velocity - for that we are dependent on visual information. Thus if an observer is sitting in a large stripped drum and is rotating relative to the drum, he cannot tell whether it is he or the drum that is moving and often incorrectly perceives himself as moving and the drum as not (Dichgans & Brandt, 1973; Brandt, Dichgans, & Koenig, 1973). Once the drum starts moving, the transition from the perception of drum movement to self-movement takes only two to three seconds.

This illusion seems to be exclusively the property of the peripheral visual system as the following brief summary of Brandt et al. (1973) will show: (1) masking up to 120° of the center of the visual field hardly effects the strength of the effect, (2) presenting stimulation of up to 30° in width at the center of vision produces very little effect, and (3) given two areas of motion of equal size, one in the center and one in the periphery, the peripheral one is much more effective. In addition, only one side of the peripheral stimulus need be presented to produce a considerable effect (see Figure 14).

Apparent self-movement in any direction or rotation can be produced by presenting the appropriate motion. Held, Dichgans, and Bauer (1975) produced self-tilt in observers by having them view a 130° rotating textured disk. In this case vestibular cues are present pre-

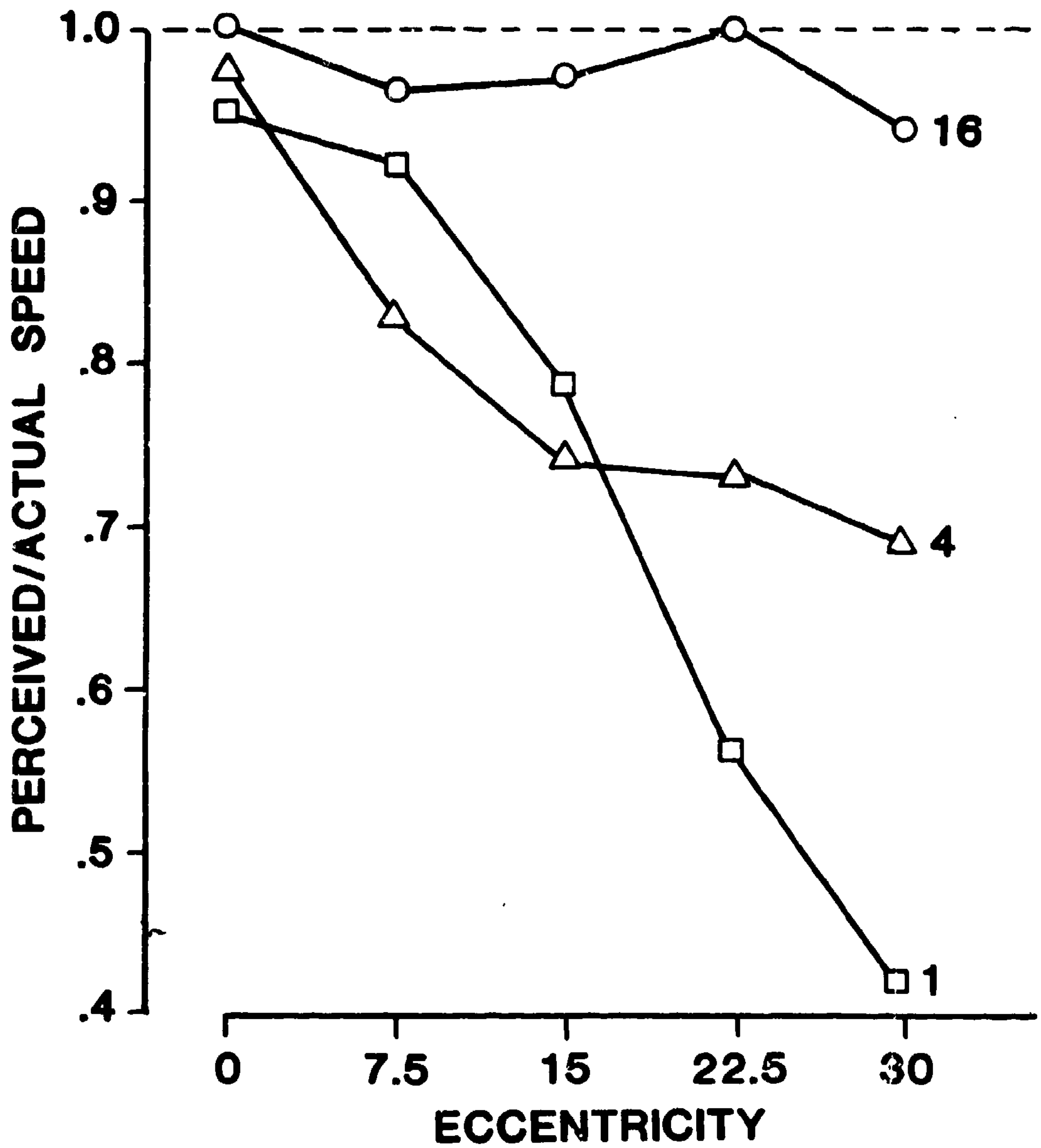

Figure 13. Perceived velocity as a function of eccentricity. The parameter of these lines is the velocity of the eccentrically viewed strip. An ordinate value of one means that the peripheral strip appeared to move at the same speed as the central one; a value less than one means it looked slower than the central strip (Tynan & Sekuler, unpublished).

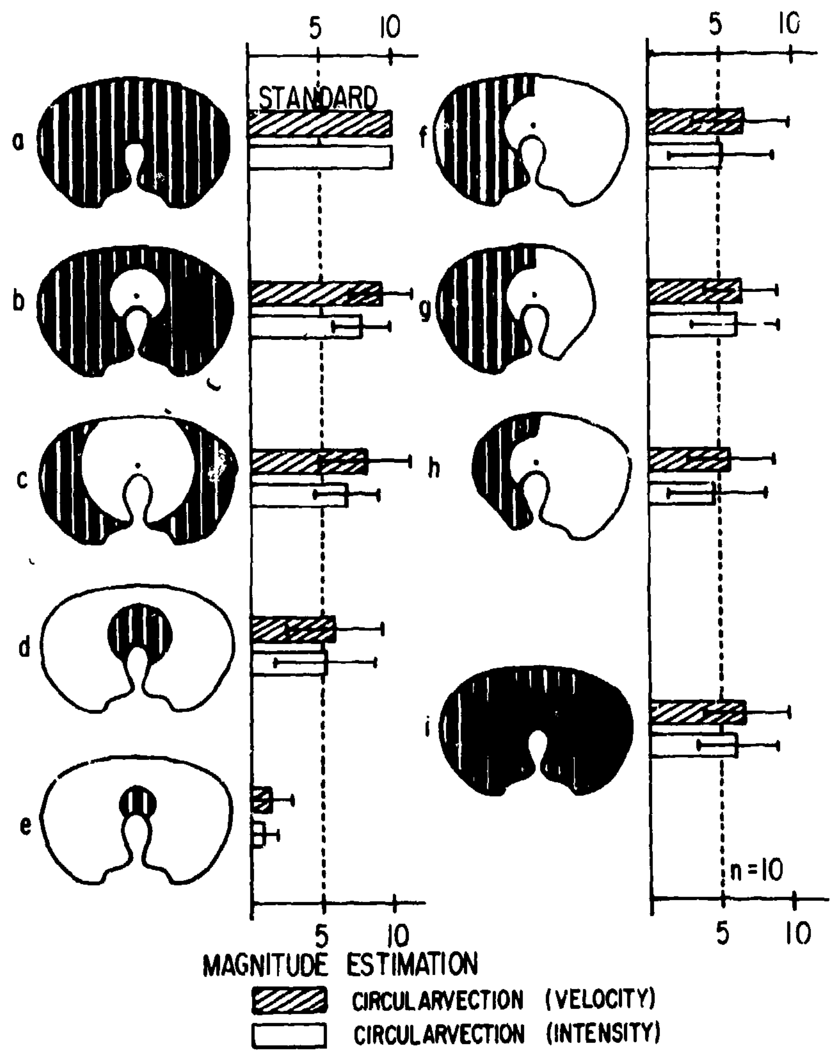

Figure 14. Magnitude estimates of the subjective velocity (shaded columns) and the intensity (white columns) of circularvection with optokinetic stimuli of differing size and location within the visual field (a--g). Stimuli presented during fixation of a stationary target with central masks subtending 60° (b) and 120° (c), and peripheral masks leaving a central stimulus area of 60° (c) and 30° (c). In addition, stimuli were exposed monocularly to the left temporal (g) and right nasal half (h) of the visual field with the central area masked. In (i) an opposite optokinetic stimulation of center and periphery is simultaneously given. In each stimulus situation (a) through (i) the average subjective velocity and the average intensity of CV are nighly correlated. (From Brandt, Dichgans, & Koenig, 1973).

venting continuous self-motion, that is, they did not feel that they were turning completely upside down. The degree of apparent tilt varied between 6° and 43° counter to the direction of disc motion. The optimal speed of rotation was 30° to 40°/sec. Again, by masking the disk into equal area concentric rings and testing the effect of each ring separately, they showed that the concentric ring (48° in the periphery) was the most effective. Johansson (1977b) was able to produce a sensation of upward or downward self-motion (what he calls the elevator effect) by presenting patterns of random moving dots to the observer's peripheral field of view (45° to 90°) via two television monitors. In this case he allowed the observer a clear view of the rest of the room, yet the effect was still present; the room also appeared to move with the observer like an elevator cage. This effect could be produced in some observers even when the monitors were masked down to 1° wide strips (a few percent of the visual field). Again, when the observer feels self-movement, he perceives the dots as stationary. This effect could even be produced in some observers when only one dot was presented to each peripheral hemifield. As far as the number of people that experience these illusions, the proportions range from 100% for most (cf. Brandt et al., 1973) stimuli to about 50% for even the meager, one dot display.

This effect is important to the human engineer for two reasons: (1) linearvection is accompanied by apparent lack of movement of the inducing stimulus, and (2) linearvection could cause dangerous disorientation in pilots. Moreover, as Johansson (1977b) has shown, even the presence of stationary reference marks does not inhibit this compelling phenomenon.

In summary then, the absolute threshold for motion decreases with eccentricity. (See Absolute Motion section for implications for display design.) Eccentric viewing, with speeds above threshold, may not necessarily result in poorer performance in terms of contrast threshold and reaction time. This is particularly true in the near-periphery and if the peripheral motion effect is influenced by mean luminance level (see chapter entitled Flicker Sensitivity).

Although the data on perceived speed in the periphery are sparse, it seems likely that the observer will misjudge the speed of an eccentric object, unless he is well practiced in such observations. Therefore, tasks which involve direct view (e.g., Airborn Target Acquisition) or extraction of peripheral motion from displays (e.g., visually coupled systems, wrap around simulators) can be expected to produce large individual differences which could be studied for purposes of training and selection as well as for design criteria.

CHAPTER 8

Flash Sensitivity

In this section the sensitivity of the observer to non-moving lights that flash or flicker is discussed. The literature review has been divided into two sections: detection of single versus multiple flashes and detection of flicker. Probably the most important variable in detection is the background luminance of the display (called adaptation level because it is assumed that the observer has adapted to the background luminance). Additional considerations are the spatial characteristics of the stimulus and retinal location.

The simplest case to consider is the detection of a small spot of light (about 1°) viewed with the center of vision. Reviews by Herrick (1973c) and Roufs (1972) show that most of the data on the detection of single flashes can be described by a simple rule: with other variables held constant for all flash durations below some value (called the "critical duration"), a constant amount of <u>energy</u> is needed if the flash is to be just visible. "Bloch's law" is the name given to this observed trade-off between luminance and duration. The law states that stimuli which represent a constant product of luminance and duration yield constant visual effects. This reciprocity breaks down at longer durations; thereafter constant luminance alone yields constant visual effect, a fact which could be of considerable importance to display designers. This critical duration ranges from 90 to 150 msec, depending on adaptation level of the stimulus (i.e., the background luminance upon which the flash is superimposed). From Herrick's data, the authors have derived the following equation which expresses the critical duration (in milliseconds) as a function of background luminance:

$$\text{critical duration} = -19.75 \log L + 63.9, \qquad (1)$$

where Lum is background luminance in cd/m^2.

Of course, the minimum energy needed during the critical duration is also a function of background luminance. Another equation can be derived from this same study for threshold energy (a product of milliseconds and luminance) as a function of background luminance:

$$\log \text{threshold energy} = .648 \cdot \log L + .835. \qquad (2)$$

Taking the antilog of the left hand side and dividing it by the duration of the flash (if it is less than the critical duration) one derives the threshold luminance of the flash. Dividing the threshold luminance by the critical duration, one can obtain the luminance needed to detect a flash of a duration greater than the critical duration (since threshold luminance is constant for durations greater than the critical duration).

Roufs' (1972) data are similar qualitatively, although difficult to compare with Herrick's because the former used the Troland as his luminance measure which takes account of variation in <u>retinal</u> luminance with variations in pupil size as background luminance changes (see Appendix A). For this reason Herrick's experiment is closer to the applied situation. However, Roufs' review of several studies shows that estimates of the energy needed to detect a pulse may vary by as much as a log unit between similar experiments. Still, Herrick's data are at least a rough approximation of flash thresholds. These results hold for the restricted conditions of this report regarding one stimulus configuration (a target of about one deg in diameter viewed foveally). Baumgardt and Hillman (1961) tested the validity of Bloch's law for both large stimuli and eccentric viewing. They tested observers with stimuli ranging up to 8° in diameter at a location 20° in peripheral vision. Bloch's law was still valid even for their largest target, but their data are not in a form that allows us to calculate changes in detectability with target size.

Other data are available on the changes in sensitivity that occur with changes in retinal location (see Haines, 1975 review). In this area researchers generally used flashes of some long and constant duration. Riopelle and Bevan (1953, cited in Haines, 1975) examined absolute sensitivity at many points throughout the visual field against a zero luminance background. Their results are presented graphically in Figure 15 (from Haines, 1975). They used a 1° diameter target of white light with a duration from 500 to 750 msec. Sensitivity was greatest at ±5° temporal from the fovea and 15° to 30° nasal. Taylor (1964b) measured sensitivity against a background luminance of 257 cd/m^2 with targets up to an eccentricity of 12.5°. He varied the size of his target from one to 120 minutes of arc at a flash duration of 333 msec. His data are presented in Figure 16. The drop in sensitivity with retinal location is less for larger than smaller targets due to the greater spatial summative capacity of the peripheral retina. Figure 17 is a plot by Taylor showing the relationship between target size and contrast (Appendix B) for a point just above the fovea. Also reported in this study are composite data from several studies on the change in the size-contrast relationship at different background levels. Reproduced in Figure 18, these data were collected using continuously presented rather than flashed targets.

It has long been recognized that a steady dim target presented to the peripheral retina will tend to become invisible after a few seconds. This phenomenon of stimulus saturation is known as Troxler's Effect. More recently though, Singer, Zihl, and Poppel (1977) described a related and more striking form of saturation associated with flashing rather than steady targets. Their observers fixed a central mark while a small spot was flashed for 500 msec every 4 sec. After several minutes of repeated presentations the observer's threshold for these flashes increased between 0.5 and 1.0 log units. The area of decreased sensitivity extended spatially beyond and surrounded the flashed spot (27' to 116'). This adaptation effect increased with retinal eccentricity, and persisted for 8 to 10 minutes in the absence of further stimulation. Curiously, this decreased sensitivity could be eliminated and normal sensitivity instantly restored if a target was presented to a homologus area of the contralateral visual field. The reduction in sensitivity could be prevented if the observer simply moved his eyes towards the target every time it was presented.

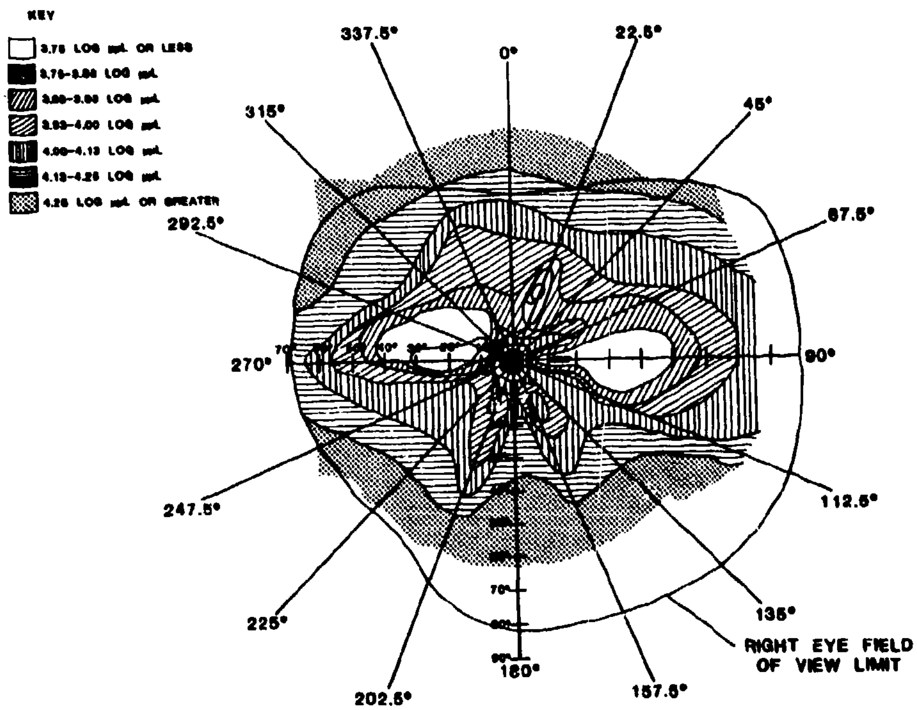

Figure 15. Distribution of absolute achromatic retinal sensitivity for binocular viewing. (From Haines, 1975).

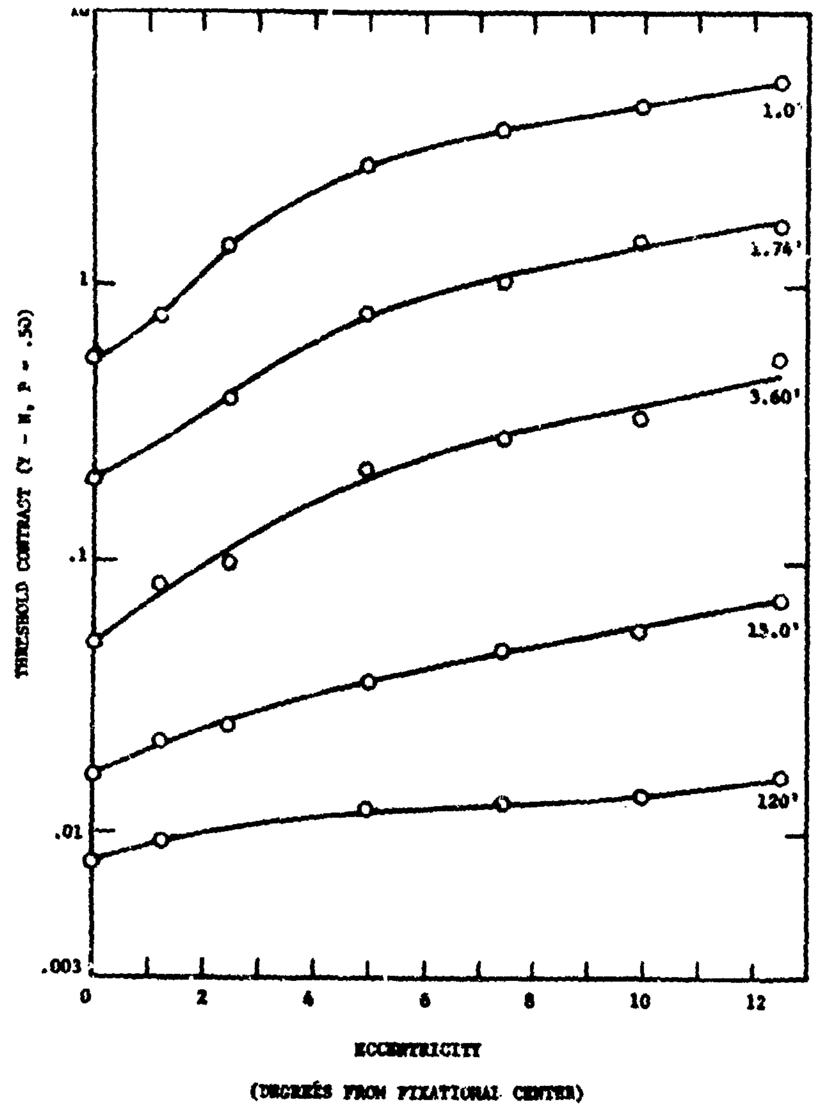

Figure 16. Threshold contrast as a function of retinal position and target size for binocular photopic vision. Four observers, for which the plotted average values represent 0.50 probability of detection in a "yes-no" experiment. Each data point is based upon 2400 observations. (From Taylor, 1964b).

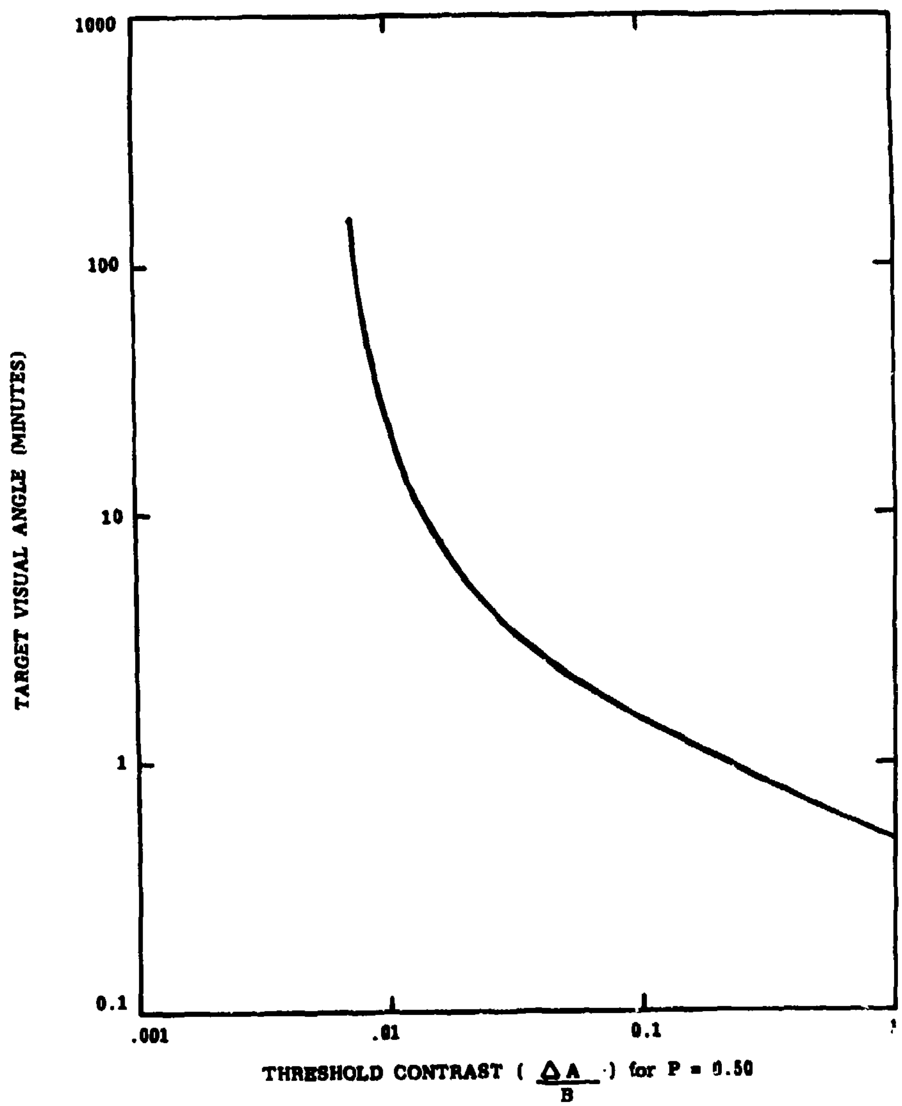

Figure 17. Determination of the target size and threshold contrast dependency made under controlled conditions of central foveal fixation and an invariant target duration of .33 sec. The data represent averages from five observers who made a total of 45,000 observations, using 18 target sizes. (From Taylor, 1964b).

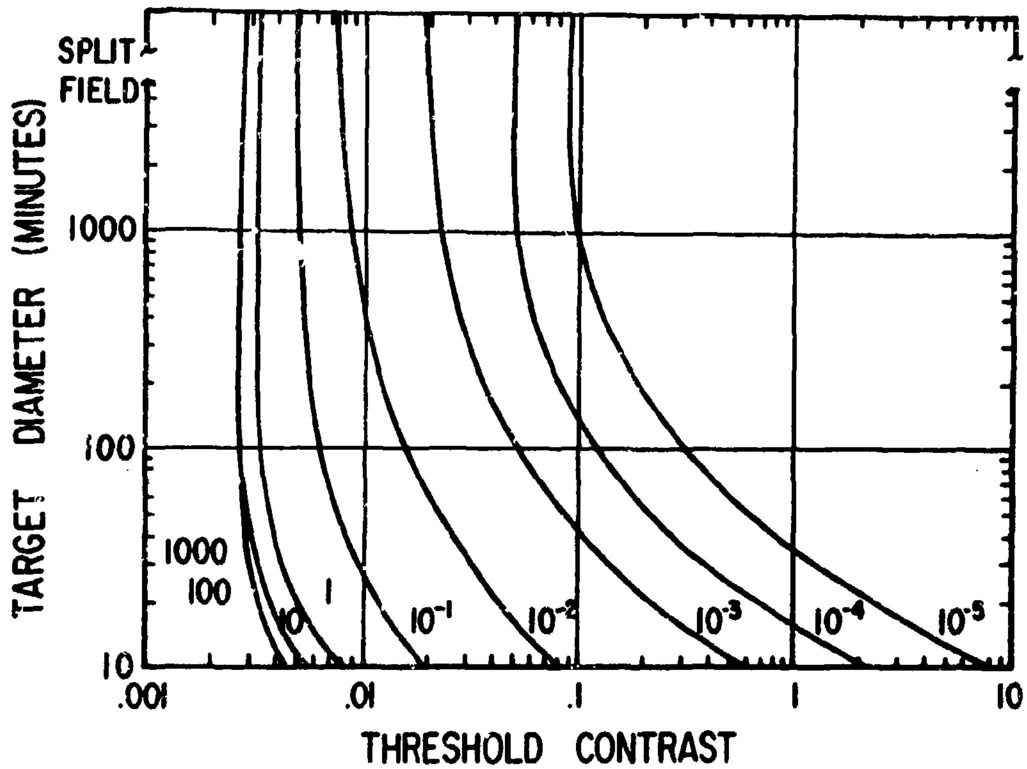

Figure 18. Threshold contrast as a function of the diameter of a uniform circular target. The assumption is made that asymptotic values of contrast would be reached in the case of a "split-field" (i.e., with a target of infinite radius). Each curve refers to a different adaptation luminance, expressed here in footlamberts. (The value in footlamberts times 3.426 yields the value in cd/m^2.) (From Taylor, 1964b.)

Although Singer et al. (1977) proposed an intriguing and complex physiological explanation for their results, it may be that the effect is simply another manifestation of the fact that continued attention to a central fixation point reduces peripheral sensitivity. (Webster & Haselrud, 1965; Ikeda & Takeuchi, 1975.) Therefore, when peripheral stimuli are to be detected while attention is focused elsewhere care must be taken to avoid the consequences of the Troxler effect.

In the case of visual effects which are produced by two or more flashes presented to a single retinal locus in rapid succession, a single rule cannot be adduced. Specifically, the effect which a flash of light produces in the visual system does not end when the light is extinguished. Ikeda (1965) and others believe that the neural circuits of the visual system "ring" after being stimulated by a flash, like a bell or an electronic circuit may react when a pulse increase of voltage is applied to it. Figure 19 shows Ikeda's conception of the dampened oscillations that may follow a flash. These curves are derived by stimulating the eye with two (12.5 msec) pulses of light separated by varying intervals, t, shown on the abscissa.

On the ordinate 0.3 indicates complete summation of the two flashes, as would be expected if there are zero intervals between them; an ordinate value of zero indicates no summation (i.e. the two flashes together are only as detectable as one flash alone). The (a) curves are for increments of light and the (b) curves for decrements (i.e. diminishing). Where either curve reaches its minimum, the visual system behaves as though there were inhibitions between the responses to the two flashes; the combined effect of the two flashes is less than the effect of either flash alone. Uetsuki and Ikeda (1970) produced similar data for different background luminance levels. The interval at which this minimum detectability occurs changes with background luminance to over 100 msec at low levels.

Herrick (1974) found that most of the literature he reviewed showed a similar U-shaped relationship between the inter-flash interval and detection. Moreover, this relationship was relatively independent of flash duration. Perhaps of more interest to design engineers is the period for which a second flash will join with a preceding one. Roufs (1973) using 2 msec flashes, found that they would sum completely as long as the interval between them was not greater than one third of the critical duration found for his single flash experiments at the same mean luminance. Similarly, Herrick (1973a) finds this "two-flash critical interval" for 5 msec flashes to be less than one half of the critical duration for a single flash (Figure 20).

Herrick (1973a) studied the effect of trains from 2 to 12 flashes. Each flash was 5 msec duration, but the inter-flash interval was varied. Herrick defined a quantity which he called the "critical duration". For a given number of flashes, this is the longest duration over which threshold is determined by constant energy. As is usually the case, duration is measured from the onset of the first flash to the offset of the last flash. For example, using a display consisting of three 5 msec flashes, if the "critical duration" was 70 msec, one could deliver the flashes with 5 msec between each and total duration would

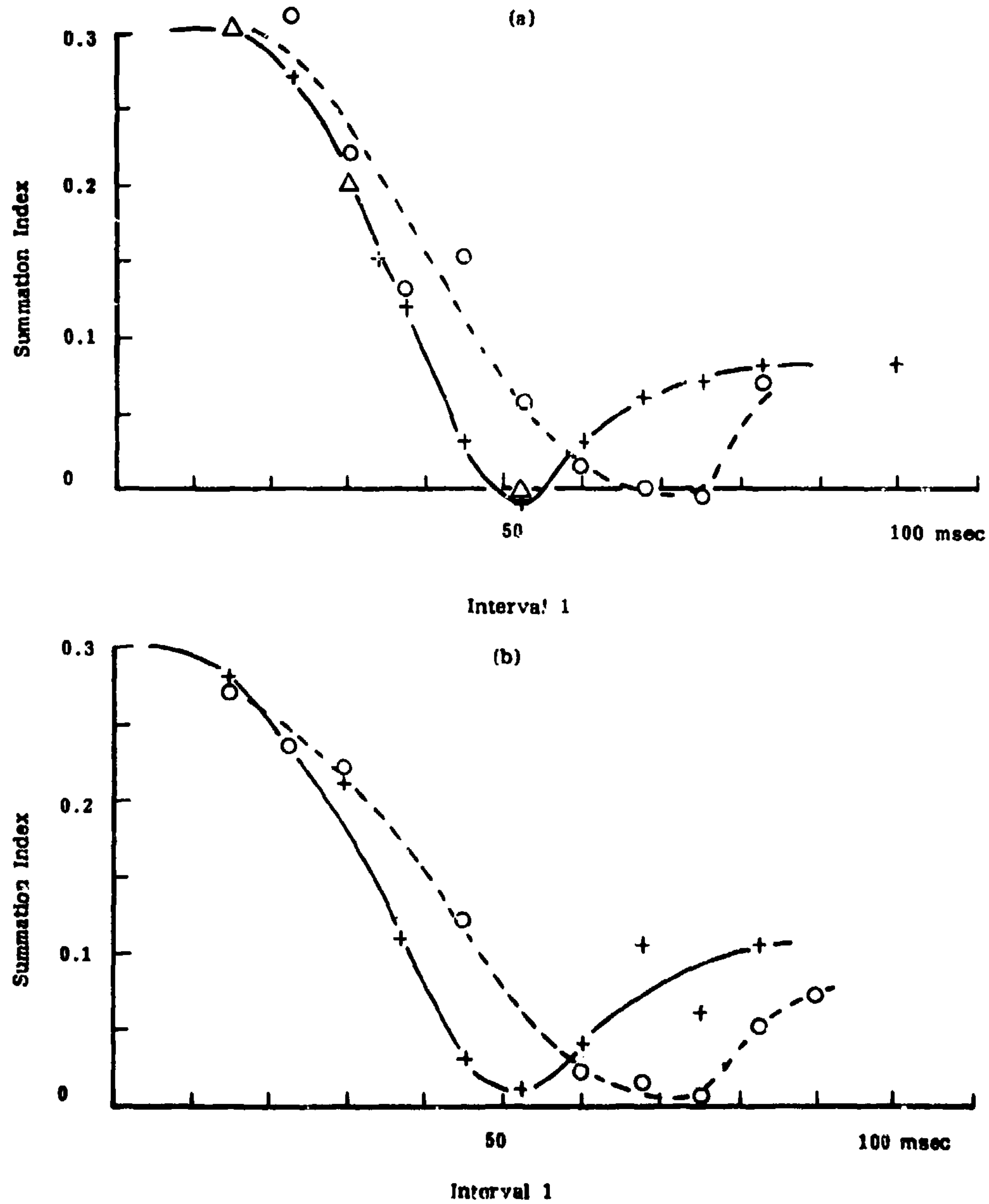

Figure 19. Summation index (σ_o) as a function of the interval between two flashes of 630 nm for two adapting levels from the subject M1. Crosses for 328 trolands and open circles for 61.2 trolands. Panel a shows data for summation of two incremental pulses; panel b shows data for summation of two decremental pulses. (From Ikeda, 1965.)

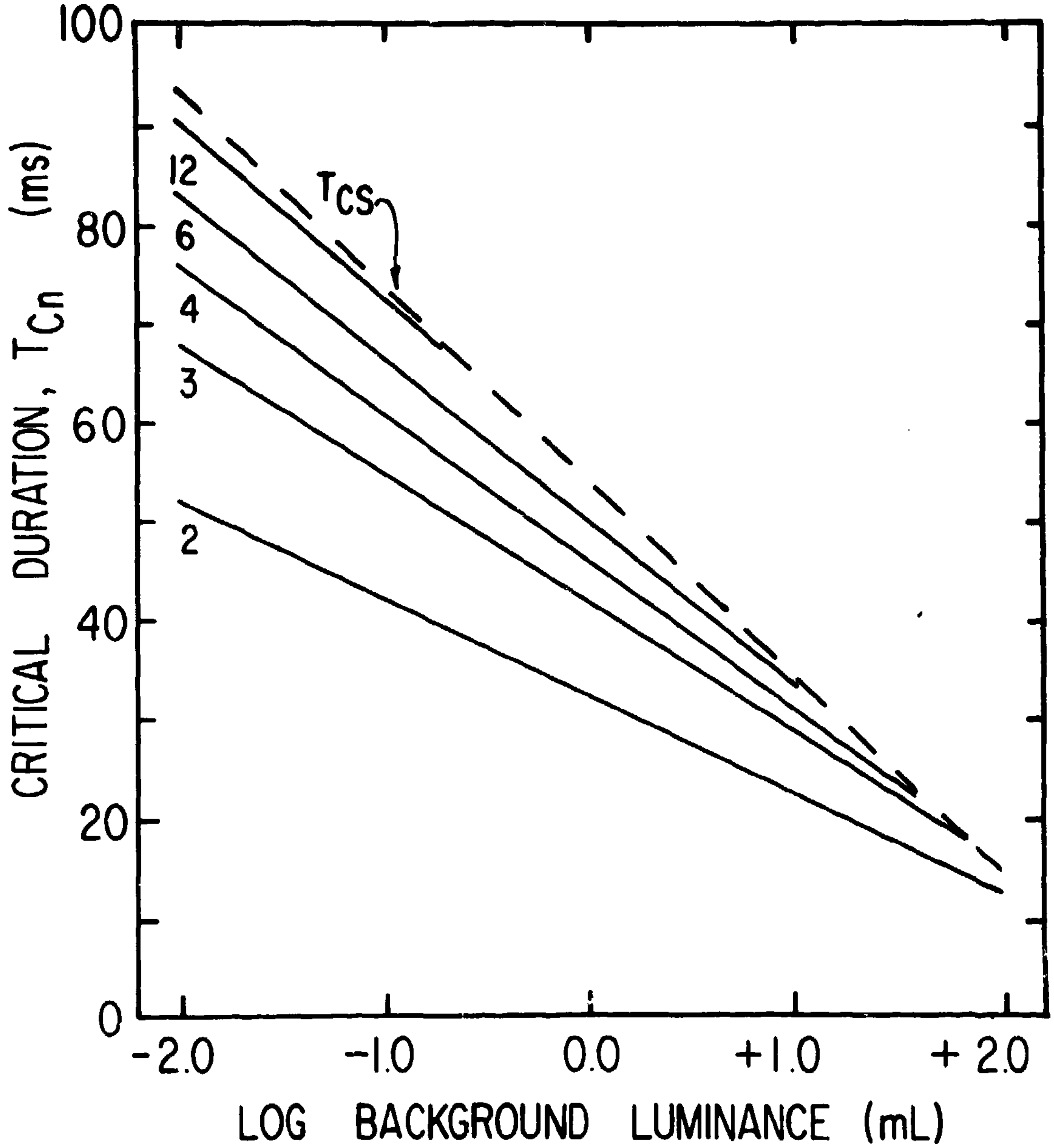

Figure 20. Critical duration as a function of background luminance. The number next to each curve gives the number of identical 5-msec flashes. The term T_{cs} refers to the critical duration of a variable-duration, single-flash experiment. (From Herrick, 1973a).

equal 25 msec; or with 20 msec between each flash for a duration of 55 msec. All that matters is that total duration does not exceed 70 msec. Figure 20 from Herrick (1973a) shows a set of curves for this critical duration as a function of flash number and background luminance. Herrick also found that the energy constant associated with each critical duration was independent of the number of flashes, including single flashes, so that equation 2 may be used to calculate this energy value. Also, at any background luminance, the interval between flashes that makes them <u>least</u> effective in stimulating the eye, is independent of the number of flashes.* Figure 21 lists these intervals for the background luminances at which Herrick made measurements. The threshold luminance necessary to see the flash at this "least effective" interval is also independent of flash number, but is dependent on background luminance. The relationship between the threshold luminance and background luminance is provided by the following equation, derived from Herrick's data:

$$\text{Threshold luminance} = .296L + .9508, \qquad (3)$$

where L is background luminance in cd/m^2.

The response of the visual system to multiple flashes in the periphery is similar to that at the fovea, except that the loss of sensitivity with increased inter-flash interval is monotonic rather than U-shaped. Herrick (1973b) presented flashes of about 1° in diameter, at a location 14.2° in the periphery against a completely dark background. Critical duration was about 70 msec for two 10 msec flashes and 100 msec for multiple flashes. Flash duration had no effect over the range of 5 to 20 msec. Van den Brink and Bouman (1954) compared critical duration for 2 flashes presented at the fovea and up to 10° into the periphery and found no change in critical duration. They also found that critical duration was independent of changes in spatial parameters of their targets.

*It should be noted that while this flashing light can be useful to compel attention, it may also be employed to "fool" the eye - for example when countermeasures are necessary for purposes of security.

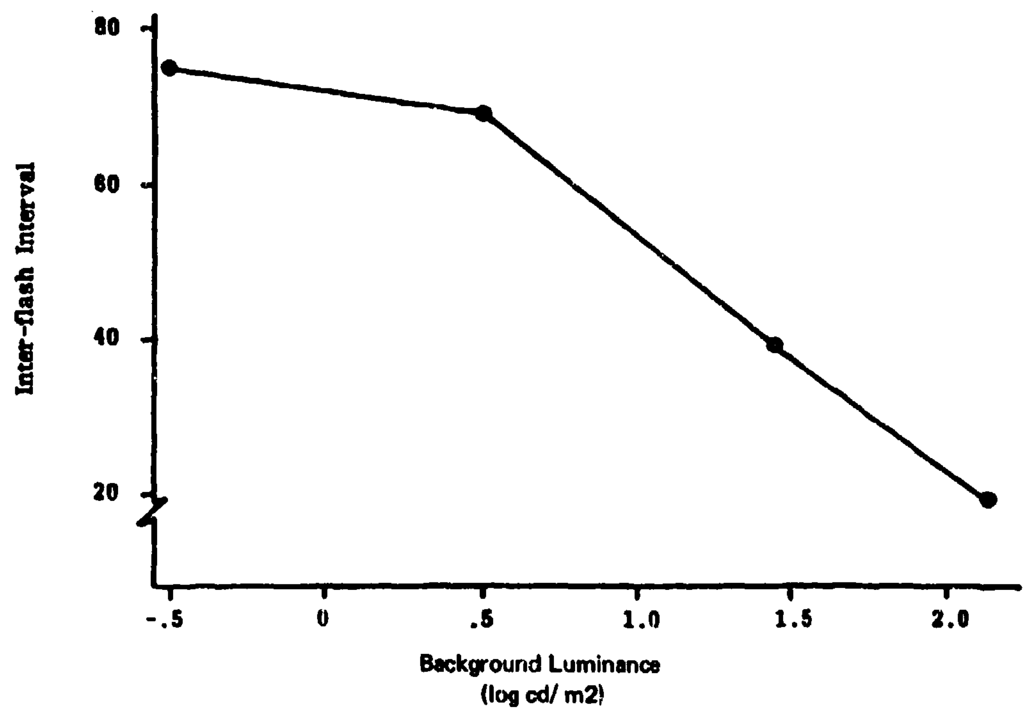

Figure 21. Inter-flash interval providing the highest threshold as a function of background luminance. (Calculated from Herrick, 1973a).

CHAPTER 9

Flicker Sensitivity

After examining the visibility of flashes of light and short flash trains, the next logical step is to review data on the visibility of lights which flicker continuously. Although research on visual flicker has been a scientific endeavor for over 200 years, most of this research has unfortunately been concerned with just one particular phenomenon --Critical Flicker Fusion (CFF). This is a measure of the temporal frequency at which a modulating light will appear to flicker, or the frequency at which the flicker appears to fuse. Ginsburg (1970) compiled a bibliography on CFF covering the period 1953 to 1968 and numbering 1293 articles. This information is certainly useful to the designer who wishes to present information intermittently, but have it appear flicker free, as in television and film systems. However, for other applications (e.g., warning lights) the designer may <u>want</u> the flicker of the light to be seen and desires to know how much to modulate a light of a given temporal frequency to insure that the modulation is perceptible or maximally identifiable. For example, to keep secure an electronic data link, it might be possible using flicker to recombine with the eye, a coded interrupted signal. This latter problem will be discussed, along with the critical flicker fusion literature, to summarize what is known about the effects of display size, color, area, etc. on general flicker sensitivity.

The first issue concerns how sensitive an observer is to different frequencies of flicker. Kelly (1961a, 1961b) created what he called the "standard observer" by combining flicker sensitivity data for eight observers. He used a Ganzfeld (full field) light and varied the amount and frequency of its modulation. The waveform of the modulation was sinusoidal (Figure 22) and modulation (m) was between 0 and 1.* M=1 means that the peak luminance of the light is twice the mean luminance, and that the minimum of the wave is zero luminance. This is the maximum amount of modulation; m = 0 means that the light is on steadily at the mean luminance. Kelly's data are plotted in Figure 23. The left hand ordinate is in terms of m. The observers are most sensitive (i.e., the lowest value of m needed to see the flicker) at a frequency between 10 and 20 Hz (not 4-6 Hz as suggested in MIL STD 1472B). Observers are less sensitive at frequencies above and below this range. At approximately 70 Hz, maximum m is required for flicker detection. This corresponds to the critical flicker fusion for these conditions. The variance among observers is greatest at 16 Hz, near peak sensitivity. When a single observer is equally sensitive to two frequencies, one high and one low, variance in his threshold would be substantially greater for the lower than for the higher frequency.

*[1] $m = \dfrac{L_{max} - L_{min}}{L_{max} + L_{min}}$ where L_{max} = maximum luminance and L_{min} = minimum luminance of the waveform

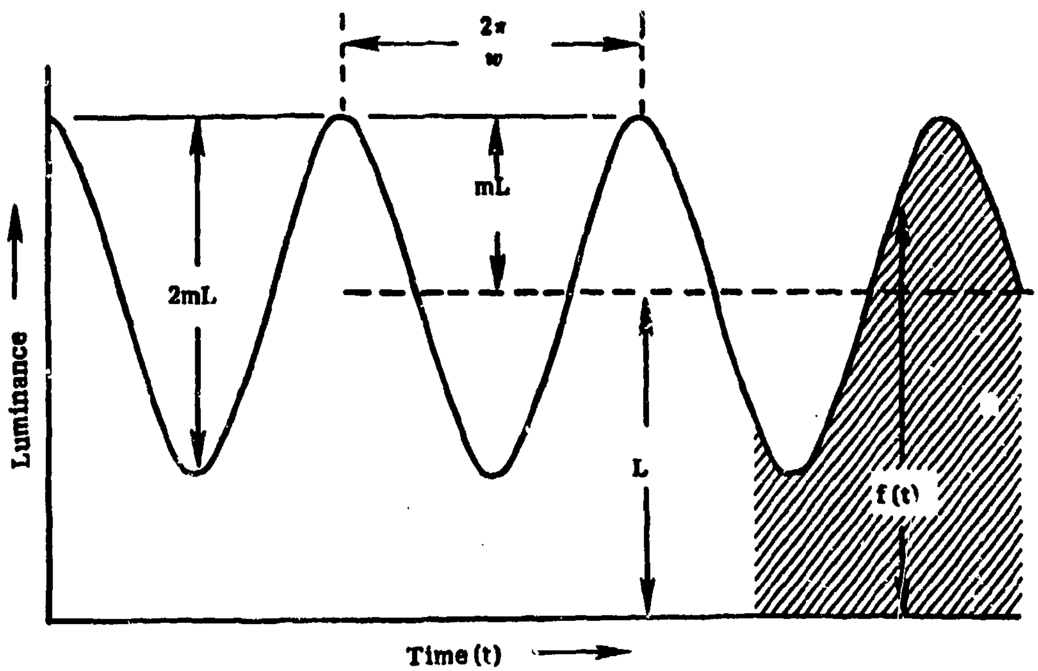

Figure 22. Stimulus waveform used by Kelly and others. This waveform is the sum of a sinusoidal component, of amplitude mL, and a constant component, L. The time-average luminance, L, is often called the "adaptation level", and the dimensionless ratio, m, is called the "modulation". (From Kelly, 1972).

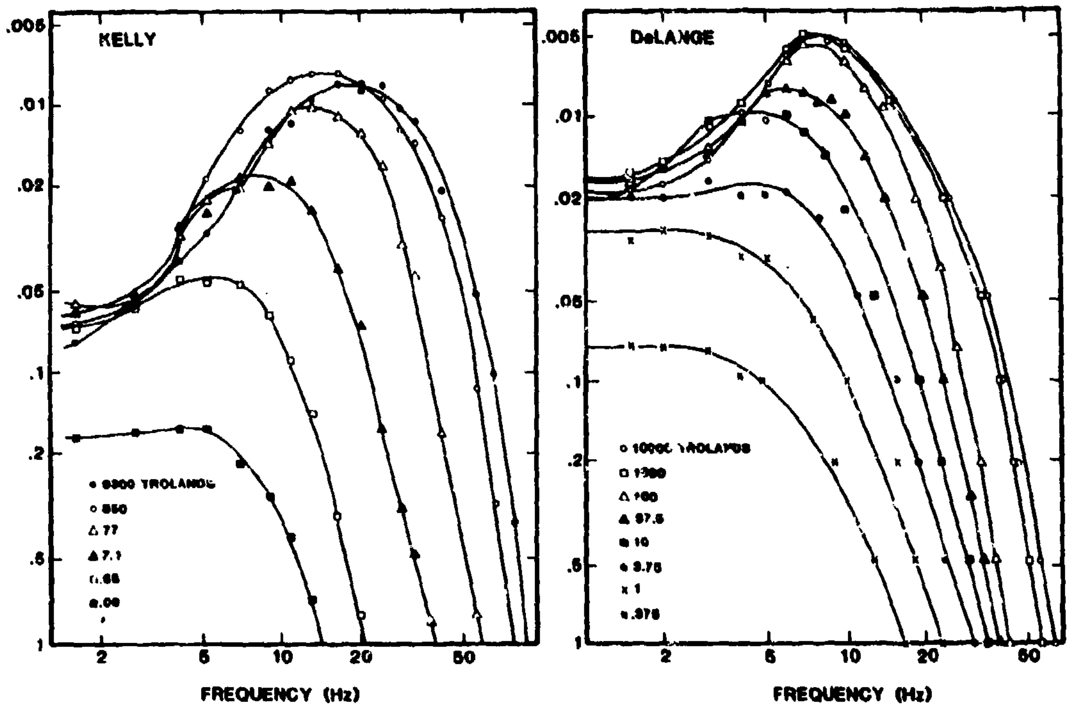

Figure 23. Photopic modulation sensitivity data. Th curves on the left were obtained with a large flickering field; those on the right with a small flickering spot on a steady surround (Kelly, 1961; deLange, 1958, as reproduced in Kelly, 1972).

It is felt that the most important display parameter from a design standpoint is mean luminance; which controls the adaptative state of the eye. Two rather complete sets of data on this are presented in Figure 23 (from Kelly, 1972). The left-hand data are from Kelly (1961a) for a 65° diameter target; the right-hand data are from deLange (1958) with a 2° target surrounded by a steady field of the same mean luminance as the target. There are four important characteristics of these data. (1) At low frequencies, threshold modulation is constant across mean luminance (except for the lowest luminance level). This means the data obey the Weber-Fechner law, threshold = $\frac{\Delta I}{I}$ = K. From a slightly different perspective, the threshold amplitude of the modulation (m) increases proportionately with mean luminance. (2) at low temporal frequencies, the visual system is less sensitive to the larger target than to the small one; less than 2 percent modulation is needed to see deLange's target while more than 6 percent is needed for Kelly's. (3) Peak sensitivity occurs at a higher temporal frequency for the large than for the small target. (4) At frequencies greater than 10 or 20 Hz, target size is not as important, though critical flicker frequency is higher for the larger targets (this reflects the Granit-Harper law, to be discussed later).

The display designer probably does not come across many problems involving the <u>sinusoidal</u> modulation of light; most real-world problems are of square or rectangular modulation ("on" or "off"). However, the reason Kelly, deLange, and others are so interested in sensitivity to sinusoidal modulation is that one can predict threshold sensitivity for almost any temporal waveform shape from the sinusoidal data. The design engineer considers the eye in the same way an electronics engineer considers an electronic audio amplifier. Knowing the "frequency response" of the amplifier allows the engineer to calculate the response of the amplifier to a complex sound such as speech or music. This is the main application of the mathematics of the Fourier analysis. (A simple treatment of this can be found in Bracewell, 1965).

Since this Fourier approach permits generalizations from one set of conditions to another, an example of its application is considered in this section. Consider the response of an observer to a train of square or rectangular flashes, with flash duration not necessarily equal to the inter-flash interval. According to the Fourier theory, we can consider the flash-train's waveform as equivalent to the sum of many sinusoidal waveforms of different frequency, modulation, and phase. One of these, the first component is the same frequency as the flash-train and has a greater modulation than the other sinusoidal components of the flash-train's Fourier representation. Moreover, the component most deeply modulated, determines threshold. The equation for this modulation (m_s) is:

$$m_s = \frac{\partial}{\pi R} \cdot \sin(\pi R) \cdot m_f \qquad (4)$$

Where R is the pulse-to-cycle fraction, the on-time of the flash divided by the sum of on-time and off-time, and m_f is the modulation of the flash-train. The flickering light can now be treated as a sine wave of modulation m_s and its expected threshold read from Figure 23, using the average luminance of the flash-train as mean luminance. For an example of these types of calculations see Kelly (1961a, 1961b). This will only be approximate since the designer will probably not have a light of exactly 2 or 65 degrees diameter and may not use units of retinal illuminance (see Appendix A).

These linear models of flicker perception also can account for a phenomenon which is counter-intuitive. A light may be flickering at a frequency far above CFF, yet if the frequency suddenly changes, the transition may be seen (Sen, 1964; Forsyth & Brown, 1961). Bird and Mowbray (1973) examined this phenomenon parametrically using a two degree diameter target at a mean luminance of 398 cd/m^2, with the light modulated at 88%. Their data are summarized in Figure 24; the dashed lines are predictions based on their linear model. If the period of the first flash-train is 2 msec (500 Hz), then looking at the right most line, the period of the second flash-train that will produce a visible transient 100% of the time is 6 msec (167 Hz).

Levinson (1968) found that transients could also be produced by a sudden change in the modulation of a light flickering above CFF. Under conditions which produce a CFF of 50 Hz, his observers could see a 20% change in modulation at a frequency of 100 Hz. This phenomenon is also accounted for by linear models. The important point, however, is that the design engineer should not assume that a display will be flicker free just because it is operating at frequencies far above CFF; frequency or amplitude modulation may produce visible "side-band" frequencies. Additionally, vehicular motion may potentiate these effects.

Kelly (1974) used an adaptation procedure to isolate the spatio-temporal sensitivities of chromatic mechanisms which may well correspond to the early processing stages of the color system. Because the spectral sensitivies of the three chromatic mechanisms overlap so much, it is unlikely that many non-laboratory displays would actually mimic the effects which Kelly observed. Still, the differences in spatio-temporal responses of the three isolated mechanisms (shown in Figures 25 and 26) can be used to advantage in display design. In particular, the limited temporal and spatial resolving capacity of the blue-sensitive mechanism should be taken into account if one seeks a display capable of evoking high resolution responses in either domain.

Other variables that affect an observer's sensitivity to flicker will be considered in detail. Since contrast sensitivity functions analagous to those which deLange and Kelly collected for foveal vision are lacking, the authors have to rely on a flawed indicator of flicker sensitivity, the CFF frequency. The higher the CFF, the more sensitive the observer is to high frequency flicker under the specified conditions. Unfortunately, this simple assertion is based on some tenuous assumptions. If one seeks to know the highest frequency at which flicker can be seen under some particular set of conditions, CFF is quite appropriate. But there is a less-than-perfect correlation between the peak of temporal modulation sensitivity function and the cut-off frequency (CFF) for that function. This imperfect correlation means that one can not use CFF measured under some conditions to predict the temporal frequency which, under those same conditions, would yield the most pronounced sensation of flicker (i.e. the peak frequency

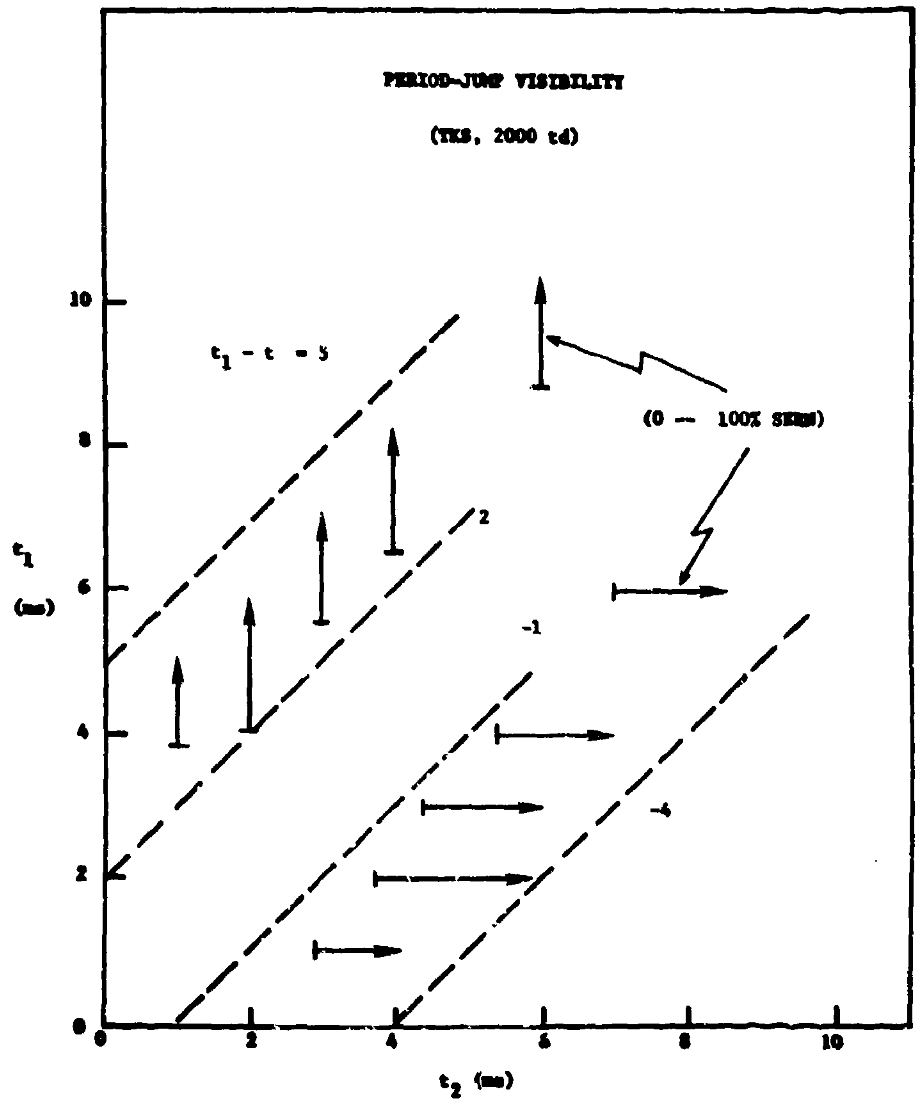

Figure 24. Partial visibility ranges representing frequency of seeing measurements for period-jumps t_1-t_2. Theoretical lines of constant sensation (sub- and supraliminal). (From Bird & Mowbray, 1973).

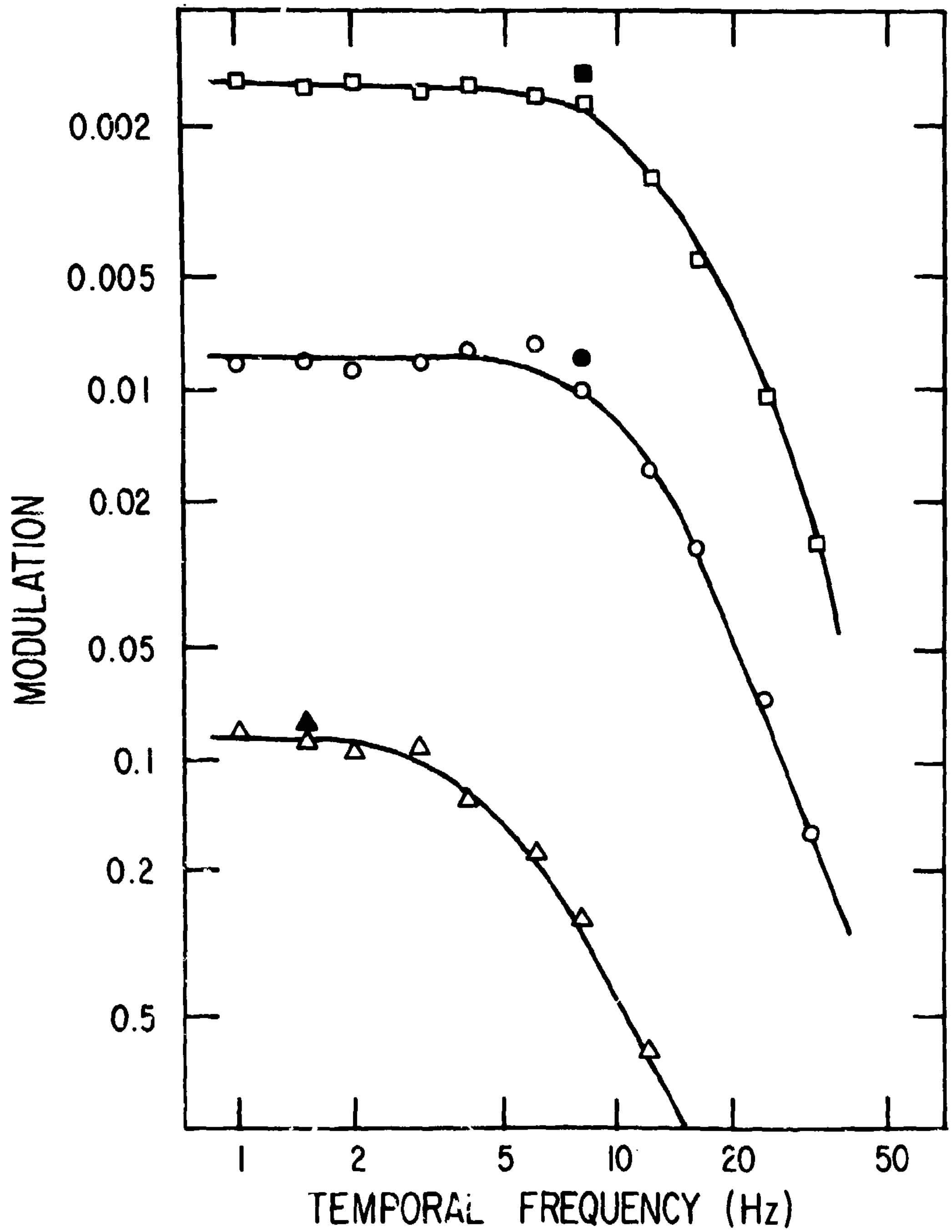

Figure 25. Flicker sensitivities of color mechanisms with optimum grating patterns: 3 c/deg for green (squares) and red (circles); 1 c/deg for the blue (triangles). Retinal luminance equals 10 td. Filled symbols show comparable data points transferred from Figure 26. (From Kelly, 1974).

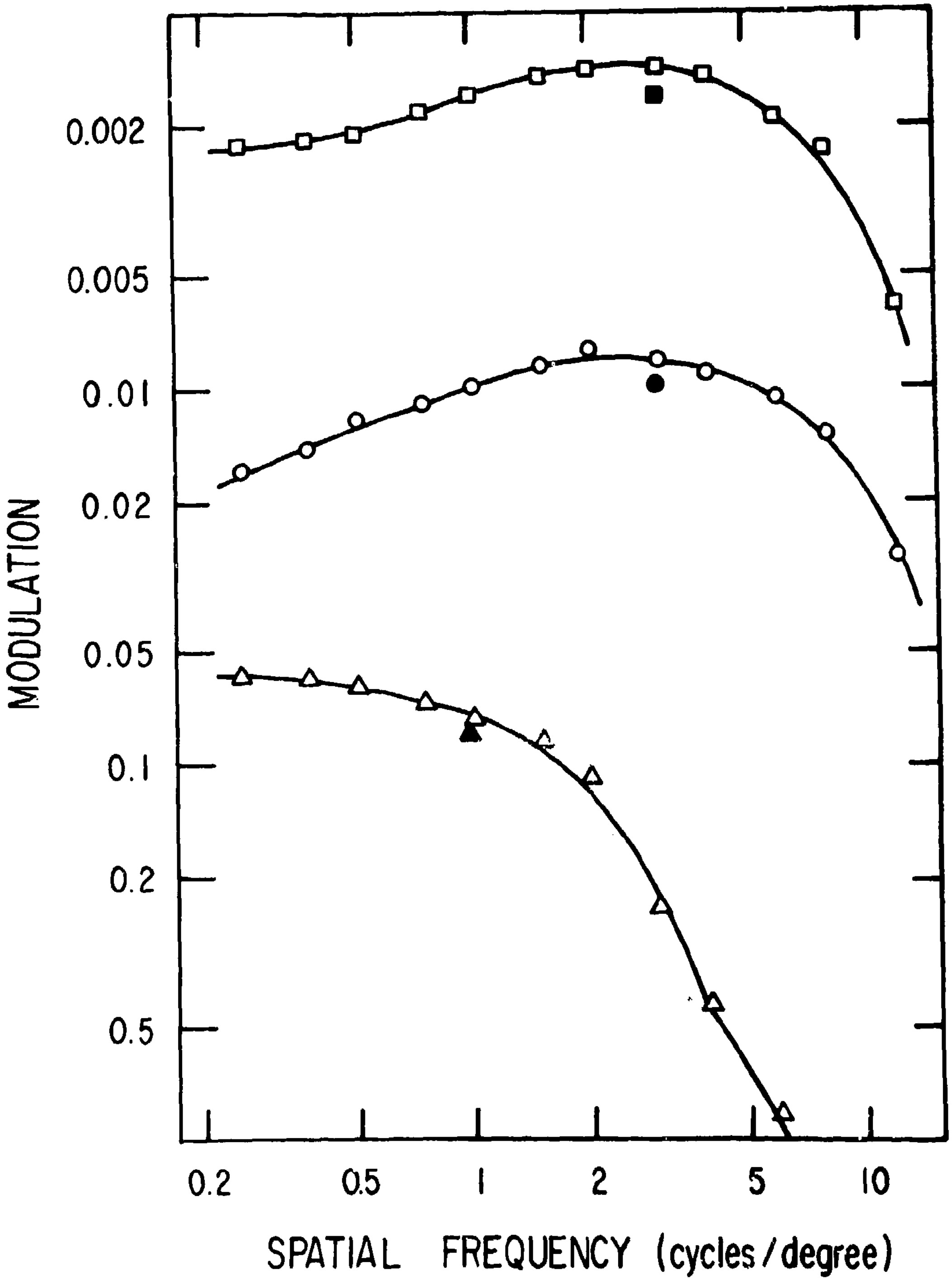

Figure 26. Contrast sensitivities of color mechanisms with optimal flicker frequencies: 8 Hz for the green (squares) and red (circles); 1.5 Hz for the blue (triangles). Filled symbols show comparable data points transferred from Figure 25. (From Kelly, 1974).

of the temporal modulation function). Nor, could one use the CFF to estimate any other desired point on the temporal modulation function. For example, the fact that different sets of conditions yield quite different CFFs, does not guarantee that if one presented the two conditions, each modulated at one half its own CFF, the two rates of flicker would appear to be discriminately different.

Despite its weaknesses, CFF is often the only available datum we have on some parameter's effect on temporal responses. For example, consider the effect of the size of a flickering object in central vision. In general, CFF increases linearly with an increase in the log of an object's area (the so-called Granit-Harper Law). Traditionally, area has been expressed as mm^2 on the retina, but one can convert this measure to diameter in degrees (assuming a circular target) as follows:

$$\text{diameter} = \text{arc tan } (.0676\ A), \text{ where } A = mm^2 \text{ on retina.} \qquad (5)$$

Kugelmass and Landis (1955) summarized the data of six experiments that tested the validity of this law and found that it held well for a range of stimulus diameters of from 1' to 5° of visual angle, corresponding to a range of CFFs of 15 to 45 Hz. Roehrig (1959a, 1959b), however, found that the law held well for diameters up to 30°. He also tried to find the limit on CFFs by using the largest target (49.6°) and highest luminance (1875 cd/m^2) that his apparatus could produce. Under these conditions he recorded CFFs ranging from 80 to 107 Hz for five observers.

However, it can be seen from Kelly's data that CFF is influenced by mean luminance; the Ferry-Porter law states that CFF increases linearly with log luminance. In order to predict flicker fusion frequency, one needs to take both laws into consideration simultaneously. Kugelmass and Landis (1955) found that there is an interaction between area and luminance; the slope of the Ferry-Porter equations change with changes in area of the target. However, Foley (1961) obtained a good fit to his data using an additive rather than an interactive model. We have followed suit and used an additive model based on Roehrig's data which covers an even greater range of target areas than does Foley's. Thus a rough prediction of CFF can be made using the equation:

$$CFF = 27.66 + 6.25\ (\log A) + 14.7\ (\log L)$$

where L is luminance in cd/m^2 and A is area in mm^2 on the retina.

It would be interesting to verify this relationship between area and luminance at different retinal locations. However, to the authors' knowledge, no one has tackled so large a task. But there is some partial evidence on the effect of retinal location. Ettinger (1959) found that when targets are larger than 1.5°, the periphery of the visual field (15° to 35°) tends to become more sensitive relative to the fovea. Brooke (1951) measured CFFs at several retinal locations and at several levels of luminance for a 2° spot. He found that at high (3000 cd/m^2) luminances, log CFF fell nearly linearly from 50 to 20 Hz as the spot was moved horizontally from zero to 40° from the retina. At .3 cd/m^2 however, CFF was constant across the retina. At a lower luminance, .03 cd/m^2, at all locations 10° or more from the fovea, he measured higher CFFs than the foveal location, approximately 13 Hz vs. 7 Hz. Hecht and Verrip (1933), as reported by Pirenne (1962) found very similar data, also for a 2° target. For example, with a luminance approximately equal to 0.4 cd/m^2 (actually reported as one Troland retinal illuminance) they found CFF equal across the retina. Brooke (1951) reported the same outcome for virtually the same luminance, 0.3 cd/m^2. Hylkema (1942) has shown that the difference between foveal and peripheral CFF diminishes with advancing age. This factor may be of more importance for display design in the private sector than in the military however.

Welde and Cream (1972) have shown that the sensitivity of the peripheral retina to flicker must be taken into consideration in any applied setting. They were interested in the perception of flicker in television screens and asked observers to report on the flicker of a television screen seen in the periphery. The screens always flickered at the standard 60 Hz interlaced rate, subtended about 30° of the visual field and had mean luminances ranging from 10.3 to 30.8 cd/m^2. Flicker was most easily seen with fixations 30° to 60° of angle from the television set. Note that the periphery of the retina is more sensitive to flicker than the fovea in this study even though luminance is about a log unit higher than in the previous studies. This difference is probably due to the greater retinal size of the television targets.

The spatial composition of the flickering display is another important parameter. Using a modulation sensitivity measure, Kelly (1959) found that the observer's sensitivity to low rates of flicker can be increased by the presence of sharp contours in the visual field. For example, blurring the edges of a 3° spot maximum reduced sensitivity to the spot to low frequency flicker by one half; the same manipulation did not affect high frequency response, including CFF. Using a 16° x 8° flickering, bar-pattern, Kelly (1972) found that low frequency sensitivity was most enhanced when the spatial frequency of the grating was two cycles per degree of visual angle. Similarly, Waygood (1969) found that the detection of very slow continuous changes in luminance (6 to 4% per second) was enhanced by the presence of contours.

Returning to Welde and Creams' 1972 work on television flicker, one should note that they found no effect of variations in the spatial parameters of the images (image complexity). This agrees with Kelly's general findings of little effect of spatial parameters on the CFF.

Likewise, color seems to have little effect on CFF over a range of luminances. Giorgi (1963) reviewed the literature on the effect of color on CFFs and found contradictory evidence -- some researchers found an effect, but many did not. In a very carefully controlled experiment, Giorgi did find an effect of color but it was very weak, and probably had not risen above experimental variance in many other experiments. However, Hecht and Shlaer (1936) found that while there seemed to be no effect of color over most of the useful luminance range, as the luminance values begin to encroach on the scoptic range (less than 3 cd/m^2) color does begin to have an effect. So, at about .03 cd/m^2, a green object produces a 10 Hz greater CFF than a red one.

Finally, brief mention should be made concerning the effect of observer variables on CFF, as this has been an area of great interest both to clinical and human factors researchers. Many observer variables have been studied, such as age, intelligence, fatigue, stress, emotional state, etc. (see Ginsburg's bibliography, 1970). However, age produces probably the most dramatic effect on CFF. Landis and Hamwill (1956) reviewed the literature on the correlation between age and CFF and found values ranging from $r = 0$ to $r = -.74$. Misiak's (1951) work is often cited because of his large number of observers (320) and substantial age range (7 to 89 years). Although he found a significant correlation (-.55) between age and CFF, Misiak's range of mean CFFs (for each age group) was only 43 to 36 Hz, and he says "that there were CFFs at age 82 as high as at age 7, and there were CFFs at age 7 as low as at age 80." This is to be expected from Kelly's (1961a, 1961b) data which show that ± 1 S.D. spanned a range of 8 Hz, yet the effect of age in Misiak's study was only 7 Hz. Very probably if frequency is employed for coding purposes in visual displays this CFF test should be part of medical screening in the same way that other visual acuity tests are conducted.

Weale (1963) reviewed the work on CFF in senescent observers and proposed that some 70% of the age-related decline in CFF was due to simple optical factors. It is well established that with advancing age the crystalline lens "yellows" and loses some of its exquisite transparency; it is also well established that pupil diameter decreases with age (senile miosis). Combined, these factors would produce a substantial decrease in retinal illumination, a decline which the Ferry-Porter Law (see above) would translate into a drop in CFF.

CHAPTER 10

Suprathreshold Flicker Perception

The previous chapter reviewed the literature on the "thresholds" for the detection of temporal events: the threshold luminance increment needed to see a flash, the modulation of background luminance necessary to see a flickering light, and in the case of CFF, the frequency of a flickering light at which one can barely see flicker. This section will review research on the perception of temporal events which are suprathreshold. Given that some flash or flicker train is clearly visible, what does it look like and how does the observer respond to it. Among other things this section shall examine the perceived duration of a flash, the perceived rate of flickering lights, how well one can discriminate among flicker frequencies, and how rapidly one can react to temporal events.

Fundamental to all these concerns is the correspondence between the perceived duration of a flash of light and its actual duration. The imprecision of this correspondence is well established and, in particular, the shorter the duration of some flash, the less well does its perceived duration correspond to the actual duration. Thus no matter how short a time the light is on, it will appear to be on for some irreducible minimal amount of time. Efron (1967) relates an 1887 paper by Charpentier that demonstrated this clearly. Charpentier asked observers to discriminate between a 6 msec flash and another flash whose duration varied from trial to trial. Observers could not tell the difference between the lights unless the variable one was at least 66 msec in duration or longer. From this and other data Efron reasons that short lights always appear to be about 50 to 70 msec in duration.

In related work, Haber and Standing (1970) measured the perceived duration of flashes by asking observers to adjust the onset of a click sound to appear simultaneous with light onset. They also had them match the click to the perceived off-set of the flash. The difference in time between these two clicks is an indirect measure of the perceived duration of the flash. The stimulus was a matrix of black letters on a white (16 cd/m^2) background about 5° square. The flash could be preceded by an adapting field of the same luminance, and could be followed by the same field. The results are shown in Figure 27 for the conditions determined by the presence or absence of the adaptation field (from Haber & Hershenson, 1973). If perceived duration always equalled the actual duration, the points would fall on the straight diagonal lines. But perceived duration was usually longer, a fact which Haber and Standing attributed to perception persistence after flash off-set. In support of this hypothesis, Haber and Standing were able to eliminate the difference between perceived and physical duration by presenting a dense masking pattern immediately after the off-set of the flash. This operation could be expected to eliminate persistence. As Figure 27 shows, persistence was greatest when the flash occurred in the dark (over 400 msec for a 20 msec flash) and was reduced to 175 msec when the flash occurred in the light.

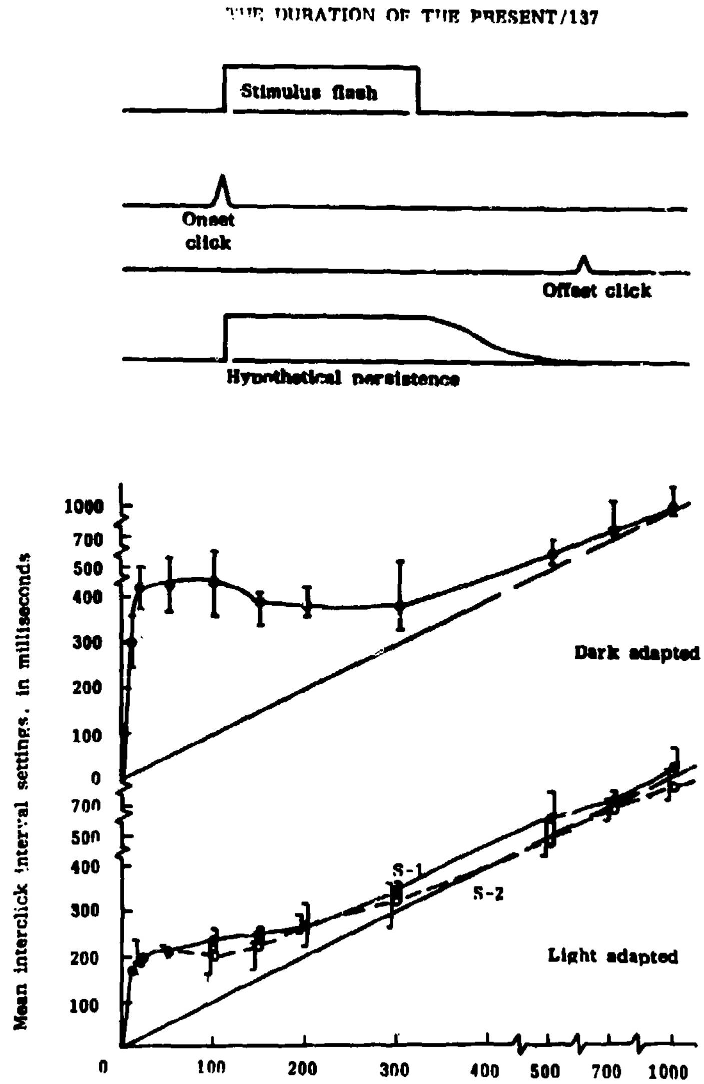

Figure 27. Schematic representation of the presentation sequence of a light pulse with a click heard near its onset or near its offset (top) and the resulting mean interclick interval as a function of exposure duration of the pulse in both a light and dark adapted condition (from Haber & Hershenson, 1973).

In an ingenious experiment, Eriksen and Collins (1967, 1968) examined the behavioral consequences of this post-stimulus persistence of perception. Eriksen and Collins flashed a quasi-random dot pattern for 6 msec and then, after a variable interval, presented a different dot pattern for 6 msec. If the dot patterns have been presented simultaneously, some of the dots would have formed a 3-letter nonsense syllable. The observer's task was to identify the nonsense syllable from the two temporally separated components. As the interval between the flashes was increased from zero to 100 msec, performance decreased steadily; for longer intervals still, performance was nearly constant. It seems then that the observers were able to combine the persistence of the first flash with the presentation of the second one to perceive the combined pattern. The background luminance for one of these studies was the same as for Haber and Standing (16 cd/m^2). Considering the difference in method, the correspondence between the two is quite good.

The work by Eriksen and Collins shows that though observers can discriminate separate temporal events, that is, see flicker, they can still integrate the information from several flashes. Analagously, a television raster display might paint its picture at such a slow rate that flicker would be perceived, yet the observer could still tell what the image was. Indeed, Welde and Cream (1972) found that flickering in a television image did not seem to disturb the observer's perception of the image depicted on the screen. However, precisely this same persistence might make it difficult to discriminate between flashes of light on the basis of duration. This recalls Efron's claim that observers can not discriminate among flashes less than 60-70 ms. Haber and Standing's data indirectly suggest that this may be true of even longer flashes, depending on light adaptation conditions. Note that in the dark adapted condition, Haber and Standing's curve for flashes ranging up to 300 msec is quite flat. This suggests that all these flashes appeared of equal duration, 400 msec. Of course if observers directly compared these flashes they might be able to discriminate between them based on other cues, such as brightness differences. However, the data suggest that flash duration may not be a good way to convey information to an observer, at least for durations less than 500 msec.

For many applications, the display designer may not care how long a flash seems to last, but only how rapidly an observer can respond to the flash. It would be helpful to have general rules relating reaction time to changes in the parameters of a flash. The first rule one might consider is Bloch's Law: below some critical duration there is a trade-off between duration and luminance of a flash so that reaction time is determined by the energy delivered by the flash. Both Raab and Fehrer (1962), and Grossberg (1968) have examined this question and come to the conclusion that unlike threshold visibility, reaction time does <u>not</u> follow Bloch's law. Raab and Fehrer found that if such a trade-off existed, it held only for flashes less than .5 msec and for flash luminances greater than 100 cd/m^2 (against a dark background). Grossberg (1968) used even shorter durations, but found that reaction time was dependent on a combination of energy and luminance. In both cases, as luminance increased it quickly became the single controlling parameter, evidently because an observer reacted not to the entire time interval of the flash, but only to its onset.

Bartlett and MacLeod (1954) were interested in how reaction time depended on background luminance, flash luminance and retinal location. Reaction times were measured using a small spot (20') located either at the fovea or 11° 20' above the fixation mark. The flash was always 575 msec. Figure 28 shows data from two subjects at zero background luminance and two retinal locations as a function of flash luminance. Note that reaction time to dim flashes is faster in the periphery at this low background luminance level. This was true for both dim and dark backgrounds but not for the brighter one. Bartlett and MacLeod fitted a family of curves to their data of the form:

$$\text{Reaction Time} = \frac{1}{B \log (I/I_o)} + k \qquad (7)$$

where B, k, and I_o depend on field luminance. I_o is a unit of "effective" field luminance; it was adjusted for different retinal positions and subjects. The values for these parameters are provided in Table 4, taken from their paper.

We can compare Grossberg's, and Bartlett and MacLeod's data only at zero background luminance as Grossberg did not use any other value. Reaction time to Bartlett and MacLeod's spot remains at approximately 200 msec until flash luminance drops below .5 log cd/m^2; then it increases to about 500 msec at -1.5 log cd/m^2. Grossberg's reaction times (for a 500 msec flash) increased from 280 msec at .5 log cd/m^2 to approximately 500 at -2.3 log cd/m^2. Unfortunately, Grossberg did not use a wide enough range of flash luminances to estimate the luminance value at which his rection time would asymptote.

The effect of shortening flash duration can be seen by comparing Grossberg's data with those of Raab and Fehrer. At a luminance of .57 log cd/m^2 (the only flash luminance value that overlaps the range used by Grossberg), Raab and Fehrer's range of durations was 20 to 2 msec and reaction time decreased monotonically from 280 msec to 220 over this range. For Grossberg's flash luminance value of .46 log cd/m^2, reaction time decreased from 360 to 290 msec over the same range of flash duration. The absolute change in reaction time is about the same. Grossberg's reaction times do not change for durations about 20 msec but one cannot look for the same trend in the data by Raab and Fehrer because they did not use any durations above 20 msec. However, only Raab and Fehrer use high flash luminances. Their curves showing reaction time as a function of flash duration are asymptotic for flash luminances greater than 2 log cd/m^2.

Haines (1975) presents data for reaction time to a small (45') dim (2.29 x 10^{-3} cd/m^2), white spot, flashed for 50 msec. He tested 72 locations in the visual field and plotted his data in terms of iso-response curves (Figure 29). These data suggest that the observer may respond faster to a peripherally viewed spot than one at the center of the visual field, but do not suggest as great a difference in reaction

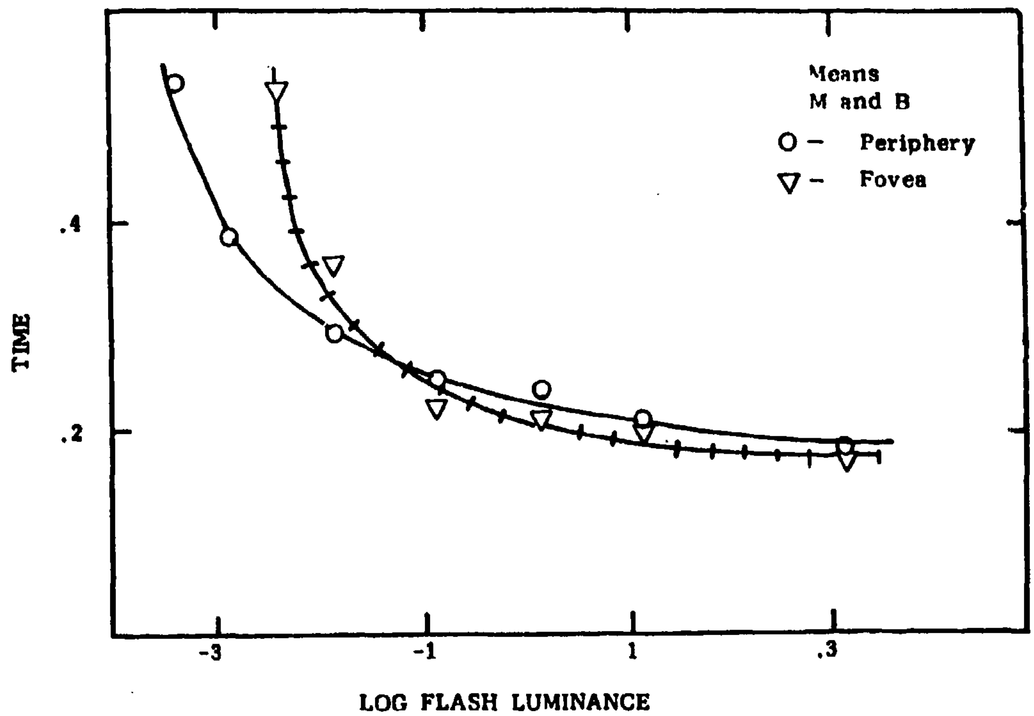

Figure 28. Reaction time and log flash luminance for the dark-adapted eye. Each curve is based on means of both subjects; one curve representing peripheral and the other curve foveal data. (From Bartlett & MacLeod, 1954).

TABLE 4

Constants employed in fitting hyperbolic functions
to latency-flash functions of subjects B and M
for peripheral (P) and foveal (F) stimulation
The constants are defined in the text.

	Subject B						Subject M					
Field		P						P			F	
luminance (log mL)	B	$\log I_o$	K	B	$\log I_o$	K	B	$\log I_o$	K	B	$\log I_o$	K
$-\infty$	0.002	-4.7	140	-.005	-2.9	157	0.002	-4.4	105	0.007	-2.7	119
-0.4	0.008	-1.4	190	0.008	-2.0	179	-.007	-1.3	145	0.009	-1.8	145
+1.6	0.021	+0.6	200	0.028	0.0	194	0.014	+0.7	160	0.028	0.2	155

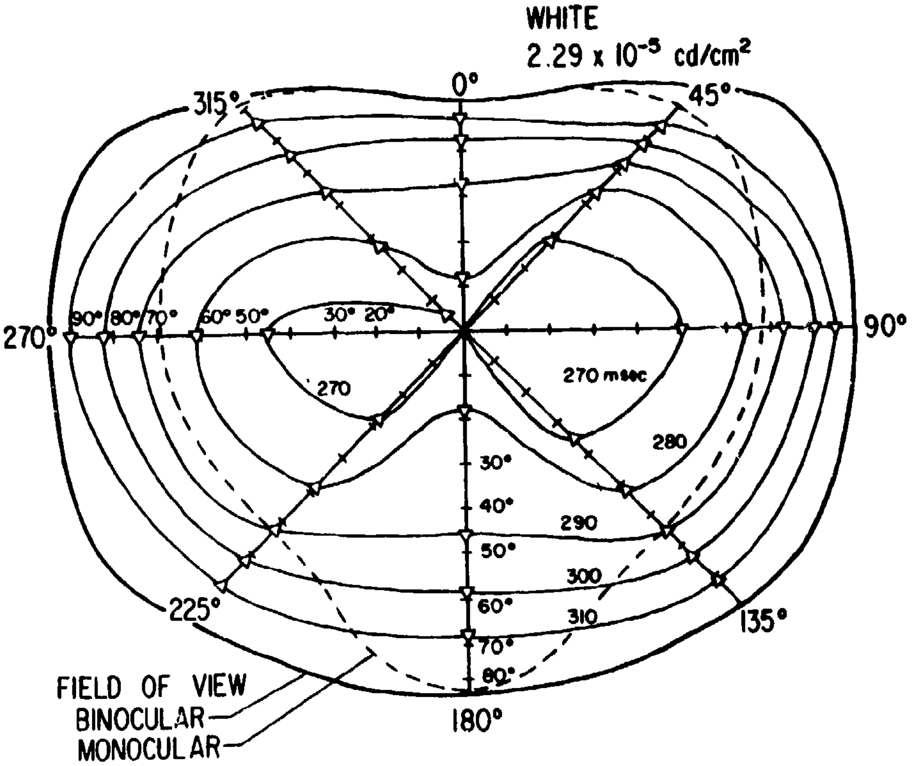

Figure 29. Iso-response time zones for the binocular visual field and white stimuli. (From Haines, 1975).

times as do the data of Bartlett and MacLeod. It shows however that observers respond to flashes in the horizontal meridian faster than to flashes positioned along the vertical. A similar asymmetry between horizontal and vertical meridia is found for flash sensitivity, motion sensitivity and motion difference sensitivity (see related chapters of this report). This knowledge can be easily employed in to improve detectability of information coded in visual displays.

Tolhurst (1975) suggests that the spatial characteristics of an object may be important for reaction time, especially when the visibility of the object is marginal. He measured the reaction time to flashed gratings presented about the fovea. The contrast of the patterns was very near threshold. When the spatial frequency of the pattern was low (0.2 bars/deg; bars of 2.5 deg width) the observer reacted to the transients in the flash, i.e., either to the sudden on-set or off-set. When the spatial frequency was higher (3.5 bars/deg; bars of 8.5' of arc width), reactions occured at anytime during the duration of the pattern. This was also true of the low frequency patterns if the on-set and off-set of the flash was gradual. This implies that for low spatial frequencies, the visual system is sensitive to temporal transients, but for high spatial frequency patterns, it integrates contrast over time. This suggests that for experiments using square or circular targets, the size of the target could affect reaction times.

Short flashes may seem much longer than they really are, because the perceived flicker rate of a flashing light may be less than its actual rate and the persistence of one flash would interfere with the perception of the next. Therefore, there seems to be a maximum number of flashes per second that we can perceive regardless of the frequency of the target or its CFF. This limit is estimated to be surprisingly low: about 6 to 8 Hz (Cheatham & White, 1952; Forsyth & Chapanis, 1958; White & Eason, 1966).

Bartley (1938) noted that just below CFF the perceived rate of a flickering light always seemed to be the same. Since a dim light has a lower CFF than a bright one, the dim light's actual flicker frequency would be less than that of the bright one; yet the two would seem to be equal. This means that close to CFF the perceived rate of a light increases with a reduction in luminance. LeGrand (1937, as reported by LeGrand 1968) found that a 7° flickering light appeared to flicker at a reduced rate as it was viewed with eccentricities increasing from 15°. In this case, the background was dark so the luminance may have been more effective at the more peripheral location, which would bring this observation into line with Bartley's law concerning brightness enhancement.

However, these findings do not agree with measures of perceived numerosity. In this case, an observer had to count or guess the number of flashes presented in a short train of flashes. One would think that these results would be in accord, qualitatively, with changes in the perceived rate of a continuously flickering light, but they are not. White & Eason (1966) measured perceived numerosity as a function of a number of flashes of light (presented at a frequency of 25 Hz) for three light adaptation levels (34.26, 342.6, and 3426 cd/m^2) and at retinal eccentricities up to 70°. They found that in the first 300 msec of the flash-train (6 flashes), the number of flashes seen was affected by adaptation and retinal location (lower background and greater eccentricity meant fewer flashes were seen). For the rest of the flash-train, flashes were seen at a rate of 6 to 7 Hz. White and Eason report that observers did notice a dramatic change in perceived rate as retinal location was varied, yet this did not affect numerosity judgments. They offered no explanation for this paradox.

Forsyth and Chapanis (1958) performed a similar experiment except that they varied frequency and location. Their target was a circle .5° diameter and had an incremental luminance of 5663 cd/m^2 against a 70 cd/m^2 background. They also found that the limit of perceived rate is 6 to 8 Hz, but their curves show perceived number of flashes as a function of actual number to be linear (Figure 30). They feel that this is due to averaging across many observers (n=36). Table 5 provides the slopes of these lines for every condition of location and frequency, and completely describes their data. For a flash-train of 20 flashes, an increase in retinal location amounts to a maximum loss of 3 to 4 flashes.

The difference in the reported experiences of perceived rate versus perveived numerosity suggests that care must be taken in transferring this information into design criteria. It is felt that the display designer should consider carefully the exact nature of the information that an operator will need to extract from a flashing indicator before applying the data from either of these approaches.

Previous research shows that no matter how high the actual flicker frequency of the light may be, the maximum rate of flicker that an observer can perceive is 6 to 8 Hz. Yet observers are quite sensitive to small differences in frequency, according to a series of studies done by Mowbray and Gebhard. Depending on the particular conditions used, they found from 280 (Mowbray & Gebhard, 1955) to 375 (Gebhard, Mowbray, & Byham, 1955) just noticeable differences over a range from 1 to 45 Hz. The latter report that this just noticeable change (Δ F) never exceeds 6 Hz (this at 22.5 Hz). Mowbray and Gebhard (1960) examined the fovea and peripheral locations up to 30°. As soon as the .5° diameter spot was positioned outside of the fovea (in this case 5°+ of eccentricity), Δ F no longer peaked at 22.5 Hz, but decreased monotonically from about 2.5 Hz to 2 Hz over a range of frequencies from 5 to 35 Hz. Differences between the Δ F from experiment to experiment, may be due to differences in luminance and spot size. The high discriminative ability, 375 just-noticeable-steps, found by Gebhard, Mowbray and Byham, (1955) was probably due to their experimental method: two frequencies were presented successively with no interval between, thus the observers would have seen transients as the frequencies were switched (see Flicker Sensitivity). However, this does not account for the high difference sensitivity found by Mowbray and Gebhard (1960). Since this latter study allowed a one second interval between presentation of the to-be-compared frequencies.

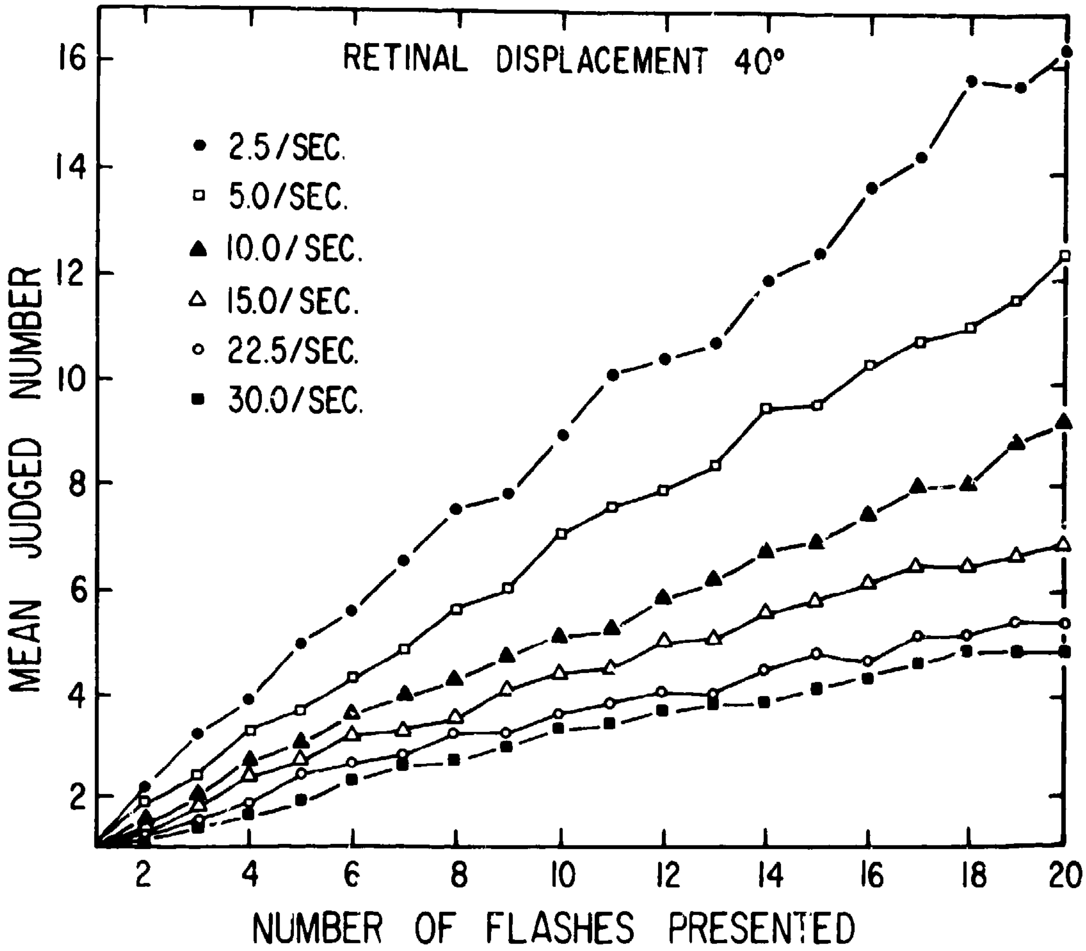

Figure 30. Mean judged number as a function number of flashes presented at a retinal placement 40° temporally from the fovea. (From Forsyth & Chapanis, 1958).

TABLE 5

Slopes of the Regression Lines Relating

Mean Judged Number to Presented Number

Retinal Displacement	2.5	5	10	15	22.5	30
0°	.947	.648	.507	.397	.306	.266
2.5°	.911	.641	.478	.376	.282	.250
5°	.902	.632	.470	.363	.272	.242
10°	.878	.625	.443	.358	.267	.245
20°	.846	.605	.432	.335	.258	.239
40°	.795	.584	.412	.311	.231	.210

With suprathreshold responses to flashes, the design engineer will be interested in reaction time measures. Unfortunately, we have only been able to find one researcher who examined the difference between reaction time to the onset of a steady light and a flickering one. Gerathewohl (1953, 1954) found that reaction to a small spot in a 6.4 to 9 cd/m^2 field was faster when the light flickered than when it was steady, but only when contrast was low (.19, as opposed to 1.0 and 74.2, see Appendix A). Interpretation of these data is complicated by the fact that the subject was engaged in a complex psychomotor task and in addition was uncertain as to the location of the target light.

CHAPTER 11

Brightness Enhancement

Generally, the brightness of a single flash is greatest when its duration is between 50 and 100 msec. This phenomenon is termed the Broca-Sulzer effect. For a flickering light, brightness is greatest when flicker frequency is between 3 and 15 Hz. This brightness is greater than when the light flickers at a frequency above fusion (its average or Talbot brightness). The enhanced brightness of a light flickering at below-fusion frequency is known as the Brücke-Bartley effect.

All the data to be reported in this section were collected in one of two ways: either the observer rated the brightness of the light (magnitude estimation), or he matched the brightness of a flashed or flickering light to a standard light whose parameters were constant. In the second case, the duration, size, etc., of the standard light is arbitrary and varies from experiment to experiment. Thus, either technique presents relative and dimensionless values that can show some manipulation has increased or decreased brightness by some proportion relative to another condition.

Some authors have already considered a few facts relating to the increase in a flash's brightness as a power function of its luminance (Anglin & Mansfield, 1968; Mansfield, 1973). In addition, below some critical duration, one can trade duration for luminance to maintain a given brightness (Bloch's constant energy law). The relationship takes the form:

$$\text{Brightness} = k \cdot D^p \qquad (8)$$

where E is energy, and k is a scaling factor that varies with changes in conditions. The value of p normally is 0.5, but for a point source, p grows to 0.94. Although brightness changes with target location (fovea and 20° temporal), size (.05 to 4°) and wavelength, the proportional increase in brightness with energy remains unchanged for durations below 100 msec. That is the duration at which the Broca-Sulzer effect occurs. This agrees at least qualitatively with Raab (1962) and Osaka (1977).

For a flash of duration longer than that which is optimal for Broca-Sulzer effect, (see Figure 31), the relationship takes the form:

$$\text{Brightness} = k \cdot L^p \qquad (9)$$

Where L is luminance. The exponent p, in this case, is slightly in excess of 0.3. Again this exponent is also invariant with location, size, and wavelength. Under these conditions, the exponent for point sources declines to 0.5. Varying the size, wave-length, and retinal location of flashes has little effect on the exponent in the brightness-luminance relationship (Mansfield, 1973).

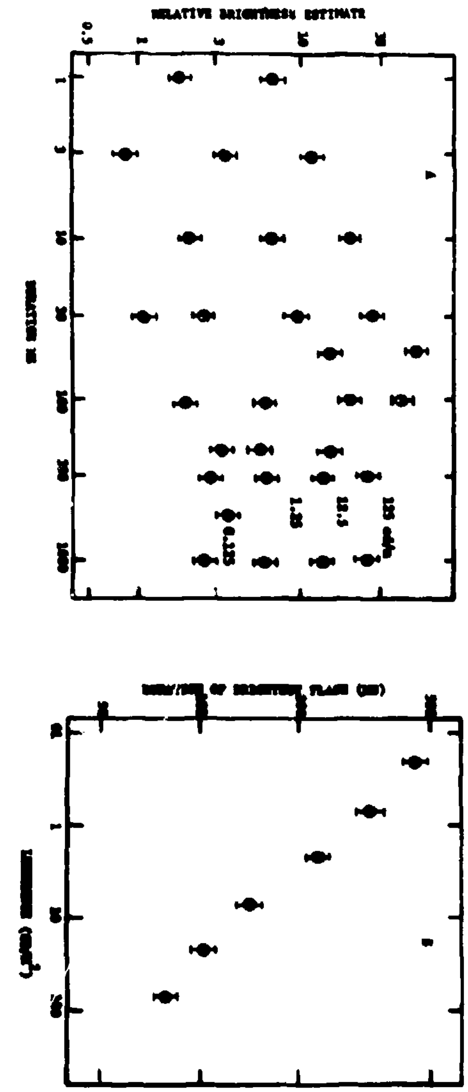

Figure 31. Brightness relations for a foveal target. (A) Brightness estimation. Brightness as a function of flash duration at different luminance levels for a 0.72° foveal target of white light. Each point represents the average of at least 10 observers' estimates. Standard errors are indicated by the vertical bars. The solid lines drawn through the points represent equal-luminance contours and the parameter indicates the luminance (cd/m^2). (B) Brightness maximization. Duration of the brightest flash as a function of luminance for a 0.72° foveal target of white light. Each point represents the average of 17 observers' settings with standard errors indicated by the vertical bars. The line was fitted by least squares (from Mansfield, 1973).

Regarding the Broca-Sulzer effect itself, Mansfield also found that the duration producing the greatest enhancement changed with flash luminance (L), and in this case fit the equation:

$$\text{optimal duration} = k \cdot L^{q} \qquad (10)$$

Again, for an extended source q varied between -.30 and -.32, but for a point source equaled about 0.48. Figure 31 provides data for one set of conditions, a white foveal target of 0.72° subtense. In this case k = 278 and L = -.34. Of course, the data could also be described by the equivalent formula:

$$\text{optimal duration} = -195.1 (\log L) + 353.6 \qquad (11)$$

which is the form used throughout most of this report.

One can see from Mansfield's data (Figure 31) that the optimal duration may be fairly long for a very dim flash on a dark background. White, Collins and Rinalducci (1976) report a similar effect for a dim light in the periphery (a 1° target at 7° eccentricity). Optimal duration ranged from 200 msec for one observer to 400 for the other.

The previous experiments which we have reported were all performed against zero background luminance. With the few dim backgrounds used in those studies the Broca-Sulzer effect did not become evident until test flash luminance was appreciably greater than the background luminances. White et al., suggest that if background luminance is greater than zero, the target must be 1 to 1.5 log units above its own contrast threshold for the Broca-Sulzer effect to exist.

Osaka (1977) provides some evidence that these enhancement effects are stronger in the periphery than in central vision. Under his experimental conditions (zero background luminance), he did not observe the effect in the fovea, but did in the periphery. The luminances used in this study, .86 to 8.6 cd/m^2 may have been too low to see the effect at the fovea. Osaka also observed that at a flash luminance of 2.7 cd/m^2, a peripheral flash looked brighter and "crisper" than a foveal one. In addition, Osaka found that brightness increased by .1 log unit (about 26%) as target size was increased from 16 to 116 min of arc in diameter.

This agrees with Marks' findings (1968, 1971) for flashes of fixed duration. When background luminance was zero (Marks, 1971), a flash seemed brighter in the periphery than in the fovea. When photopic background luminance levels were used (Marks, 1968) brightness decreased steadily with increased eccentricity. The effect varied from condition to condition, but, on the average, perceived brightness decreased .2 or .3 log units as eccentricity increased from 0° to 60°. Thus peripheral placement of instruments would be of some advantage under low luminances and foveal would be better for bright backgrounds.

The Broca-Sulzer effect seems heavily dependent on the spatial parameters of the stimulus. Arend (1973) found that he could eliminate enhancement completely by blurring his 1.5° target with +3 diopters of defocusing. (This eliminates much of the high spatial frequency content from the display). Similarly, Kitterle and Corwin (1979) found that enhancement of the apparent contrast of a flashed grating pattern was greatest at the highest spatial frequencies he used. Unfortunately, his range of spatial frequencies (.25 to .73 cycles/deg) does not provide information on what the optimal spatial frequency may be, or what the least effective one may be.

Under the proper conditions, a flickering light may appear brighter than a steady light of the same average luminance. As mentioned earlier, this is generally called the Brücke-Bartley effect. According to the review of the effect by van de Grind, Grüsser, and Lunkenheimer (1973), it occurs at temporal frequencies ranging from 3 to 15 Hz. The effect is most pronounced in the mid-photopic range. In fact, Bartley (1951) found that for luminances below 377 cd/m^2, brightness was actually less than that of a steady light of the same average luminance. Ball and Bartley (1966) found that the optimal luminance range for their configuration was 323 to 2150 cd/m^2. The optimal frequency for producing the effect however, changes with mean luminance. Figure 32 shows data from Rabelo and Grüsser (1961) as reproduced by van de Grind et al. Optimal frequency grows with an increase in mean luminance. This was also found by van der Horst and Muis (1969). Wasserman (1966) found that optimal frequency was highest and enhancement greatest at a mean luminance of 109 cd/m^2.

All these studies have used on-off stimuli (100% modulation) usually produced by interrupting the projecting light beam with a shutter or rotating sectored disk. Glad and Magnussen (1972) used less than complete modulation (80%) and measured the enhancement of the dark cycle of a flickering light. They found that darkness is enhanced in a manner similar to brightness enhancement. Modulating a 323 cd/m^2, 1° diameter spot of light, they found that it appeared to be half as bright during the dark cycle as a steady light of the same luminance. This effect peaked at 3 Hz. Magnussen and Glad (1975a) found that for identical display conditions, brightness and darkness enhancement occurred at the same frequency.

Since both brightness and darkness enhancement occur together, it may be more sensible to think of the pair as enhancement of perceived modulation (or temporal contrast). Marks (1970) asked observers to estimate the temporal modulation of a flickering 2.1° target. He found a modulation enhancement effect that peaked in the 5 to 10 Hz range for conditions of high mean luminance and low modulation. His optimal frequencies are probably higher than Magnussen and Glad's because of his larger target size. Optimal frequency was much lower for other conditions, but due to the restricted range of frequencies he used, this cannot be specified.

There are important interactions between spatial and temporal parameters in the Brücke-Bartley effect. The well-known effect called induced brightness or contrast enhancement (the brightness of a spot is enhanced if surrounded by a darker area and vice versa) is itself enhanced by flickering. Magnussen and Glad (1975b) flickered the surround of a steady, small (1°) patch and measured the "induced" bright-

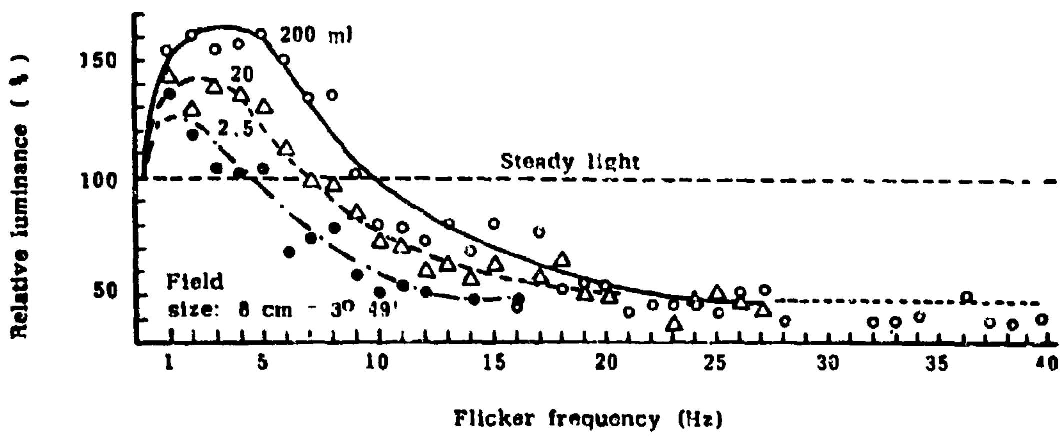

Figure 32. Brücke-Bartley effect obtained with rectangular flicker stimuli (L-D-ratio 1:1). Mesopic level of adaptation. The subjective brightness (relative luminance of the steady light, which matches the brightness of the flicker stimulus) is plotted on the ordinate, the frequency of the flicker stimuli on the abscissa. Stimulus diameter 3°39'. Three different levels of mean luminance (from Rabelo & Grüsser, 1961, reproduced by van de Grind, Grüsser, & Lunkenheimer, 1973).

ness changes. The flickering surround induced modulation in the center of the opposite phase; when the surround was brightest, the center was darkest, and vice versa. The effect was about four times greater than "static" induced contrast. Maximal contrast occurred at frequencies ranging from 2 to 4 Hz depending on display luminance. This effect is probably related to Kitterle and Corwin's spatial contrast enhancement found for flashes.

Similarly, Remole (1973a, 1973b) found that the area of enhanced contrast at the border between large light and dark areas (Mach Bands) can be extended by flickering the display. The brightness enhancement of the light area covered 10 min of arc during steady illumination. When the light area flickered from 10 to 18 Hz, this area covered anywhere from 50 to 150 min of arc.

CHAPTER 12

Effects of Flash and Flicker on Visibility

So far, in this report the data on the detection of flashes and flickering lights and the effects of temporal variation on the suprathreshold brightness of targets have been reviewed. This chapter concerns the effects of flashes and flicker on spatial discrimination. Much of this work is concerned with acuity measures and asks, "How do flash and flicker affect an observer's ability to see thin lines, or small gaps between objects, when the display is of high contrast (for example, a reading task)?" Depending on the target size, contrast and conditions of visibility, flickering or flashing a target may make it either harder to see, easier to see, or produce no change at all.

First, the effect of presenting an acuity target as a flash (i.e., for a short duration) is considered. As with the detection task, reducing the duration of a target never improves its visibility. However, simple and useful roles describe the debilitation effect of shortening the flash. The most useful of these is similar to Bloch's Law (see chapter entitled Flash Sensitivity), whereby an intensity-time trade-off governs observers' performances on acuity tasks.

Kahneman and his co-workers have studied these phenomenon for several years. Kahneman and Norman (1964) tested the applicability of Bloch's Law for both brightness and acuity performance with a $6° \times 2°$ pattern of squares and dots (mean luminance was 2 cd/m^2). This was similar to the findings of other investigators (see chapter entitled Brightness Enhancement). For the acuity task, however, critical duration was much longer, 200 to 316 ms. These findings have been replicated by Kahneman (1966) and Kahneman, Norman and Kubovy (1967) using Landolt C acuity targets.

Baker (1969) also found that time-intensity reciprocity held for an acuity task, but only under a limited set of conditions. He varied the size of his black and white letter targets (1 or 1.45 min of arc) and also the level of performance demanded from the observers. His targets consisted of five letters, but the observer could be instructed to recognize either just one, two, three, four, or all five of them. He found that reciprocity held only for low levels of performance, and only for a low range of luminances of his targets.

Baker expressed this reciprocity relationship by the equation:

$$\log It^k = C \qquad (12)$$

when $k = -1$, reciprocity holds; when k is between -1 and zero, the duration (t) needed to perform the acuity task decreases too slowly to keep energy constant as the luminance (I) is increased. As the task was made more difficult, k increased to -.6 for both letters and Landolt C stimuli. As luminance was increased, k shifted between -.25 and -.40 (depending on task difficulty) for the larger letters. For the smaller letters, k shifted to 0.45 and was independent of the task difficulty.

The obtained values of C (the luminances needed for any given duration) are peculiar to the targets used. However, depending on the difficulty of the discrimination, it seems that for acuity tasks above a minimum value of luminance, time is the most important factor.

Baron and Westheimer (1973) support this notion. They found that at relatively high luminances (127 to 509 cd/m^2) the time needed to perform a Landolt C acuity task was about 400 msec., and relatively independent of luminance. The critical duration for the detection of his targets, using the same apparatus, was 80 ms.

Brown and Black (1976) used a somewhat different stimulus configuration. With gratings, they measured the luminance increment needed to detect its orientation for different background luminances and spatial frequencies. As background luminance was varied from zero to 3.183 cd/m^2, critical duration decreased from 250 to 126 msec. This was at spatial frequencies between 3 and 6 cycles/deg; at frequencies both above and below these, the critical duration was less. The range of spatial frequency to which the human visual system is most sensitive for flashes of long duration also happens to be 3 to 6 cycles/deg (see Figure 35).

In describing the visibility of a target flashed just once, the authors start with a simple idea that the less time one has to see the target, the harder it is to perform an acuity task. But the situation is not as simple for a repetitively flashed (i.e., flickering) target. Whatever the flicker frequency is, both time-averaged mean luminance and the total stimuli duration can be kept constant. But one wonders whether subjective effects, like the enhanced brightness at certain flicker rates (Brücke-Bartley effect), might affect acuity performance. The answer from Bartley and his co-workers is that it does. In fact, conditions which produce subjective brightness enhancement actually degrade acuity. Bartley, Nelson, and Soules (1963) found this when testing observers with Snellen E targets (contrast = .5; see Appendix A) using several frequencies and pulse-to-cycle (PCF) fractions (or duty-cycles) at a mean luminance of 149 dc/m^2. Acuity was the worst in every case that generated brightness enhancement. Bourassa and Bartley (1965) did a more extensive experiment in which the task was to detect a gap between two square objects, 30.5' and 76' in width. Figure 33 shows their results. The greatest loss of acuity occurred under the conditions that produced the brightest display. Thus while acuity of a target presented steadily or as a single flash, improves with increasing luminance, acuity is degraded when the subjective brightness of a flickering target is increased.

Gerathewohl and Taylor (1953) have also found that flicker did not help observers to read a special acuity chart. This chart was 50 lines of black print on a background that became progressively darker from top to bottom; 1×10^5 cd/m^2 for line one down to only 1.8×10^4 cd/m^2 at line 50 Of course, the contrast of the text also dropped as one reads down the page. They found that at 9 and 15 Hz, flickering neither improved nor degraded performance. However, they did not check to see if their conditions also produced brightness enhancement.

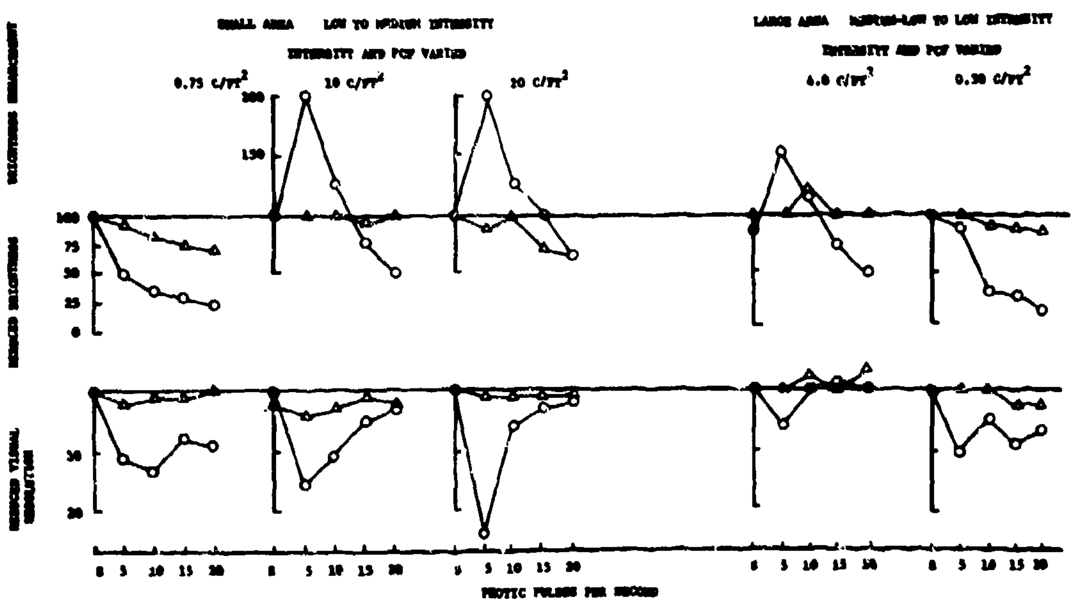

Figure 33. Curves of brightness enhancement, reduced brightness, and visual resolution for each of two pulse-to-cycle fractions under similar conditions. (For curves with open circles, pulse-to-cycle fraction equals one fourth; for curves with crosses, pulse-to-cycle fraction equals three-fourths. The effectiveness (enhancement or its opposite) is given in percents, with brightness of the steady target as a base. Visual resolution also is relative with the separation of the components of the steady target as a base; therefore values progressively above zero represent wider separation and reduced acuity or resolution. Units are given in seconds of arc). (From Bourassa & Bartley, 1965.)

These acuity tests, however, assess only one aspect of visual function, the ability to see fine detail at high contrasts (fine lines or gaps, or for grating targets, gratings of high spatial frequency). (cf. J. L. Brown (1965) for definition). What about the ability to see larger objects under conditions that hamper visibility, for instance low contrast? This shall be termed a visibility rather than an acuity task. It happens that flicker can improve performance for this type of task (Kelly, 1969; Sekuler & Tynan, 1977). As an example, see Figure 34 from Sekuler and Tynan. They measured contrast threshold as a function of spatial frequency for two rates of flicker. Lower contrast thresholds correspond to higher sensitivity levels. The jagged lines reflect the fact that their task was a tracking procedure; as they changed spatial frequency, the observer instantly adjusted contrast so that the pattern was just visible; to avoid clutter, only the mid-points of these tracks are plotted for the other function. It is clear that the 6 Hz rate of flicker improved the visibility of the low spatial frequency gratings relative to the very slow .3 Hz flicker rate. However, for the high frequencies, those which assess acuity, sensitivity was unaffected by flicker rate. Sekuler and Tynan did not state whether brightness enhancement occurred for their display.

A similar result occurs when measuring contrast sensitivity for various durations of a single flash (Nachmias, 1967, Tynan & Sekuler, 1974). Figure 35 is from the latter paper. As expected, sensitivity decreases as flash duration is decreased. However, the low frequency patterns suffer less loss, resulting in the elimination of the low-frequency roll-off of these sensitivity functions found for long duration flashes. Thus, at short durations, large targets are the most visible. At longer durations, medium size targets are the most visible.

Flicker may also enhance the visibility of targets obscured for reasons other than low contrast. Kirkwood (1968) noticed that blurry images on a large uniform background tended to disappear after a few seconds. His patterns were quite large and varied in complexity (Figure 36). It should be noted, however, that the actual patterns were blurred. Kirkwood tried to prolong their visibility by using intermittent light. Figures 37 and 38 show that the lower the rate of flicker, the longer they were visible. The more complex figures benefitted the most.

Alexander (1970) also tried to improve the visibility of fading images. Nonsense figures embedded in a blurry, matted, noise background faded in approximately one second. Flickering the entire scene at a rate of 4 or 8 Hz improved the visibility of these figures. Conceivably, this factor could be employed for certain symbols used with tactical information display (TID's) or heads up displays (HUD's) where critical information could be flickered at frequencies determined optimum for seeing.

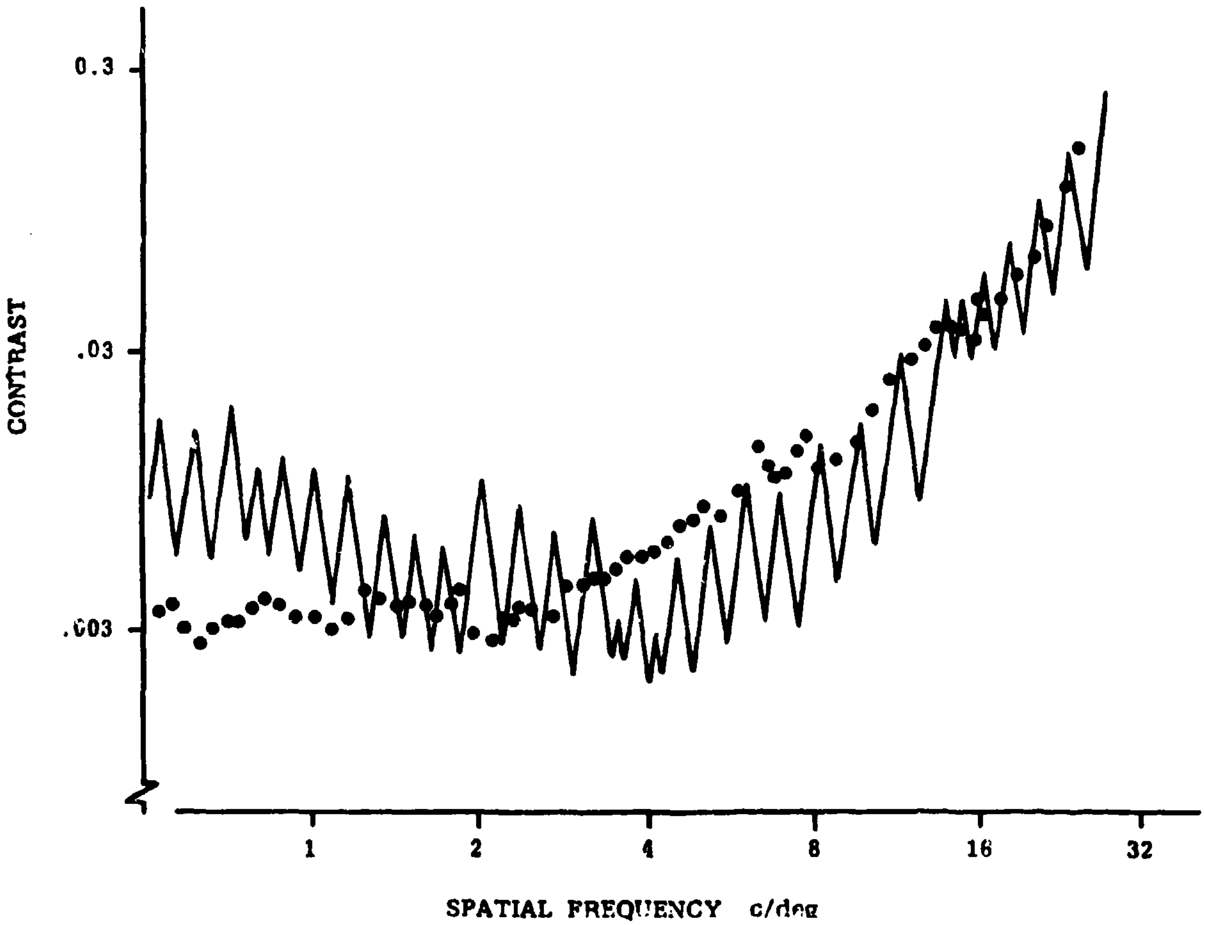

Figure 34. Contrast-sensitivity function obtained for an observer's right eye using a target flickered at 0.3 Hz (continuous line) and at 6.0 Hz (dots). Each dot is the mean of a peak and a trough from the x,y plotter record (from Sekuler & Tynan, 1977).

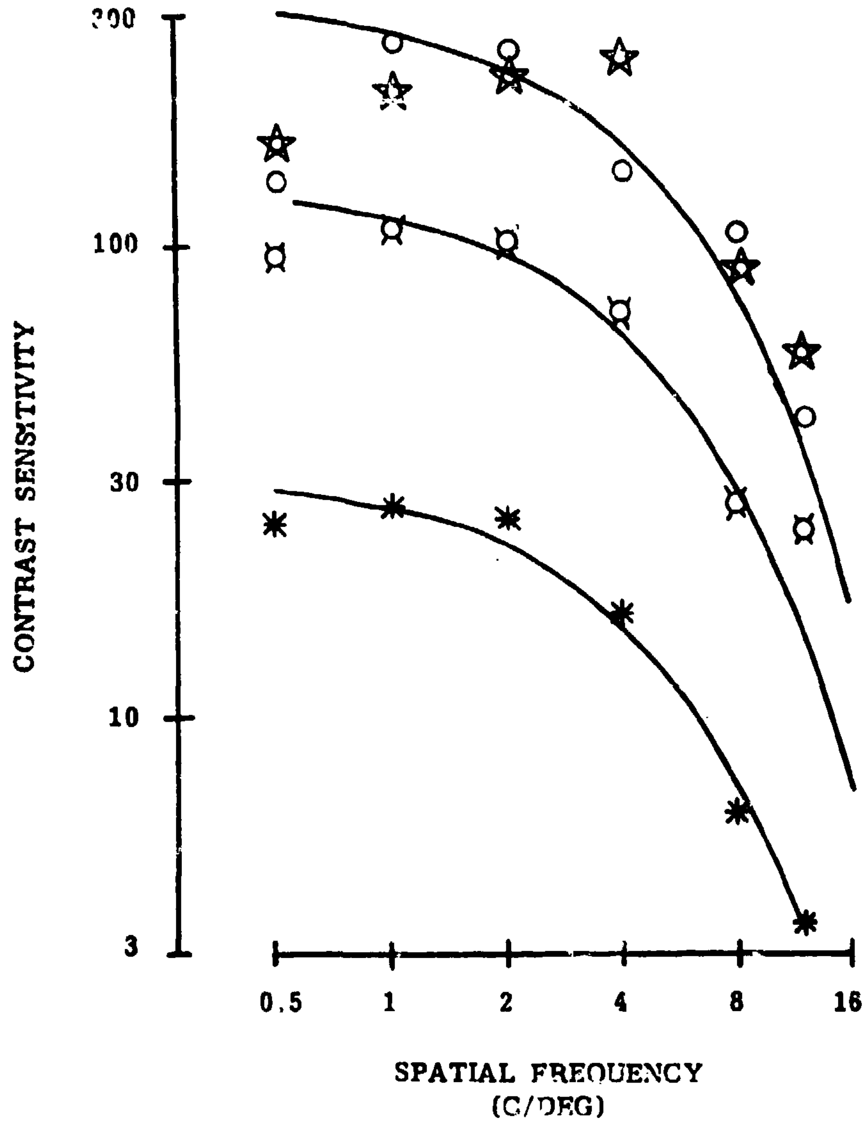

Figure 35. Contrast sensitivity as a function of test-grating spatial frequency. Results for test flashes of 16, 90, 512, and 1000 msec are given by asterisks, propellers, circles, and stars, respectively. The lowest curve is the least-squares fit to results with 16 msec flashes. The model equation was of the form, sensitivity=ke^{-cF}, where F is spatial frequency. The same curve (with adjustment of the k parameter), has been fitted by eye to data with 90 msec (middle curve), and to data with the two longest durations (top curve). (From Tynan & Sekuler, 1974.)

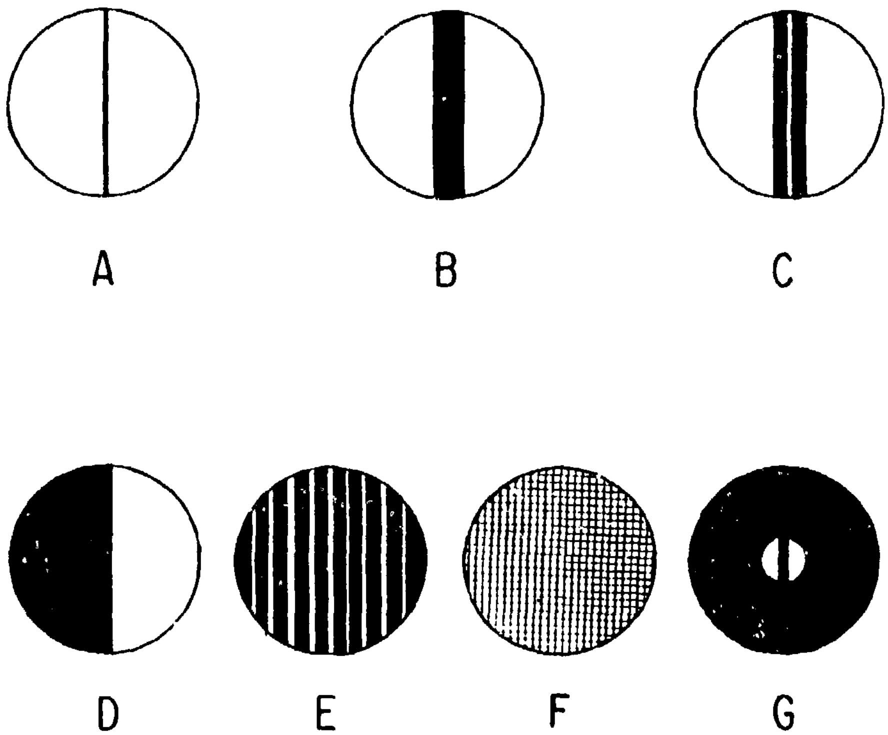

Figure 36. Test patterns used in Kirkwood's 1968 experiment. These patterns were blurred when presented to the observer.

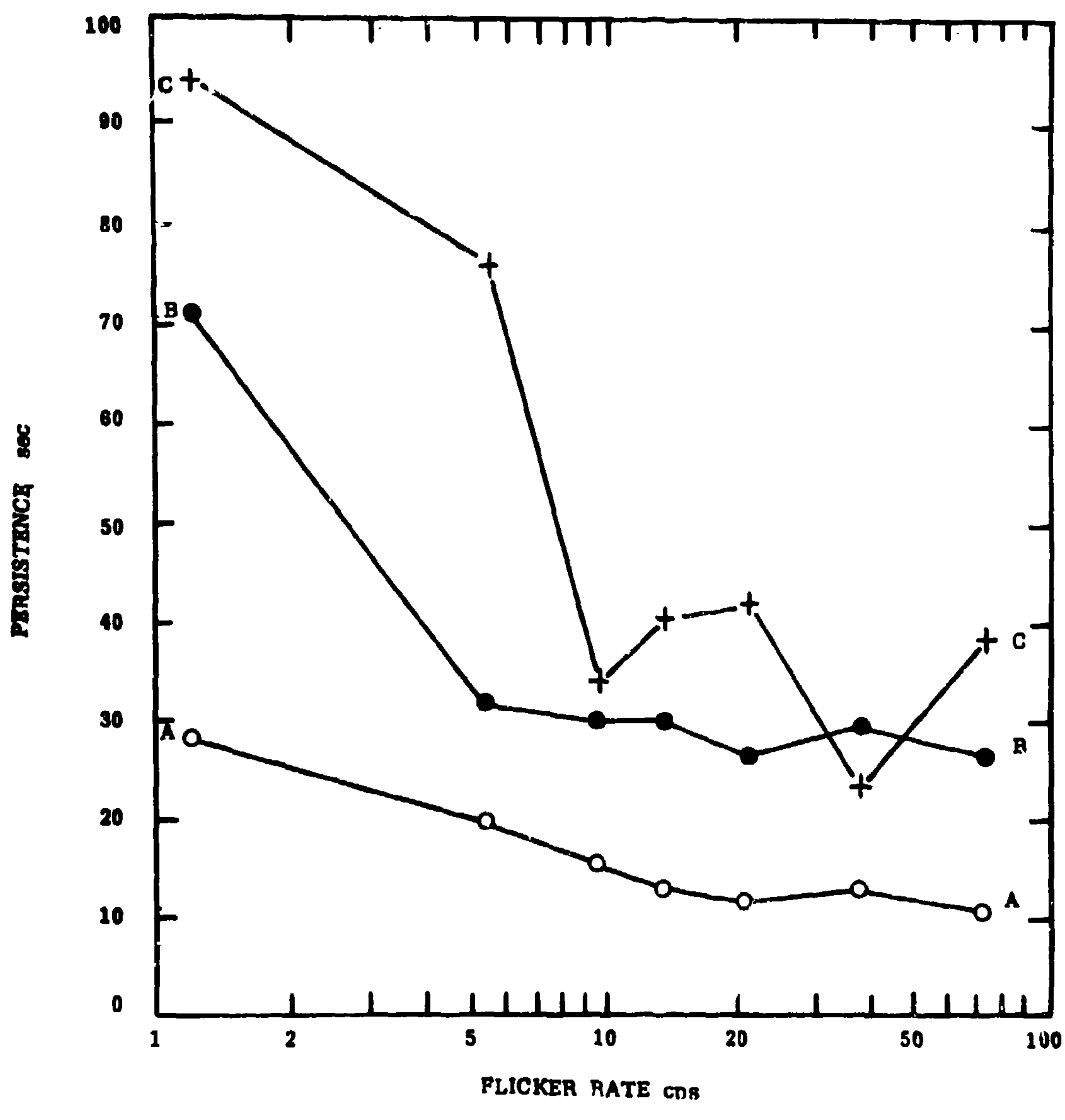

Figure 37. Relationship between mean persistence time and flicker rate for patterns A, B, C. Standard deviations average 0.38 of mean persistence times shown (from Kirkwood, 1968.)

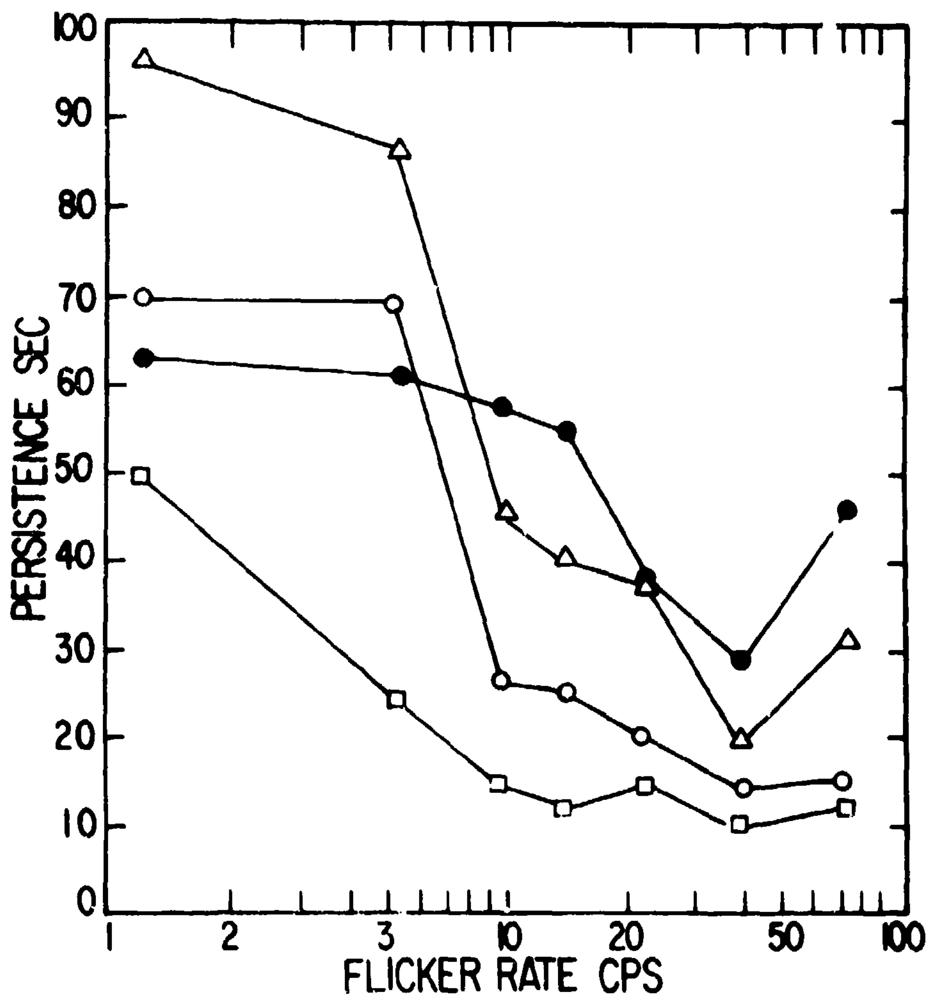

Figure 38. Relationship between mean persistence time and flicker rate for patterns, D, E, F, G. Standard deviations average 0.38 of mean persistence times shown (from Kirkwood, 1968.)

CHAPTER 13

Effects of Movement on Visibility

The effects of movement on the visibility of a target resemble those of flicker. This equivalence may result from the fact that spatially repetitive pattern movement can be specified in terms of the flicker at any one point in the visual field. An important difference between flicker and movement however, is that due to temporal summation in the visual system, movement causes apparent blurring or "smearing" of an object. The effect is the same as taking a photograph of a moving object with too slow a shutter speed (cf., Brown, 1972a).

Another difference between flicker and movement is that with movement, a target may not remain on the fovea, the region of the retina most sensitive to fine detail. Even if the observer pursues the object with his eyes, tracking errors will introduce both retinal movement and likely parafoveal viewing of the target.

This chapter is in three parts. The first part will discuss dynamic visual acuity (DVA), the ability to discriminate fine spatial detail in a moving target. The second part will deal with the effects of movement on the visibility of larger objects and for tasks other than acuity. Lastly, several attempts to measure visibility in applied settings or with displays designed to provide information particularly useful to the human factors engineer will be discussed.

Dynamic Visual Acuity

Ludvigh (1941) and his associates at the U. S. Naval School of Aviation Medicine did much of the early work on dynamic visual acuity. Ludvigh and Miller (1958) asked observers to discriminate the orientation of the small gap in Landolt C targets as they moved at velocities ranging from 0 to 120 deg/sec. The exposure time was in all cases .4 sec and illumination level was 25 ft-c. Their data are reproduced in Figure 39. The three curves represent three groupings of observers on the basis of performance. All curves have been fit by the equation:

$$\mathrm{DVA} = a + bx^3 \qquad (13)$$

in min of arc of the gap. The constant a represents static visual acuity (that is, acuity for non-moving targets) and b is a slope constant characteristic of an observer's acuity loss with increased speed, and velocity is in deg/sec. Variability in static visual acuity among observers is low (32%), possibly because all observers were screened for 20/20 vision or better. However, despite this "matching" for static acuity, variability among dynamic acuity scores (b factor) was large, 224%. Fergenson and Suzansky (1973) directly measured the correlation between static and dynamic acuity for 24 observers, unscreened and uncorrected for static acuity and found it to be essentially zero.

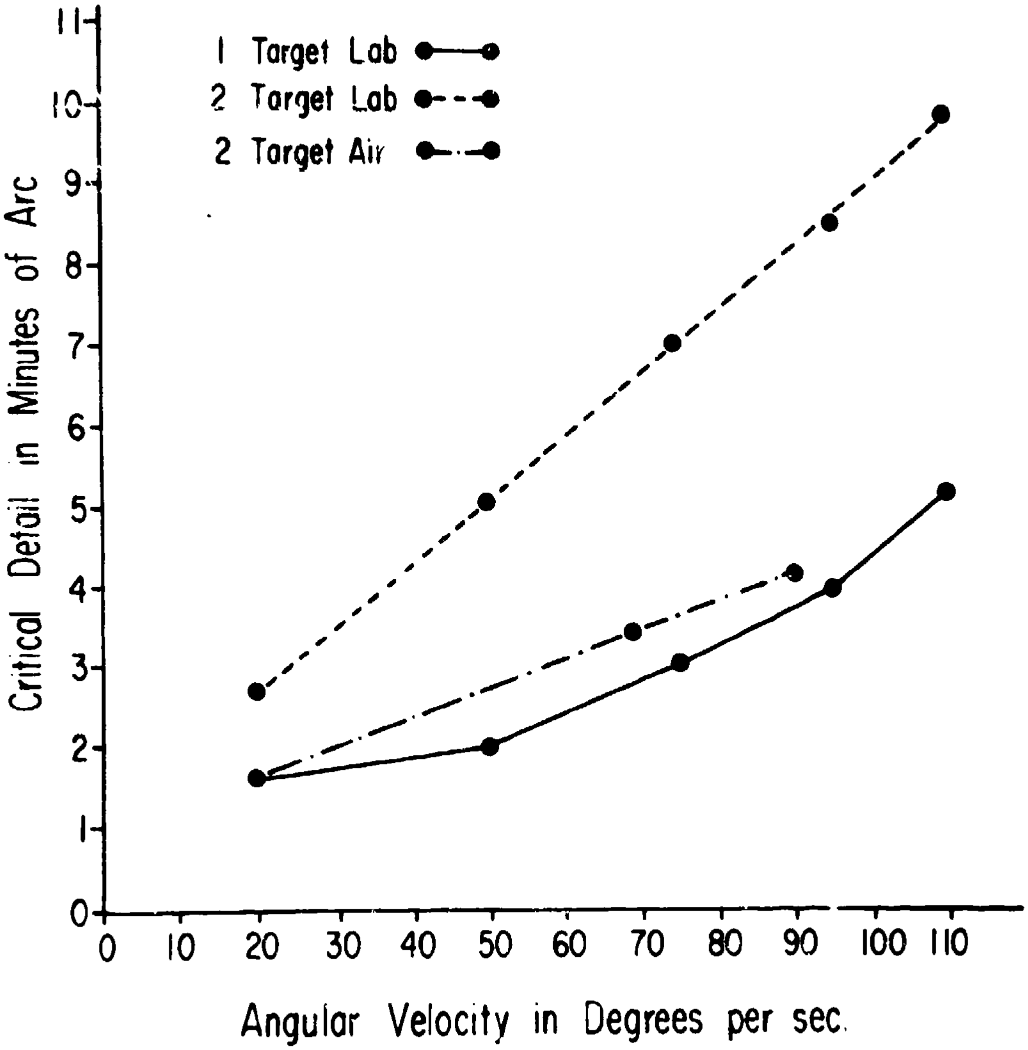

Figure 39. Observed and computed threshold values of all subjects grouped according to performance level. The circles, crosses, and triangles are the observed values, the continuous lines are graphs of the equation $Y = a+bx^3$ (from Ludvigh & Miller, 1958).

Interestingly, Ludvigh and Miller note that if some of their poorer observers had been provided with low-vision aids that magnified the targets, performance would have decreased, because not only the gap in the C, but also the velocity of the target would have been magnified by the device. Observers with poor dynamic acuity suffer much greater loss from motion than they gain by an increase in the size of the gap (since DVA increases as the third power of velocity).

A follow-up study (Miller 1958) produced very similar data when the observer moved (rotated) but the target remained stationary. Dynamic acuity, however, was slightly worse when the observer was rotated, rather than when the target moved. Miller also found that although static visual acuity did not improve much above 5 to 10 ft-c of illumination, dynamic visual acuity improved up to 125 ft-c, which was the highest illumination he used (see Figure 40).

In both of these studies, the observer was allowed to track the target with his eyes, but Ludvigh and Miller thought that errors in tracking allowed the target's image to move across the retina and cause visual smearing. Brown (1972a, 1972b, 1972c) was also concerned with such errors as well as with visual loss caused by viewing the target with parafoveal areas of the retina. Consequently, he measured dynamic acuity both with fixation at a stationary point and with tracking. Figure 41 shows data from Brown (1972c). Four observers fixated on a stationary spot and the target was presented at various eccentricities and velocities. Like Ludvigh and Miller, Brown used Landolt C targets; background luminance was 14 cd/m^2 and contrast was .74 (see Appendix A, Formula 2). Standard deviations are about 1/4 of the means. DVA was roughly linear with velocity but this is probably because Brown's range of velocities was much less than that of Ludvigh and Miller. Acuity also decreases fairly linearly with retinal eccentricity.

Brown (1972a) measured DVA (and at the same time recorded eye movements) while the observer pursued the target with his eyes. Brown concluded that tracking errors were the main causes of loss in DVA. He also noted that dynamic acuity improved with practice. Brown (1972b) repeated these measurements while varying the contrast of the targets. As Miller found when varying illumination, contrast affects DVA much more than static acuity (see Figure 41, the break midway in the functions are practice effect artifacts of the experimental design). These results agree with Ludvigh (1941) who found that a 20-fold increase in the contrast of a Snellen chart improved acuity by only one line.

When the eyes pursue a moving target, the target's slippage across the retina is considerably less than that of its background. Although most DVA studies concentrate on the visibility of the pursued target, Mackworth and Kaplan (1962) were interested in the observer's acuity for non-pursued background objects. They had observers pursue an object moving horizontally at various speeds, from 0 to 120 deg/sec. When the object reached the midpoint of the display, a test object flashed on for 99 msec, about 54' above the moving object. The test object was a set of three bright bars on a dark background. The luminance of the bars was variable and acuity was measured as the minimum resolvable stripe width. Figure 42 shows that luminance (and in this

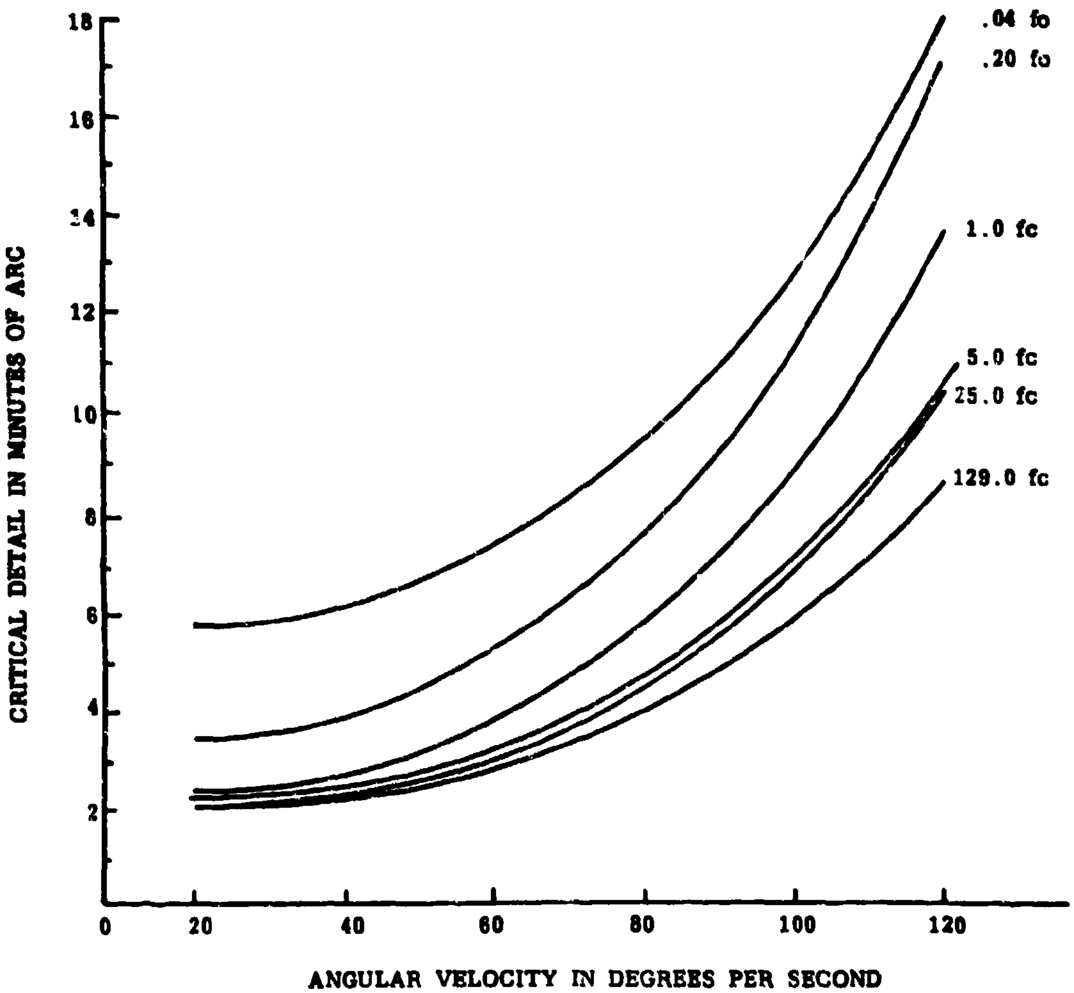

Figure 40. The effect of increased angular velocity of rotation on visual acuity at each of six levels of test chart illumination (from Miller, 1958).

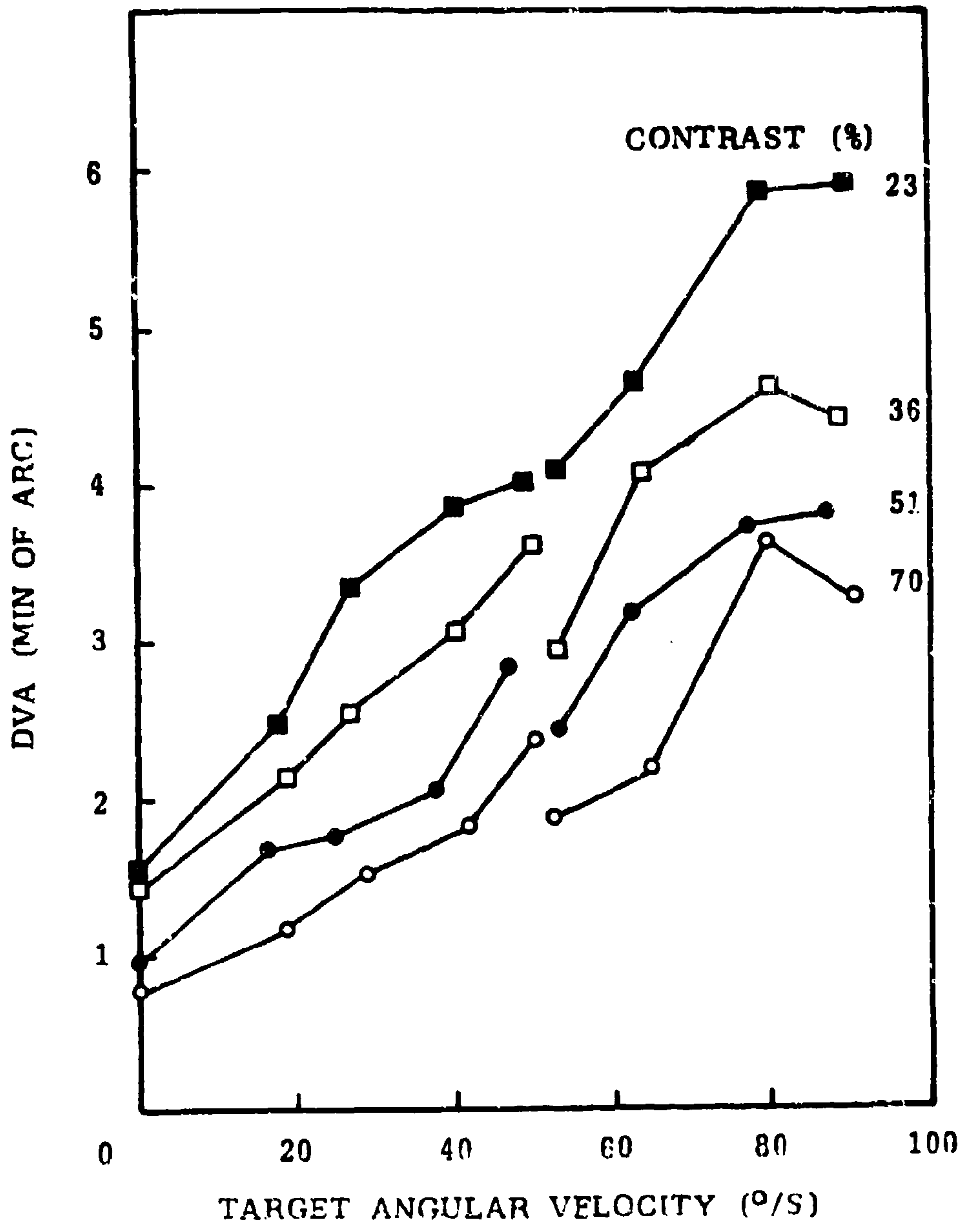

Figure 41. Mean DVA as a function of target angular velocity at 4 target contrast levels (from Brown, 1972b).

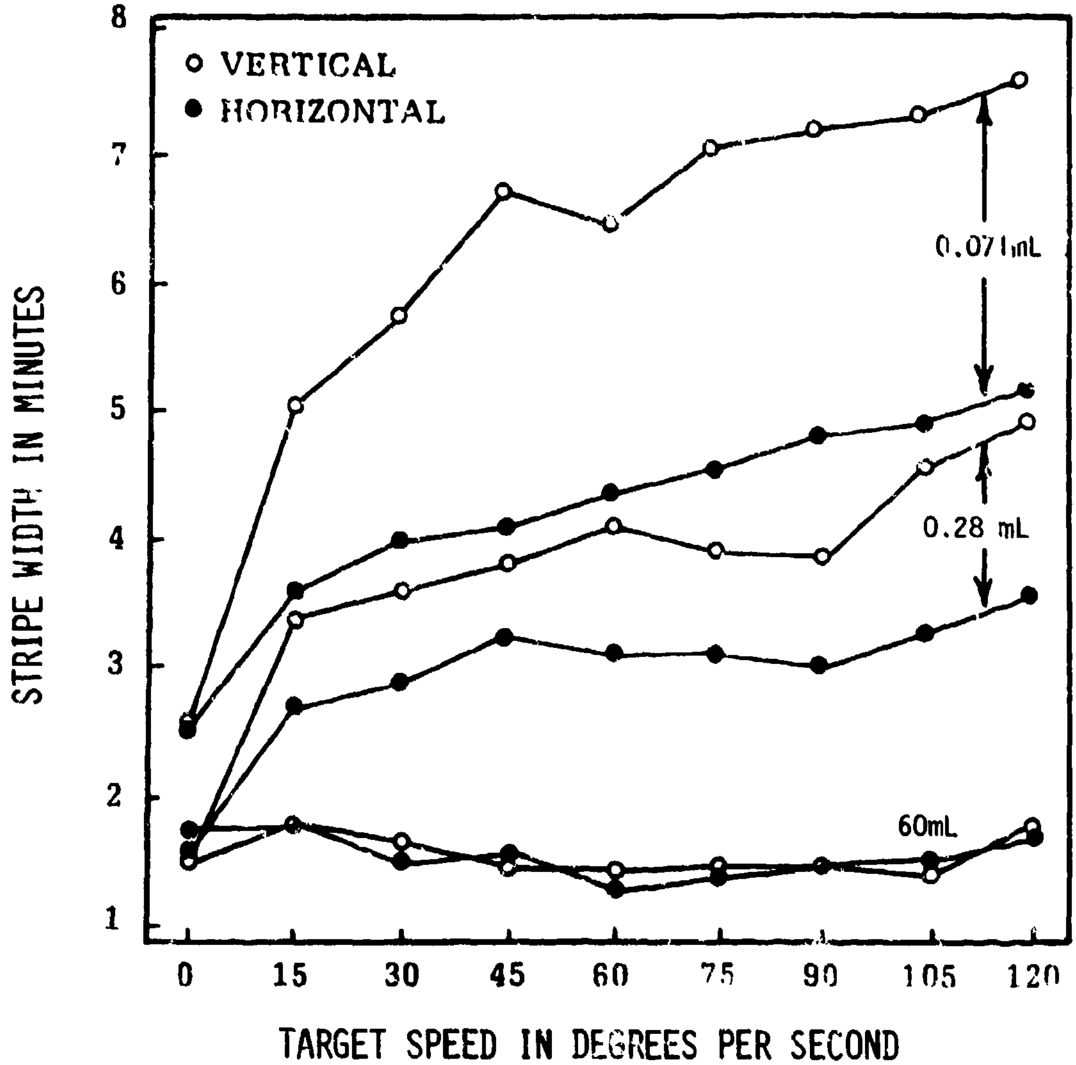

Figure 42. Minimum resolvable stripe width in minutes of visual angle as a function of target speed in degrees of visual angle per second. Thresholds for horizontal and vertical stripes were obtained at three luminance levels. Each point is the average of eight determinations on one subject (from Mackworth & Kaplan, 1962).

case contrast) again affected dynamic acuity more than static acuity. The figure shows that vertical bars were degraded more than horizontal ones. This is because "visual smearing" from object pursuit would be primarily along horizontal axis. Since the smearing would be perpendicular to the bars in the vertical condition, it would wash-out the effective contrast of the bars and reduce resolution. In the horizontal condition, smearing would tend more to enlongate the bars rather than to reduce the pattern contrast as much. For the same reason many experimenters note that the orientation of the gap in a Landolt C target is important. Mackworth and Kaplan claim that the facilitating effects of movement in the 60 ml condition (191 cd/m^2) were due to glare reduction.

"Apparent" movement reduced DVA in much the same manner as real movement. Breitmeyer, Love and Wepman (1974) alternated two circular acuity targets, 1.125 deg in diameter and 1.125 deg apart. The targets were discs with one edge slightly flattened. The subject had to judge the presence or absence of the flattened edges. Each disc was presented for 15 msec and at a range of SOA's (stimulus onset asynchronies). SOA of 95 msec produced both the best apparent movement, and the worst acuity --a drop off from 45% to 25% correct discriminations.

Non-Acuity Measures

The preceding discussion has shown that movement reduces visual acuity. As for flicker effects, acuity is not a complete measure of an observer's capabilities, and with other types of low visibility displays, movement may improve performance.

As mentioned previously, researchers often use the contrast threshold of targets as a measure of visibility. As an example, Krauskopf (1962) measuring the contrast threshold of a thin (2° 40') long line, tried to improve its visibility by moving it back and forth. For oscillations of 4 Hz, amplitudes of up to 12 min, (average velocities of up to 1.5 deg/sec) improved visibility (i.e., lowered contrast threshold). For 32 Hz, however, as amplitude increased up to 12 min, (average velocity up to 12.3 deg/sec) visibility decreased.

More complete information on visibility may be gained by testing with a series of grating displays. Van Nes, Koenderink and Bouman (1967) made such measurements at photopic levels with moving sinusoidal gratings. The borders of the display (1.2 x 2.4°) did not move, so the display looked like a moving endless striped belt seen through a window. They specify motion in terms of the temporal modulation (in Hz) at any point on the screen. The relationship between velocity and temporal frequency for a moving grating is:

$$\text{Velocity (deg/sec)} = \frac{\text{drift rate}}{\text{spatial freq.}} \qquad (14)$$

where drift rate is in Hz and spatial frequency is in c/deg.

Van Nes et al. (1967), used three temporal frequencies, zero, one, and 10 Hz. For high spatial frequencies, the 10 Hz rate made gratings less visible than the zero or one Hz conditions, but at low spatial frequencies one Hz produced the greatest improvement in visibility. Tolhurst, Sharpe and Hart (1973) made very similar, but more extensive measurements with a 6.5 deg diameter display of 100 cd/m^2 mean luminance. They also found that visibility was enhanced by movement if spatial frequencies were low (Figure 43). Peak visibility occurred at a temporal frequency of 5 Hz, regardless of the velocity, for spatial frequencies of 8 Hz or less. Sharpe (1974), however, made very similar measurements at a location 10 deg into the periphery (display diameter was 3.5 deg), and found that optimal temporal frequency changed with spatial frequency. Optimal temporal frequency for a 1.5 c/deg grating was 5 Hz (3.3 deg/sec) but for a lower frequency grating (.8 c/deg), a higher temporal frequency was better (10 Hz or 12.5 deg/sec). For a higher spatial frequency grating (5.5 c/deg), a lower temporal frequency was optimal (2 Hz or .36 deg/sec). Sharpe thought that the periphery may be "tuned" to detect rapidly moving coarse detail.

Van Nes (1968) reinterpreted the data from van Nes et al. (1967) in terms of visibility expressed as a ratio of the contrast threshold of a moving grating relative to that of a stationary grating (Figure 44). All the data are from one observer, but a second observer showed similar results except that his peak visibility gain was only about 1.7. These graphs show more clearly that the facilitating effects of movement are restricted to slow speeds and low spatial frequencies. Figure 45 shows, that the effects hold only for photopic luminance levels.

In general, whether movement improves or degrades visibility depends on the spatial characteristics of the target and the type of task the observer is required to perform. This may explain apparent descrepancies in the dynamic visual acuity literature. For instance, Breitmeyer, et al. (1974) found that apparent motion reduced acuity in a manner similar to real movement, yet they note in their paper that Erikson and Colgate (1970) performed a seemingly similar experiment, in which the observer recognized letters in apparent motion, and found no visibility loss. Breitmeyer et al. (1974) thought this apparent contradiction was reasonable since a pattern recognition task does not necessarily require attention to fine detail (high frequency information) and may, in fact, sometimes be improved by eliminating such information (Harmon & Julesz, 1973).

More support for the interaction between task and spatial frequency content is provided by a visual masking experiment by Carpenter and Ganz (1972). They showed that high frequencies were effective maskers for an acuity task but lower frequencies were effective maskers for a detection task.

Research in Applied Settings

Dynamic visual acuity has generated more interest among applied researchers than other visual phenomena because of its obvious importance to military and civilian transportation problems. For example,

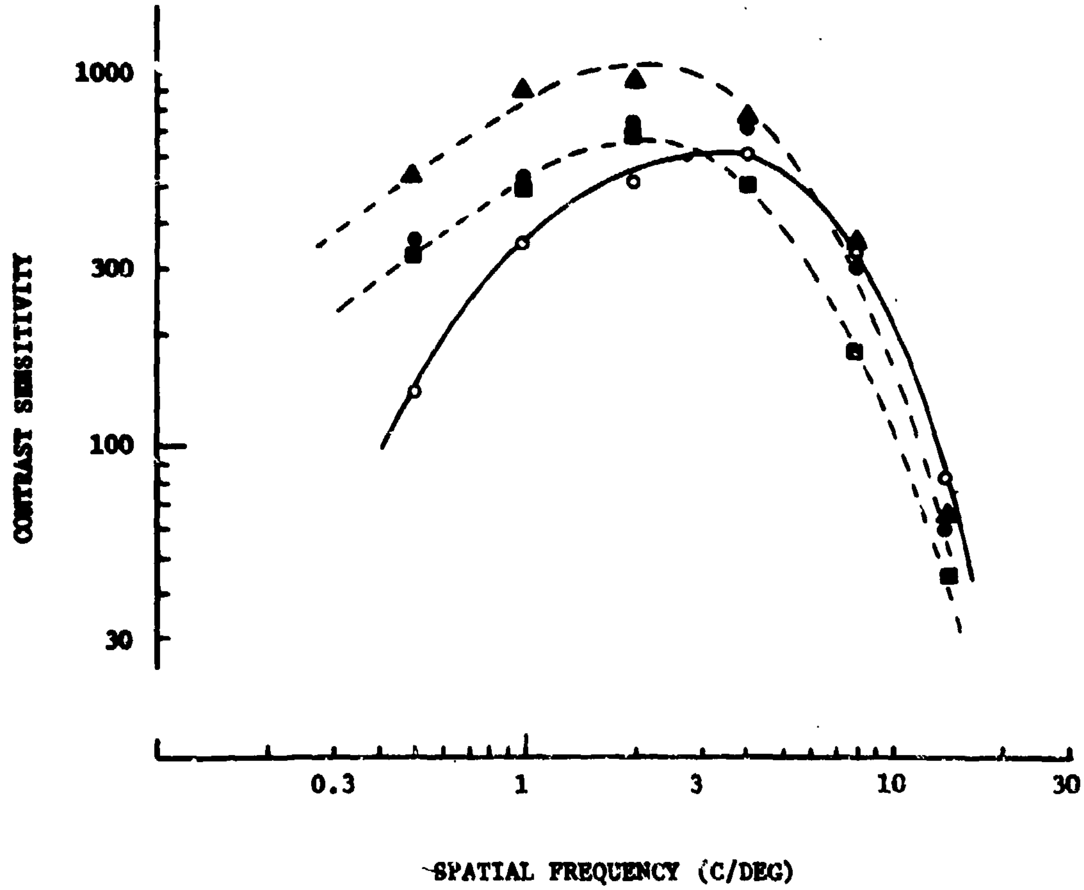

Figure 43. The sensitivity to gratings drifting in one direction as a function of their spatial frequency. The results for four temporal frequencies are shown: stationary (○); 2.5 c/sec (●); 6 c/sec. (▲); and 11.5 c/sec. (■). The continuous curve has been drawn by eye through the open circles; the dashed line has been drawn by eye through the data for 11.5 c/sec and then shifted up the sensitivity axis to fit the data for 6 c/sec (from Tolhurst, Sharpe, & Hart, 1973).

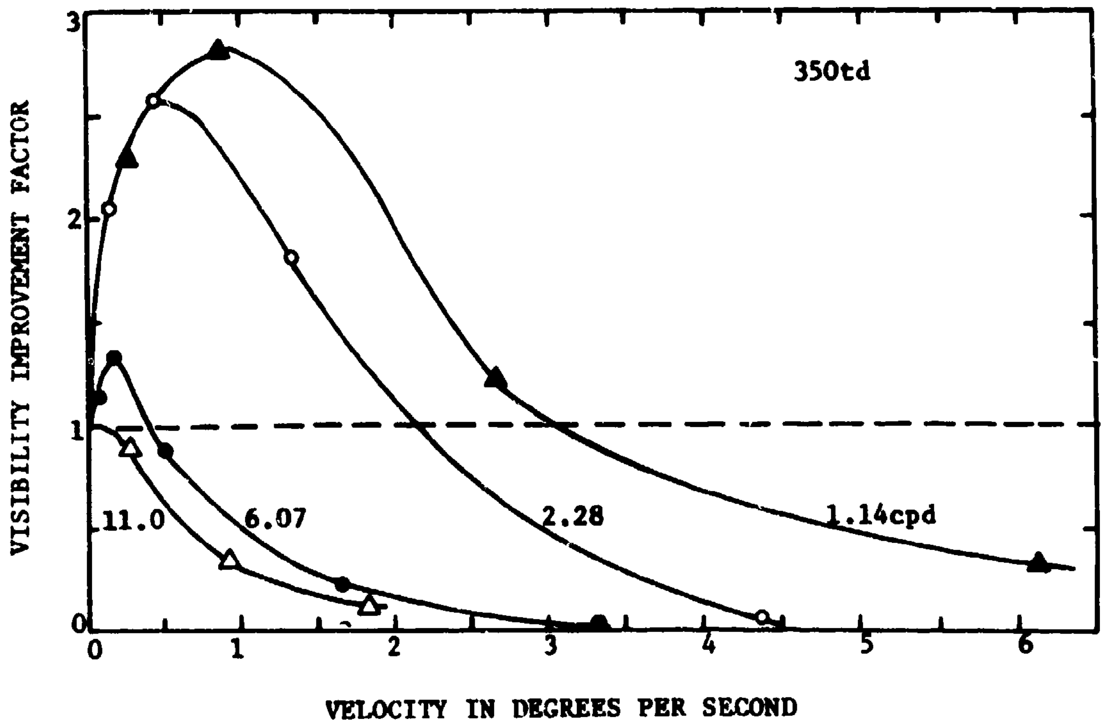

Figure 44. Visibility-improvement factors for four spatial frequencies as a function of the grating velocities, at an average retinal illuminance of 850 td (from van Nes, 1968).

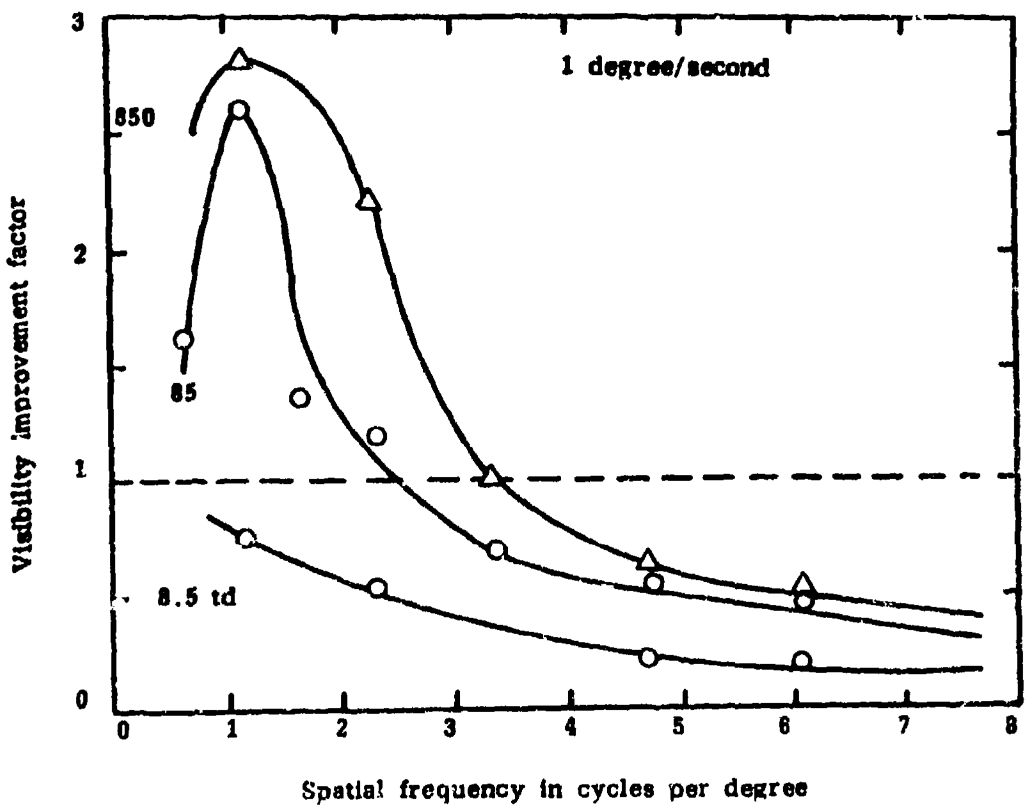

Figure 45. Visibility-improvement factors for three average retinal illuminances as a function of the spatial frequencies at a grating-velocity of 1 deg/sec (dps) (from van Nes, 1968).

Goodson and Miller (1959) tested the ability of an observer in a low-flying aircraft to see fine details on the ground. They flew observers past large single or double Landolt C targets. In order to compare their data to laboratory data, the plane was equipped with a special observation box that limited the exposure duration of the target to .4 sec. The aircraft flew at speeds that resulted in target speeds of 20, 69 and 90 deg/sec (Goodson & Miller, 1959) state that under combat conditions maximum target speed would be 110 deg/sec). Actually, the target speed was not constant during the exposure and these values are more nearly the median speed that the observer was exposed to. Figure 46 shows their data compared with other laboratory data. The data are similar although acuity was actually better in the air. They claim that this is probably due to deceleration of the target near the end of the exposure.

Gilson (1971) was also interested in dynamic acuity in the aviation setting. He gave observers the task of constantly centering a drifting needle in an aircraft-localizer/glideslope indicator. He then oscillated the entire display with an amplitude of 10 deg of visual angle, at a speed of either 5 or 30 deg/sec. It is not suprising that oscillation made the observer's task more difficult (Figure 47), but interestingly he found, as had Miller (1958), that changes in luminance affect performance more when dynamic acuity is required, than when static acuity was required.

Throughout this section, the attempt has been made to clearly demonstrate that dynamic and static acuity are only very weakly related, if at all. This has been further supported by Shinar, Mayer and Treat (1975) by using a battery of visual tests designed by Henderson and Burg (1974) to discriminate between good and bad automobile drivers. Shinar et al. (1975) found that DVA was correlated with other motion tests but not with non-motion related tests, including static acuity. More importantly, DVA was the measure that best discriminated between accident-prone drivers and a control group.

As was previously discussed, theoretically oriented studies have found that movement may improve detection or recognition performance, but not acuity. This is also true of studies oriented towards application of data on visibility. Peterson and Dugas (1972) found that movement improves the visibility of targets embedded in random or "cluttered" scenes. They used a high resolution T.V. system with a 31 x 40 deg screen of 38 cd/m^2 mean luminance. The target size was 1/4 deg square and motion was an oscillation 43' in amplitude. The backgrounds used were: a dot matrix, an aerial photo of forest terrain and a photograph of felt (random texture). Some of the results are presented in Figures 48, 49 and 50. The ordinate is the probability of detecting the target. Figures 48 and 49 show data collected with the dot matrix background, each at a different contrast. Increasing contrast from .3 to .5 (see Appendix A) was equivalent to increasing speed by one deg/sec. Figure 50 shows the results for the aerial photo background. In Figure 51 these data are replotted in terms of detection fields, the area around any fixation in which the target must be present to be detected. The larger the field, the greater the detectability of the target, and motion increases this field greatly. Figure

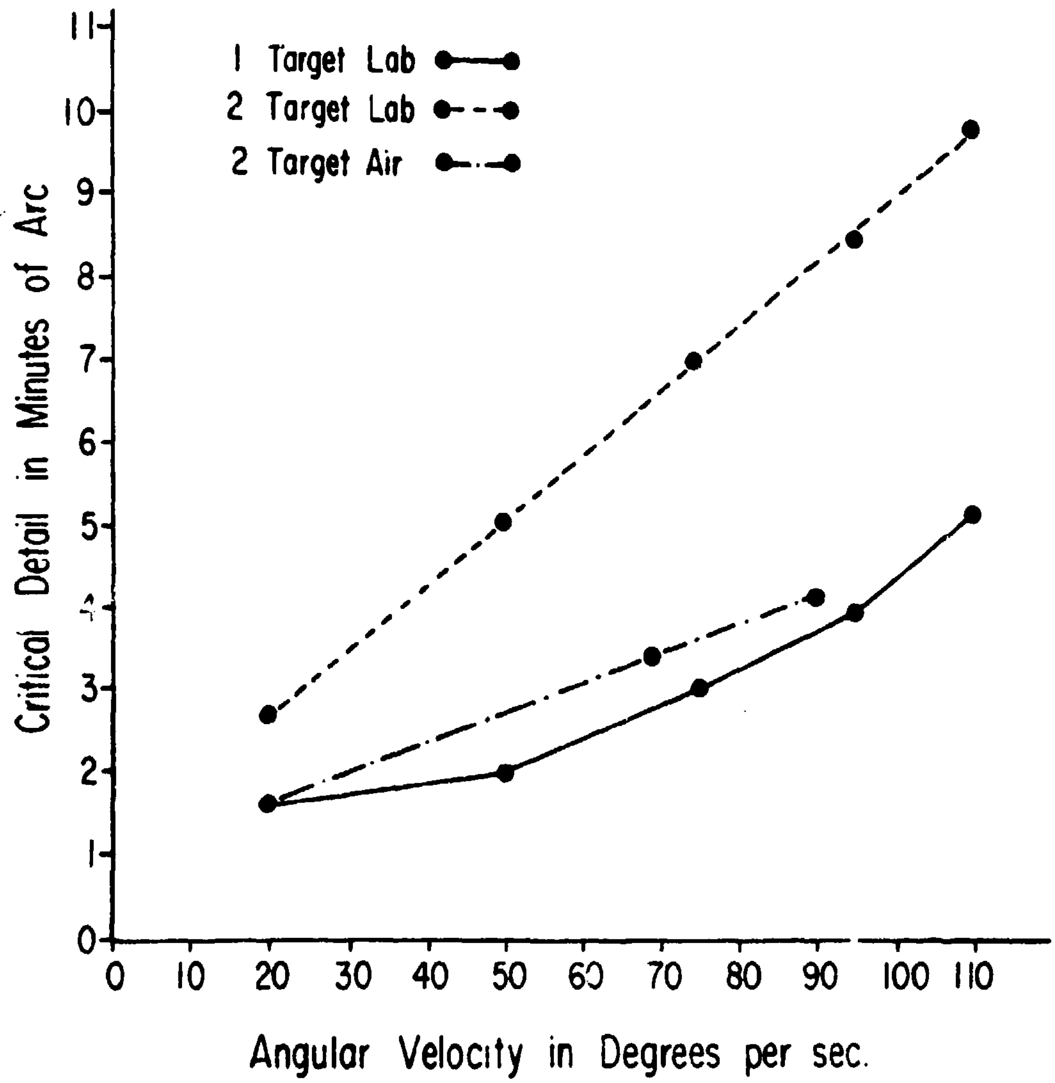

Figure 46. Means for different methods of testing visual acuity (from Goodson & Miller, 1959).

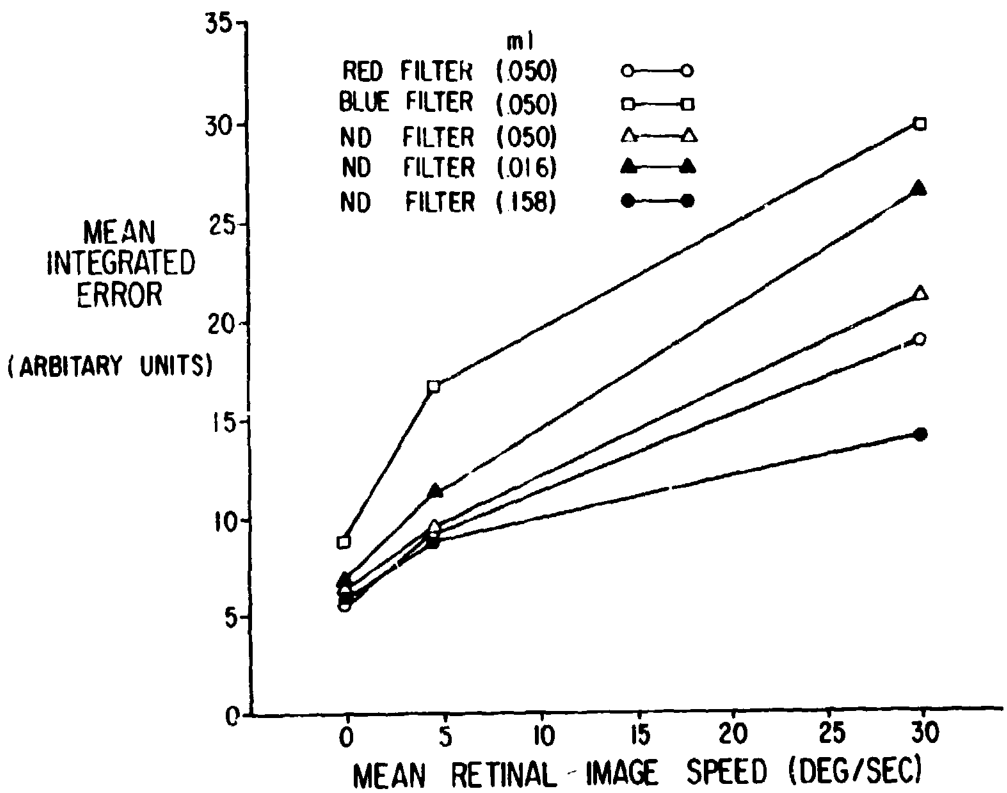

Figure 47. Average absolute velocity of the display image passing over the retina. These values were computed from the differential velocity of the eye and the display. (From Gilson, 1971).

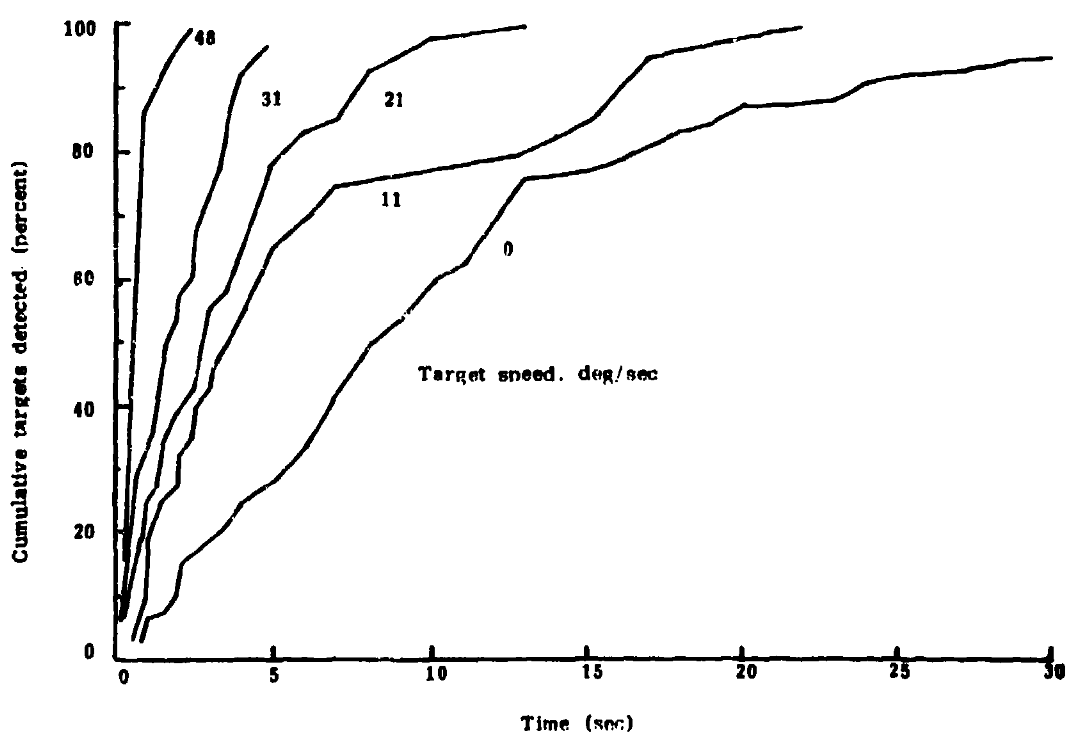

Figure 48. Targets detected within a given time period on the dot pattern background (contrast = 0.3) (from Peterson & Dugas, 1972).

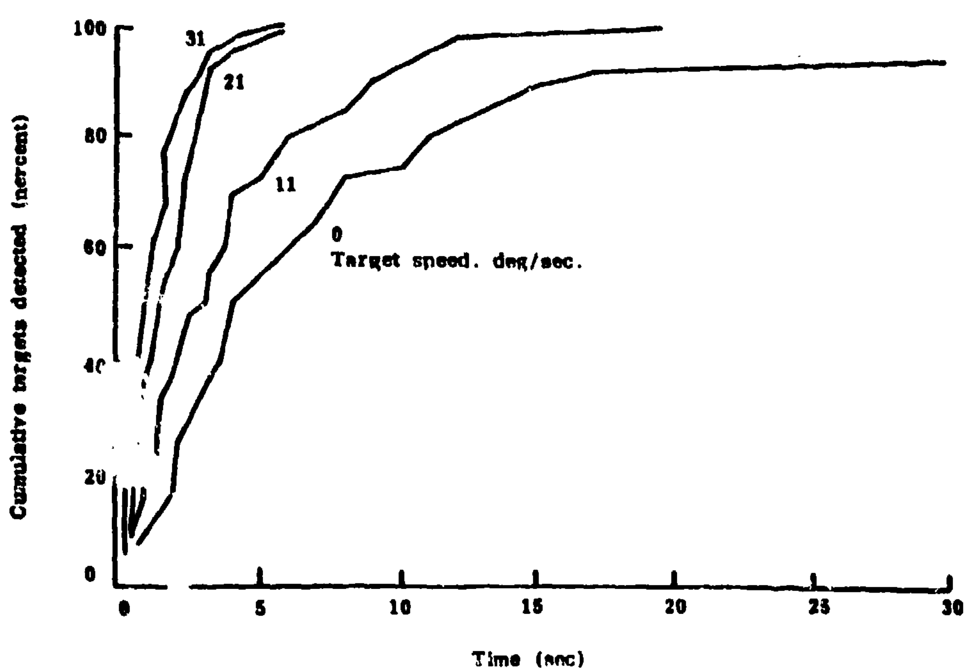

Figure 49. Targets detected with a given time period on the dot pattern background (contrast = 0.5) (from Peterson & Dugas, 1972).

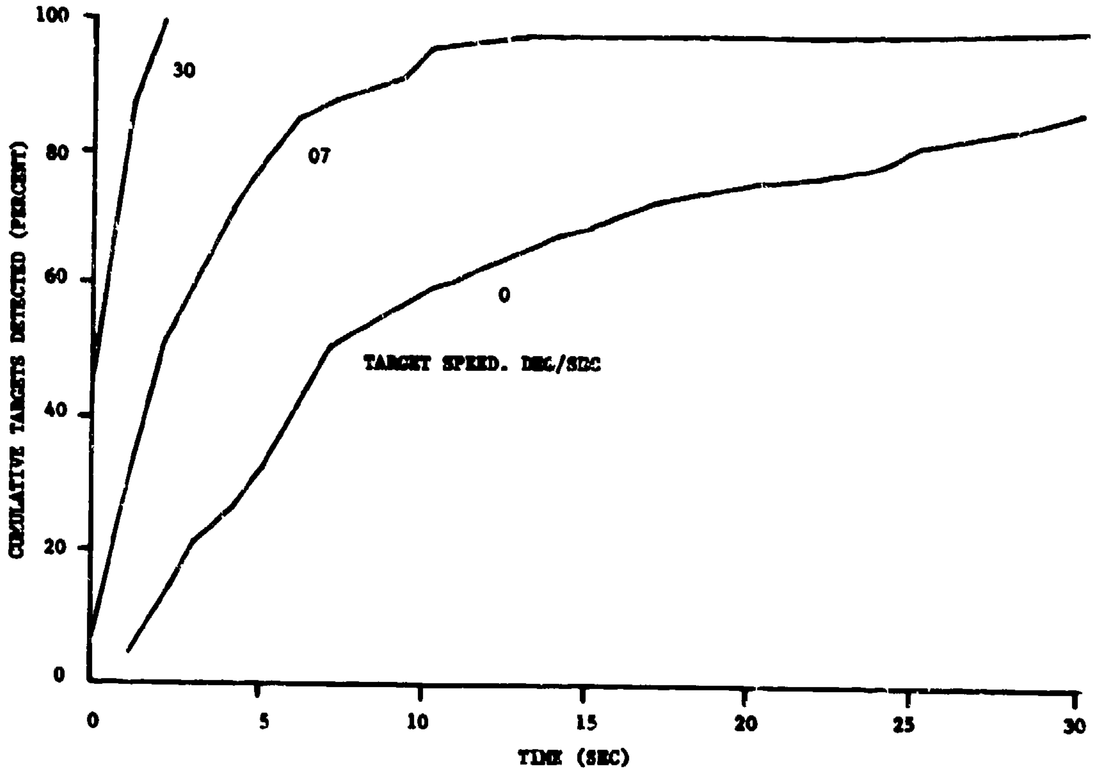

Figure 50. Targets detected within a given time period on the aerial photo background (from Peterson & Dugas, 1972).

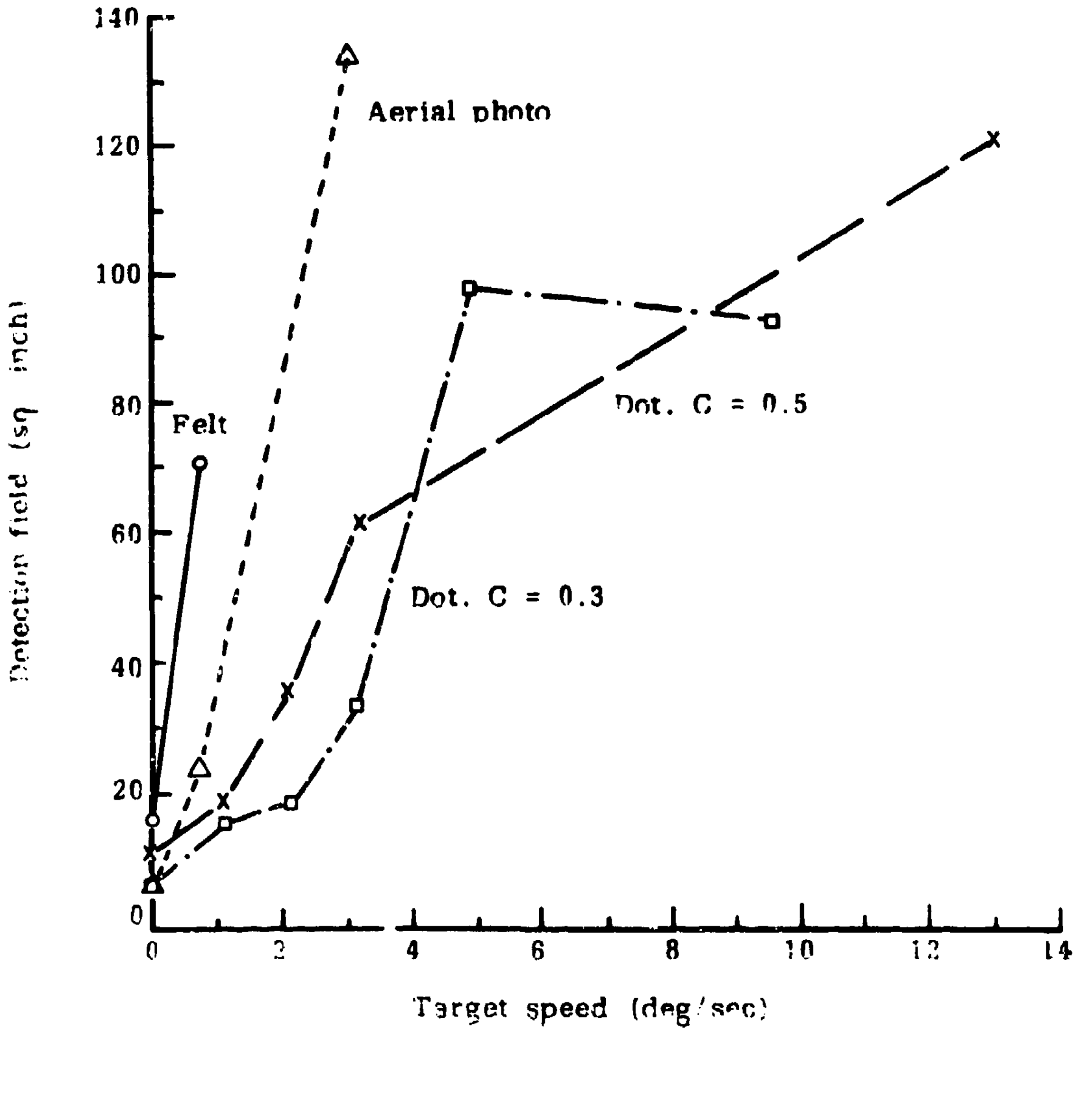

Figure 51. Variation of detection field with speed (from Peterson & Dugas, 1972).

52 shows the detection time for a stationary and moving target as a function of distance of the target from fixation (dot matrix background; the observer did not scan the screen). Beyond six deg eccentricity, motion reduces detection time considerably.

These results are similar to those of Alexander (1970) for detecting a target embedded in random noise. He investigated effects of flicker (see previous chapter), but he also noted that movement of <u>either</u> the target <u>or</u> the noise improved performance.

This phenomenon has already found practical application in a radar technique called "time-compression" (Scallan, Roscoe & Williges, 1971). They found that if several frames of radar information are stored on video disks and then played back quickly, the target will appear to move and be much easier to detect among noise and other sources of radar clutter.

The reader now has a general idea of when movement will help an observer perform a visual task and when it will impair. But there are still many more data that should be gathered. Goodson and Miller (1959), in discussing their dynamic acuity results, note that Ludvigh (unpublished) has considered the problem of relating acuity data collected in the field to more complex tasks in a way that would allow prediction of performance on the complex task. But just as the relation between dynamic and static acuity is weak, so might be the relation between dynamic acuity and complex recognition tasks. Especially if as Breitmeyer et al. (1974) suggest, dynamic acuity demands use of the high spatial frequency information in a pattern, while during a complex recognition task an observer may rely on information at lower frequencies.

A more promising approach would be to collect field data on the visibility of moving sinusoidal gratings similar to those of van Nes (1968) and of Tolhurst et al. (1973) and then analyze only data from the particular spatial frequencies which are important to the complex task under consideration. This latter approach is exemplified by Harmon (1974), who selectively filtered various bands of spatial frequencies from portrait photographs and measured the ability of observers to recognize the subjects. By combining these techniques, an engineer would know what frequencies were being "filtered" by the display motion, and how this would affect the observer's task.

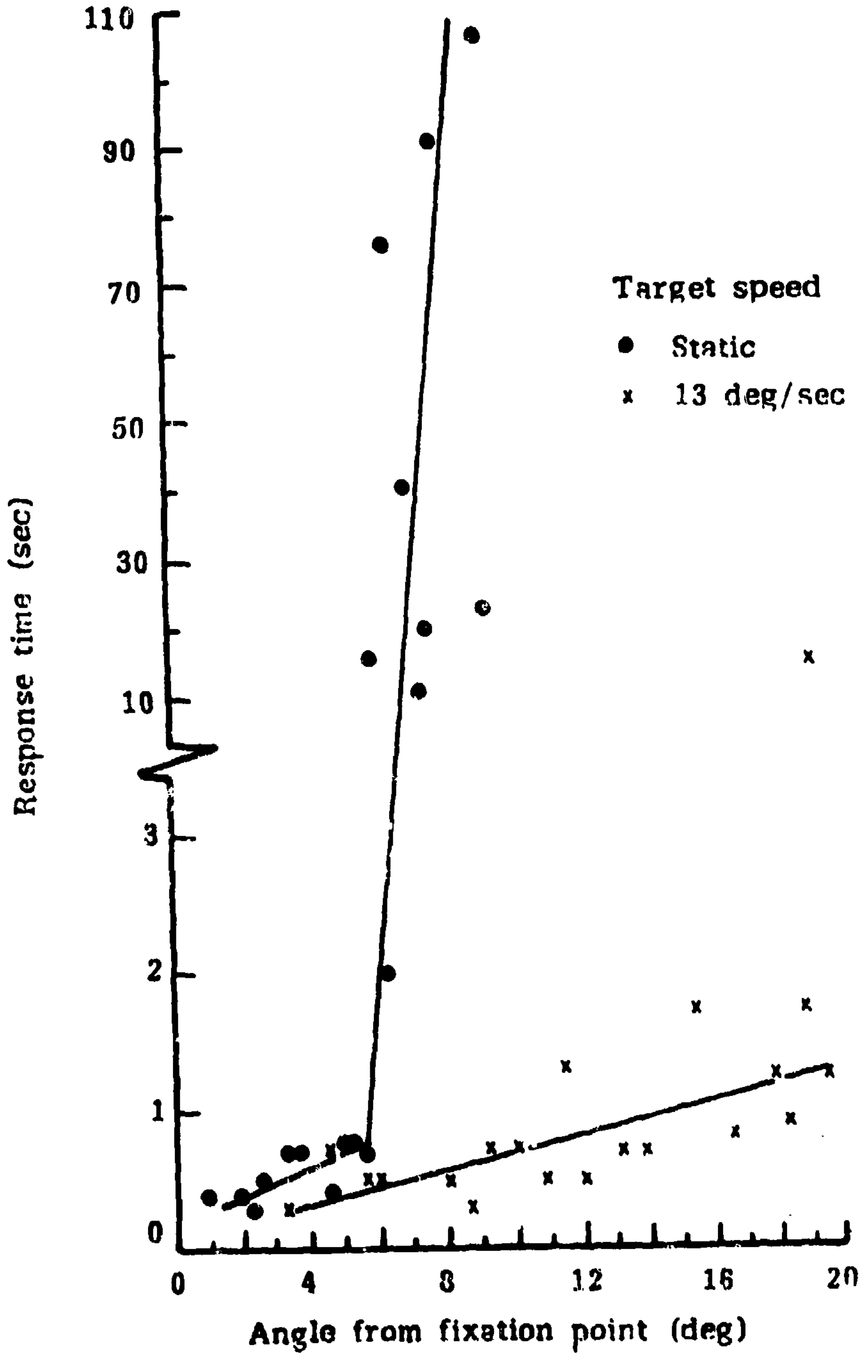

Figure 52. Detection time as a function of distance from fixation point (from Peterson & Dugas, 1972).

CHAPTER 14

Temporal Events Causing Distortion

Perceptual distortion is an ambiguous and difficult term. In this chapter it refers simply to a perceptual difference on a non-intensity dimension (e.g., length, size, color, etc.) between a steady-state display and the same display when flashed, flickered, or moved. Note that flicker-induced brightness enhancement is not included in this definition since it involves an intensity dimension (i.e., brightness). Since there is a large body of literature on this particular topic, it has been treated separately (see chapter entitled Brightness Enhancement).

In the case of movement, distortion often seems to be an indirect consequence of errors in eye movement during pursuit tracking of the moving object. The eye cannot always keep up with the object and the observer's visual system does not seem able to appreciate the error fully. As an example Mack and Herman (1972) found that when obervers tracked a small target moving along a 20° track at 4.5°/sec, they underestimated the length of the target's motion by 17% -- it only appeared to move 16.5°. At a faster speed (19.5 deg/sec) the error was only 6%.

Similarily, Bridgeman, Mayer, and Glen (1976) had observers track a "ramp" motion (i.e., the target's motion had both horizontal and vertical components, the horizontal component greater than the vertical). Observers tended to track only the horizontal component. "ignoring" the vertical. As a result, the vertical component was more accurately perceived and the motion appeared to have a steeper slope (i.e., had a greater vertical component) than it actually did.

Errors in eye-tracking also make the circular path of a target look smaller than its actual path. Coren, Bradley, Hoenig, and Girgus (1975), and Bradley (1977) had observers track a target moving in a circular path 20° in diameter. At slow velocities, the eye tracked the target well and distortion was small (Figure 53); at high speeds, the observer was unable to pursue it and so inferred a velocity derived from the movement of the target's image on the retina. At intermediate speeds, however, the eye could pursue, but could not keep up. The path of pursuit of the eye is smaller than that of the target's path, and so the target's path seems smaller in diameter at these speeds. This same type of distortion makes square or triangular motion paths appear to be "bowed" inward (Festinger & Eastman, 1974; see Figure 54). Figure 54 also shows that the distortion present during fixation of a stationary point is much less than during the pursuit condition. This suggests that in some applied situations, distortion may be lessened by instructing the operator to fixate on a stationary point in the display and <u>not</u> to follow the target with his eyes.

Pursuit eye tracking causes a different type of distortion in displays that <u>simulate</u> smooth motion -- television, computer graphics, motion pictures, etc. To economize on film, or reduce computer overhead,

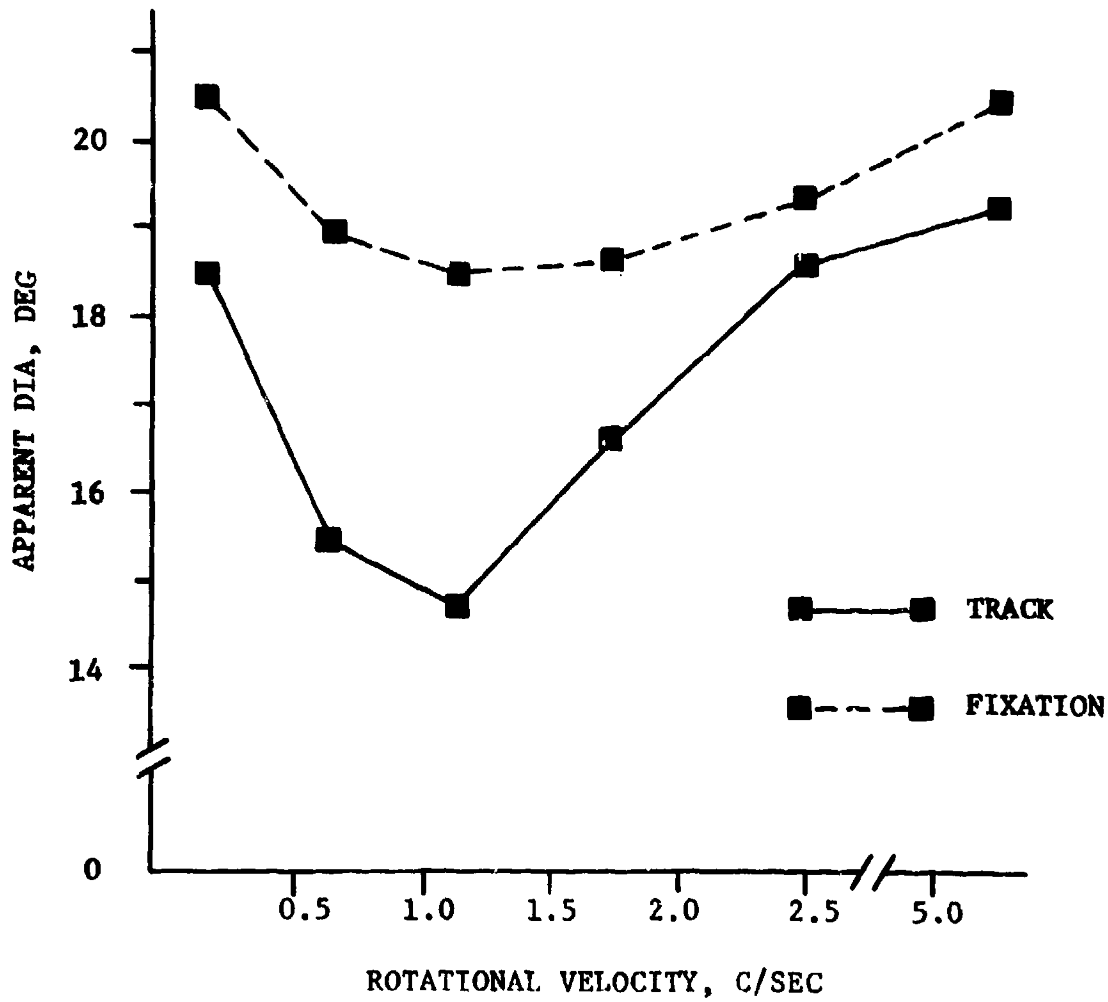

Figure 53. The apparent diameter of the target path under fixation and tracking conditions is plotted as a function of the speed of target rotating (from Coren, Bradley, Hoenig, & Girgus, 1975).

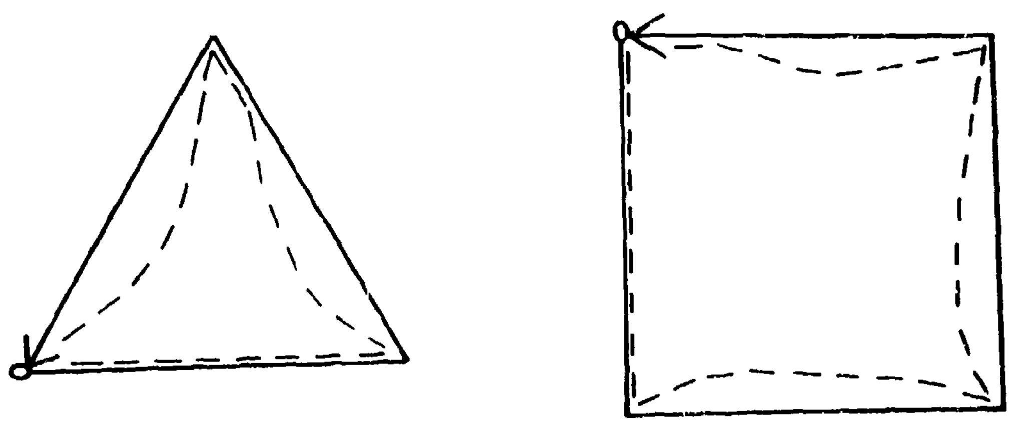

Figure 54. Perception of the path of a target moving in a square or triangular path. (Solid lines indicate the physical paths, and the arrows indicate the direction of motion. Dashed lines describe the perceived paths.) (From Festinger & Eastman, 1974).

a "moving" object may appear in the same location for more than one frame before changing location. Some motion picture projectors use a multiple-blade shutter to accomplish this. By presenting the same frame more than once, flicker rate can be increased without having to increase the number of frames of film. Certain of these systems provide a flicker-free picture, but if the eye tracks a small moving object in the scene, the observer may see multiple images of that object. Kintz and Witzel (1972) found that when a two-bladed projector was used, observers saw two images of the moving object (the projector shows each frame twice). Likewise, a three-bladed projector produced three images. The image is displaced abruptly from one position to the next, but the eye is tracking smoothly, thus for any given position, each presentation of the object falls on a different part of the retina, and several images are formed. Hempstead (1966) and Braunstein (1966) found the same effect with computer generated displays, and Riley (1977) noted a similar effect with LED displays in which the elements are sequentially refreshed.

Another type of distortion may occur even when the observer fixates on a stationary reference point. Ansbacher (1944) found that a rotating arc of light (about 36° off the circular path along which it moved) seemed to shorten to a fraction of its length when rotated at sub-fusional speeds. This phenomenon is generally referred to as the Ansbacher effect. He found that under conditions in which the radius of the motion path was 14.3 deg, the shrinkage increased as the speed was increased from zero to 1.3 revolutions per second (r.p.s.). At this maximum speed, the arc seemed to shrink to one-fourth of its physical size. Stanley (1966, 1968) using an almost identical display, found the same result and in addition varied the length of the arc. The effect is not as strong for short arcs (see Figure 55, from Stanley, 1968). Also, the effect does not occur for black arcs on a white background, (Marshall & Gordon, 1973) and if there is an effect, the arcs appear to be slightly longer when rotating (Stanley, 1966). The effect is not seen under conditions of dark adaptation (Marshall & Gordon, 1973).

In a series of ingenious experiments, Day (1973) provides strong evidence that the Ansbacher effect results from a type of masking. Considering the temporal stimulation at any one point along the path of the arc: when the leading edge passes, the sudden onset of light produces a strong sensation which results in a short period of reduced sensitivity afterwards. (See chapter on Flash Sensitivity.) This may explain why longer arcs suffer more shrinkage than shorter ones. The longer ones provide the proper temporal interval between the leading and trailing edge, so that the trailing edge is not seen. This masking hypothesis may also explain why a black arc does not behave in the same way. In practical terms, this theory can be translated into a rule for predicting when the Ansbacher effect will occur; in order to see the effect, both the leading and trailing edges of a moving target must stimulate the same retinal area. Ansbacher (1944) himself provides support for this rule. In one case he did not use an arc, but rotated a tilted straight line (i.e., not tangent to the path) and thus each part of the line swept over different parts of the retina. In this case he did not see any shrinkage. In another experiment, he sequenti-

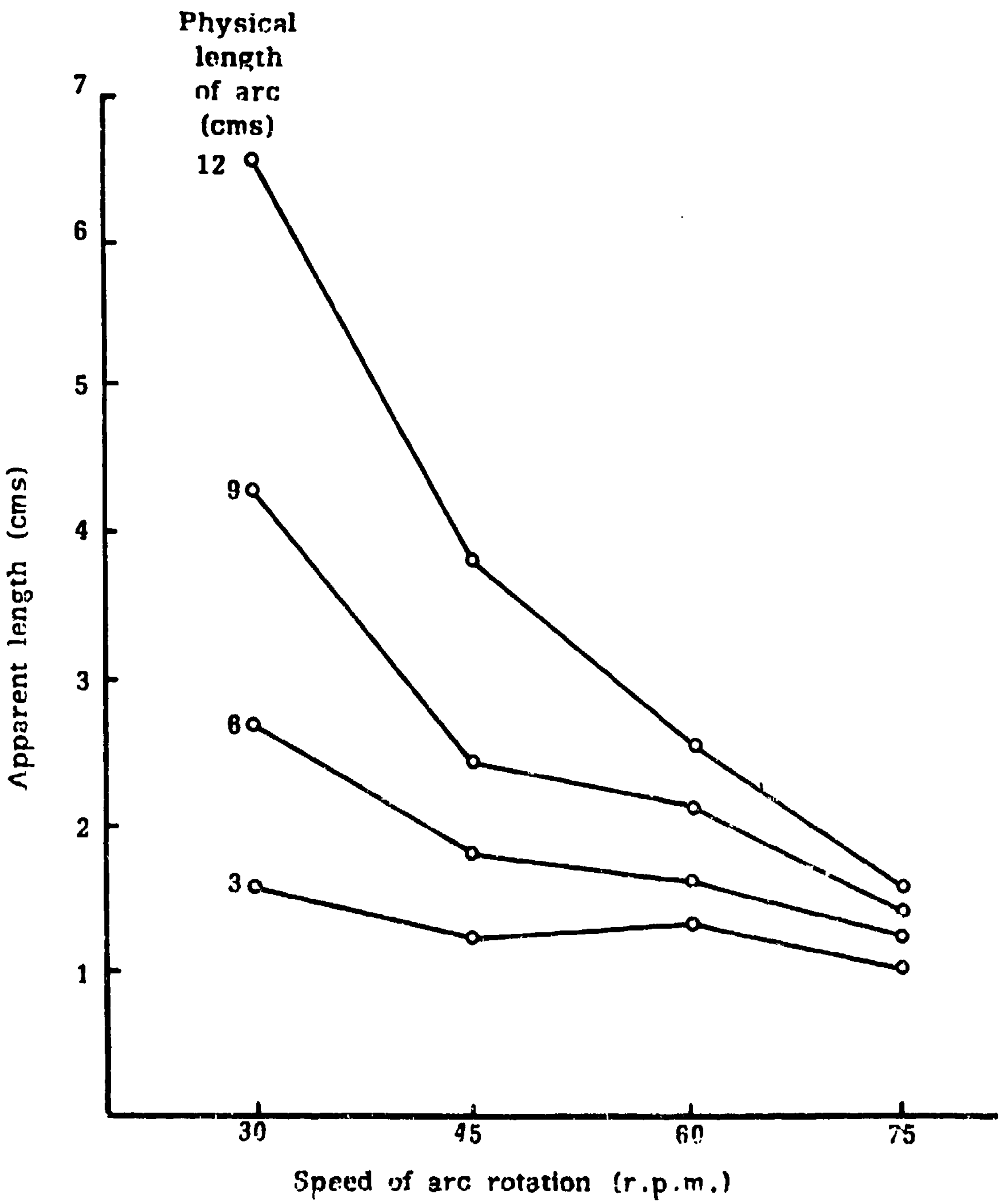

Figure 55. Mean ratio estimates of length plotted against speed of arc rotation for each length of arc (from Stanley, 1968).

ally illuminated adjacent, non-overlapping sections of arc, in other words, produced "apparent" movement of the arc and not real movement. Again, in this case each part of the arc stimulated a different retinal area and shrinkage was observed. Throughout these observations, fixation had always been at the center of the circular path.

Day (1973) found that the radius of the path had to be at least 11° in order for the effect to be reliably seen and for shrinkage to be appreciable. It seems that the effect is restricted to the periphery of vision. Stanley (1970) also found that the effect was increased if a stationary random pattern was superimposed on the display.

The display designer would be interested in knowing if this distortion also applies to targets that are moving linearly rather than in a circle. It seems that there is no reason that the effect would not occur if a bright rectangle of 5 to 10 deg in length moved parallel to its orientation at speeds of 40 to 60 deg/sec. In this case, eccentricity would change as it moved, and so might its apparent length as it moved across the retina. Pollack (1953) observed shrinkage of a linearly moving 1° spot of high velocity, but provides few details.

Tynan and Sekuler (1975a) observed that motion can produce a peculiar kind of contour completion effect. That study generated a moving granting display of low spatial frequency (.75 deg/sec) on a CRT and placed a long rectangular mask over the center, orienting it perpendicular to the bars. In the occluded area, a dim grating is seen, moving at the same speed and in phase with the flanking gratings. When the occluder is positioned parallel to the bars, the effect is not seen. Also, if the grating's motion is stopped, the illusory grating disappears. Gratings of greater than 3 c/deg spatial frequency do not produce strong illusory gratings. The effect is not due to scattered light within the eye because the illusory grating can be produced by flanking gratings on only twice their own contrast threshold. In fact, illusory gratings only .3° in height can produce illusory gratings that span a 3° occluder. A similar effect occurs if the center of a moving random dot display is occluded. In this case illusory dim random dots fill the occluded area. Weisstein, Maguire, and Berbaum (1977) have repeated Tynan and Sekuler's observations and determined that the illusory gratings can produce motion aftereffects much as real gratings do.

The distortions produced by flashes and flickering are more puzzling and varied than those produced by motion. These distortions range from mere changes in perceived luminance (similar, but not quite the same as enhancement effects), to illusory contours, as well as colors or drastic distortions in contours and colors that may be present in the display.

In the chapter on Brightness Enhancement, the types of flickering targets that were discussed were fairly simple. If more complex waveforms are used, however, peculiar phenomena may occur. For example, Anstis (1967) and Walker (1974) found that exposure to a "ramp" flickering waveform produced a brightness aftereffect. If the ramp was one of gradually increasing luminance (with an abrupt return to the lowest luminance), a subsequently viewed steady light seemed to grow gradually dimmer. The opposite aftereffect was produced by a ramp waveform that produced gradually decreasing luminance (see Figure 56). The optimum frequency of the ramp is about one Hz and the amplitude should be at least two log units (Anstis, 1967). Walker used a mean luminance of about 240 cd/m^2.

Anstis reports that neither a point source nor a Ganzfeld target is effective in producing the aftereffect, and retinal location and color do not seem to matter. In addition, Walker found that the increasing-luminance waveform produced a brighter display than the decreasing-luminance waveform. There was no effect of waveform on CFF or Talbot brightness, however.

For over 150 years, it has been known that observing a large homogenous flickering screen (usually 40°-60°) produces a variety of illusory shapes and movement. Smythies (1957) describes some of these: herring-bone patterns, checkers, spirals, whirlpools, concentric circles, families of parabolas, etc., and linear motion, oscillations, rotations, and all of them are often accompanied by vivid colors.

An example of two of these patterns is shown in Figure 57 from Young, Cole, Gamble, and Rayner (1975). In each figure, only part of the pattern is drawn, but these contours are perceived as surrounding the centerpoint. In Figure 57, the center elements were hexagons or dots of 5' to 12' in size; the larger grid elements in Figure 58 were about 1.4 to 1.6° across. The optimal frequency for seeing the fine pattern was about 10 Hz and the threshold luminance for seeing them about 10 cd/m^2. For the larger pattern the optimal frequency range was 10 to 30 Hz and threshold luminance was one cd/m^2.

These findings agree with a series of studies done by Remole (1974). He found that different types of illusory patterns were seen on a homogeneous screen at different luminances and temporal frequencies. At low photopic luminances, one sees stationary geometric patterns and color (Remole, 1973b, see Figure 59). The geometric patterns were seen better with binocular than monocular vision. At even higher luminances, movement was again seen -- swirling clusters of geometric shapes, reversing direction of rotation every two to four seconds (Remole, 1974). The luminance thresholds for this movement as a function of frequency were very similar to those for geometric figures, but displaced one-fourth to one-half log units higher. Unlike some of the other distortions discussed so far, there seems no way to prevent these powerful effects.

Consider the less extreme situation of a smaller patterned display, which has been reviewed before for effects of flicker on sensitivity and visibility. Then, consider the effect on the perceived spatial characteristics of the pattern; as studies of visibility, grating patterns have been a popular tool for manipulating spatial parameters precisely. In general, temporal modulation of gratings produces an increase in the apparent spatial frequency of the patterns.

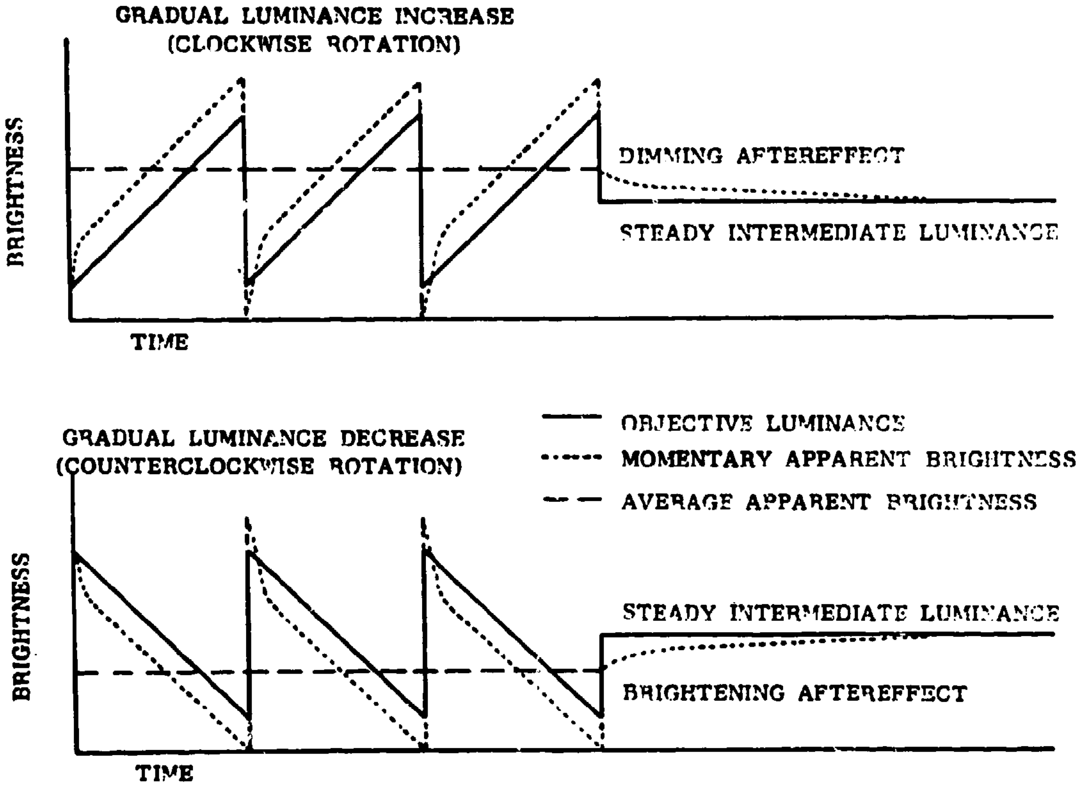

Figure 56. Diagrammatic illustration of objective luminance and apparent brightness as functions of time and rotation direction for a right-hand gradient disk. Clockwise rotation of a right-hand disk produces gradual increases in luminance and sudden decreases across time, and counterclockwise rotation produces gradual decreases and sudden increases in luminance. The sawtooth waveforms correspond only approximately to the illuminance changes occurring at each point in the retinal image of the rotating disk, since the luminance gradient in the disk is stepwise rather than smooth. Momentary apparent brightness roughly follows the sawtooth waveform of objective luminance. Average apparent brightness is greater for clockwise rotation. Exposure to gradually increasing luminance (clockwise rotation) produces an aftereffect of apparent dimming in a subsequently presented stationary uniform gray disk of intermediate luminance. Exposure to gradually decreasing luminance (counterclockwise rotation) produces an aftereffet of brightening (from Walker, 1974).

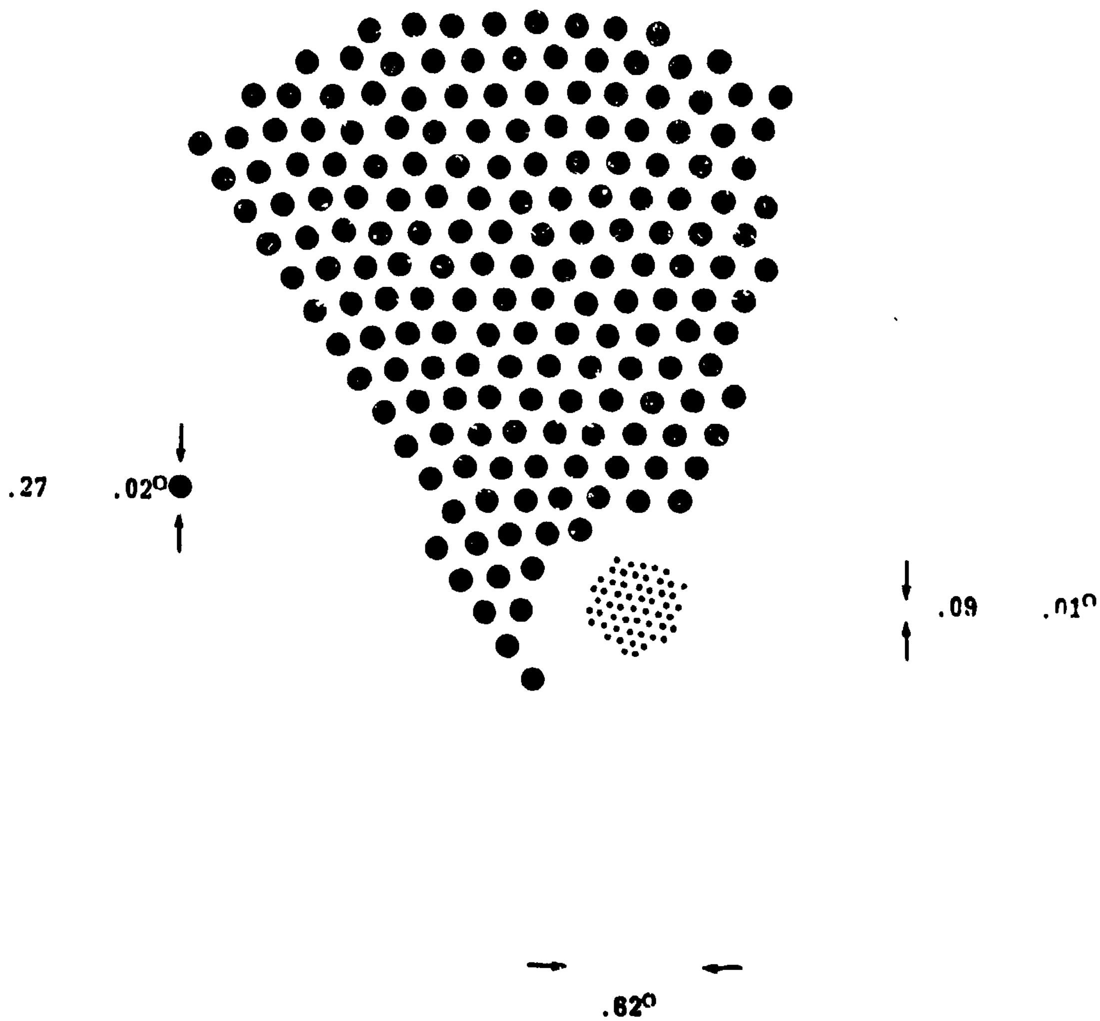

Figure 57. Main contours of the honeycomb pattern. The measurements are expressed in visual angle (mean ± 1 S.E.M., n = 5) (from Young, Cole, Gamble, & Rayner, 1975).

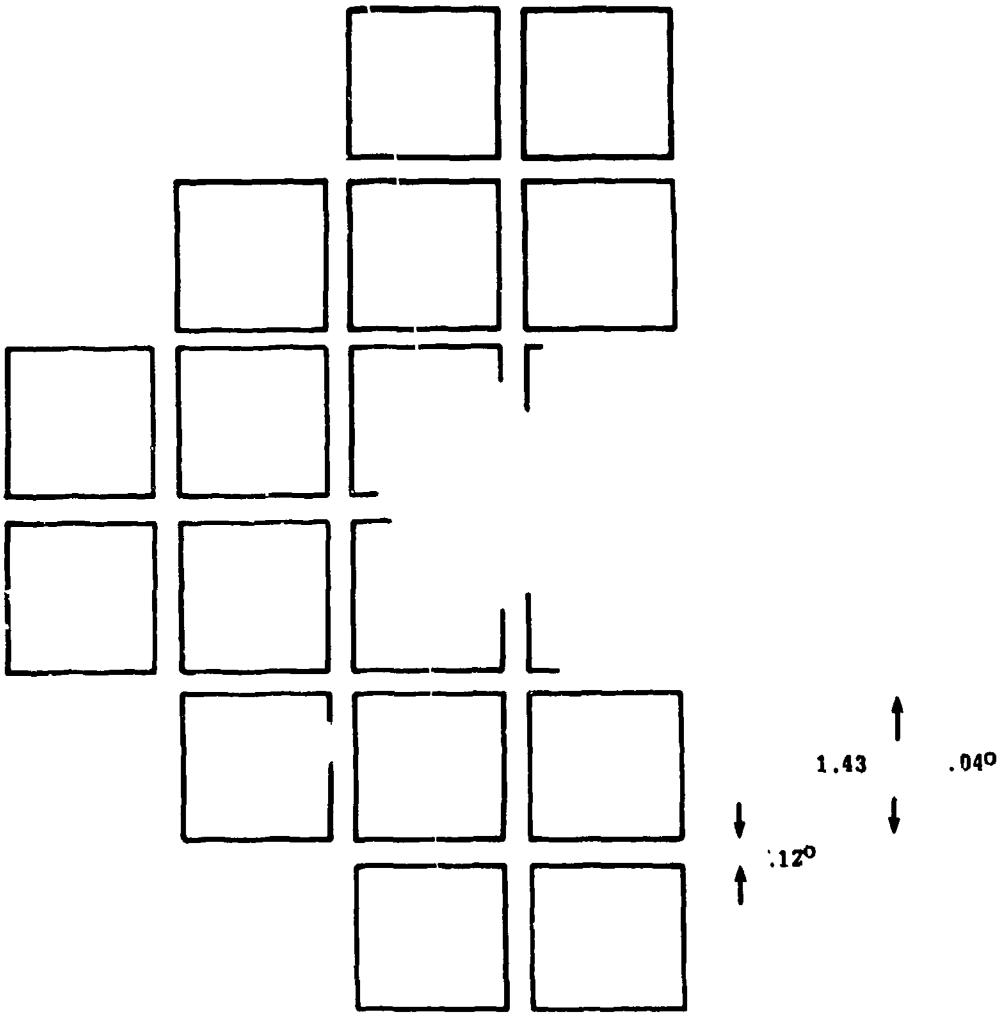

Figure 58. Main contours of the grid pattern. The measurements are expressed in visual angle (m... ± 1 S.E.M., n = 5) (from Young, Cole, Gamble, & Rayner, 1975).

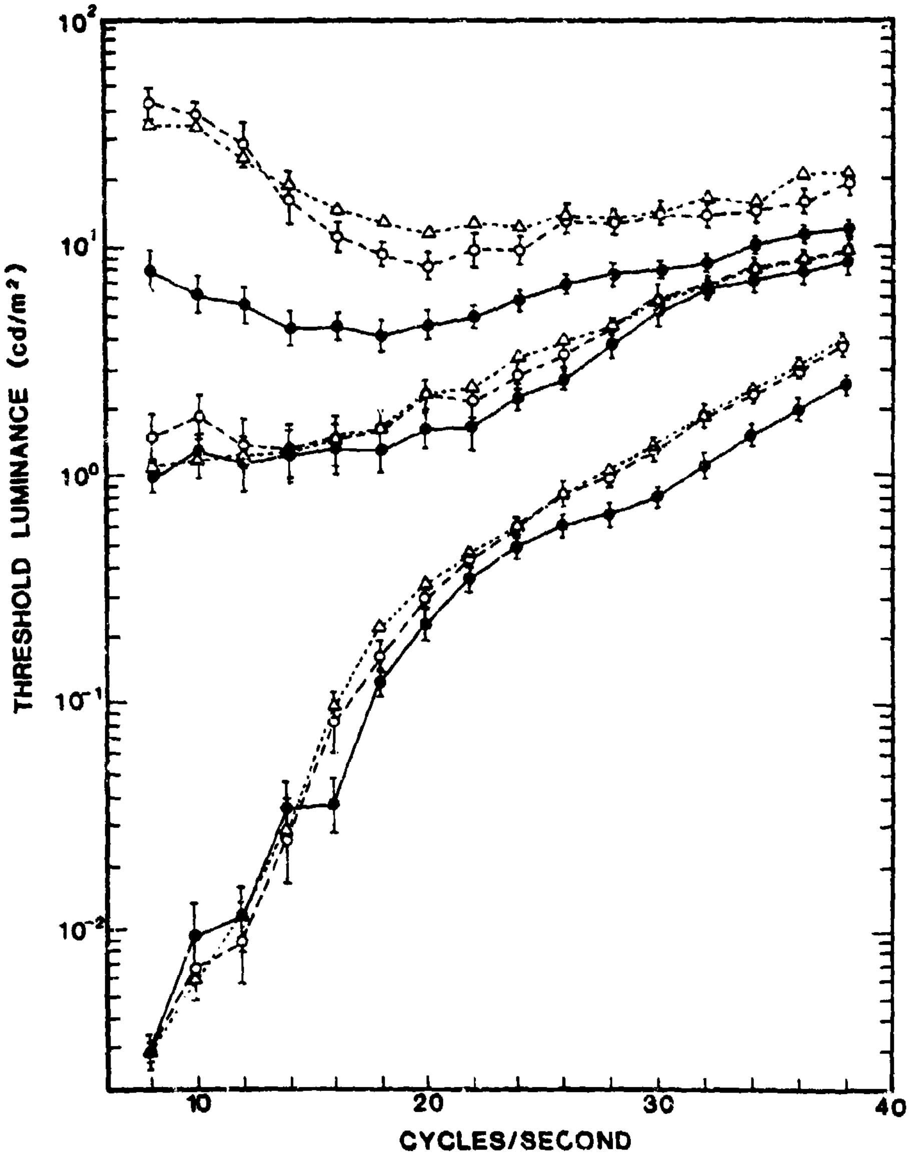

Figure 59. Luminance thresholds for geometrical patterns (upper curves), diffuse patterns (intermediate curves), and flicker (lower curves). Right eye, O, left eye, Δ, both eyes together, ● (from Remole, 1973a).

Presenting a grating as a short flash (in this case contrast is modulated rather than luminance) produces an increase in the apparent spatial frequency if the flash duration is in the range of 20 to 60 msec (Tynan & Sekuler, 1974; Kulikowski, 1975). Both found the effect was optimal for low spatial frequencies (Figure 60, from Kulikowski). Kulikowski found up to a 30% increase in spatial frequency while Tynan and Sekuler found only 10%. This difference, as we shall see, may be due to the different mean luminances used: 5 and .2 cd/m^2 respectively.

Virsu and Nyman (1974) found a very similar effect when they turned the contrast of a grating on and off at a rate of eight Hz (60 msec "on" time, see Figure 61.) Again low spatial frequencies produce the greatest effect, and optimal contrast was about .4. The effect was greatest at photopic luminance levels.

More complex types of temporal modulation may produce even greater increases in the apparent spatial frequency of a grating. Reversing the phase of a grating at a high rate (sometimes called counter-phase flicker) may double the spatial frequency (Kelly, 1966; Richards & Felton, 1973; Kulikowski, 1975; Virsu, Nyman, & Lehjio, 1974). In this case, the higher the temporal frequency (below CFF) the closer the pattern comes to doubling its apparent spatial frequency. Though this type of flicker would be rare in an applied setting, Virsu, et al. (1974) increased apparent frequencies by up to four times, using multiphase flicker. Note that the spatial frequency increases caused by the "on" - "off" types of displays seem to be distinctly different from those due to flicker accompanied by phase changes.

Findings by Erlebacher and Sekuler (1974) suggest that these similar distortions may occur in non-repetitive targets. They looked at the effect of flash duration on the perceived length of a thin 2.6° line of 28 cd/m^2 luminance, presented against a dim background. As duration was reduced from 20 to 30 msec, line length reduced by about 4%. Although small, the effect would probably be greater for figures of greater area and higher luminances.

There is at least one case when flashing makes a target seem longer than it is. Burns, Mandl, Pritchard, and Webb (1969) found that if a dim, 13' diameter spot was flashed against a dim background at a location 10 deg in the periphery for a duration of 10 to 50 msec, it often appeared as a line of 5' to 30' in length, and was, indistinguishable from a real line. The orientation of these illusory lines was usually close to horizontal, but when two dots were flashed and both looked like lines, they did not always have the same orientation. This means that the lines were not caused merely from visual smearing of the dots due to eye movements. The effect is not critically dependent on location, luminance, or duration.

One case has already been mentioned, in which an observer sees color although no chromatic objects are present: occurring along with the illusory figures seen when viewing a large flickering field. However, there are other color effects for which specific colors are determined by specific temporal waveforms of achromatic objects. Most

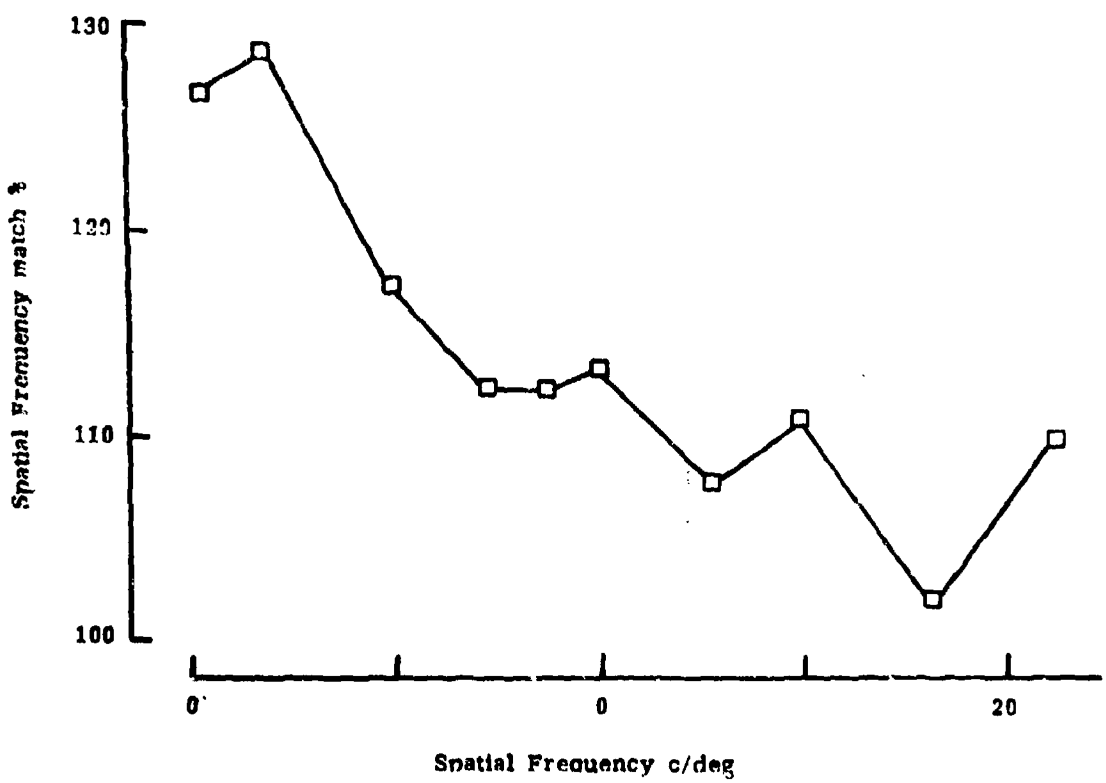

Figure 60. Spatial frequency match at a contrast of 0.5 and at a presentation time of 50 msec (from Kulikowski, 1975).

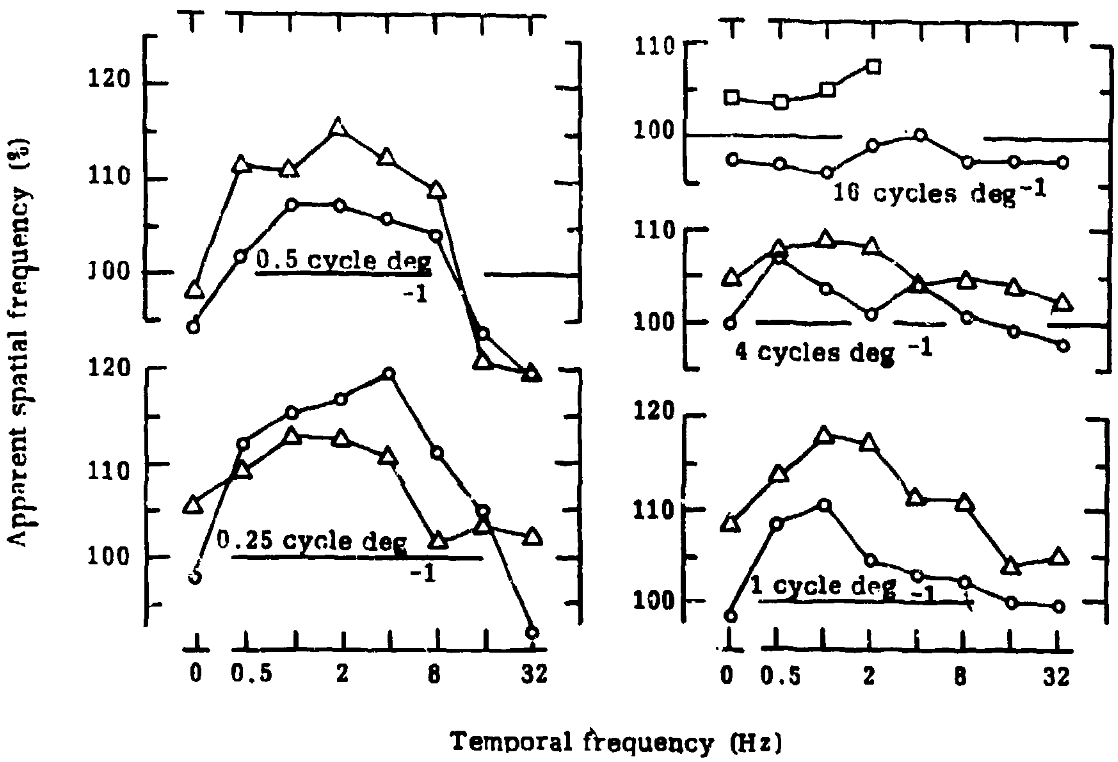

Figure 61. Apparent spatial frequency as a function of temporal frequency, spatial frequency, and adaptation level. Contrast 0.82; adaptation level for the comparison grating was a constant 5 td. (from Virsu & Nyman, 1974).

of this work has been done with a spinning disk type of stimulus called "Benham's top" (see Figure 62, from Sheppard, 1968). Three circular bands are seen when this disk is spun and each one has a different color. For a review of this work, see Cohen and Gordon (1949). These reviewers point out, however, that these subjective or illusory colors may also be produced with just flickering lights. In fact, Festinger, Allyn, and White (1971) have in a way "cracked the code" of subjective colors, and by using various complex temporal waveforms can produce almost any color.

Sheppard (1968) reports that rather simple temporal waveforms can produce subjective colors in black and white photographs or on black and white television. In fact, before color television became common, "colored" television commercials were broadcast in Europe by flickering the image. The colors occur at temporal frequencies between 5 and 10 Hz and at a pulse-to-cycle fraction of one-eighth or one-fourth.

Campenhausen (1973) found that the visual system is very sensitive to changes in the temporal relationships that produce colors in displays like Benham's top. A change in phase of less than one msec between the flicker in two parts of the top produces a noticeable change in color. If these effects are applicable to a large population of observers, it might be possible for a display to transmit information about subtle changes in the temporal relationships among the elements of a complex system by making use of these color effects. See also Carter (1980) for a review of how color improves search performance.

In addition to producing colors in achromatic objects, temporal modulation can distort the color of chromatic ones. Flash duration has two effects on color. Kinney (1965) found that colors desaturate as flash duration is reduced over a range of 400 to 50 msec. The author used both five and one degree diameter targets of 3.183 cd/m^2; desaturation was greater for the larger target. Luria (1967) and Kaiser (1968) demonstrated that short flashes of low luminance (less than 43 td and 300 ms in the latter case) produced artificial tritanopia or "blue blindness". One consequence of this blindness is a loss of the ability to differentiate colors in the blue-green part of the spectrum.

Flicker also produces dramatic changes in perceived color. Ball and Bartley (1966), and van der Horst and Muis (1969) found that colors at the low end of the spectrum looked like colors normally associated with shorter wavelengths; reds, for instance, looked more like orange or yellow. Very short wavelengths, however, appeared more like colors associated with longer wavelengths (see Figure 63). In addition, Ball and Bartley (1966) noticed considerable desaturation of short wavelength colors. These effects occurred only at luminances above 1600 cd/m^2, and Nelson and Bartley (1961) found that a pulse-to-cycle fraction of about .25 was optimal for producing both the hue shifts and desaturation effects. These effects coincide closely with brightness enhancement (van der Horst & Muis, 1969).

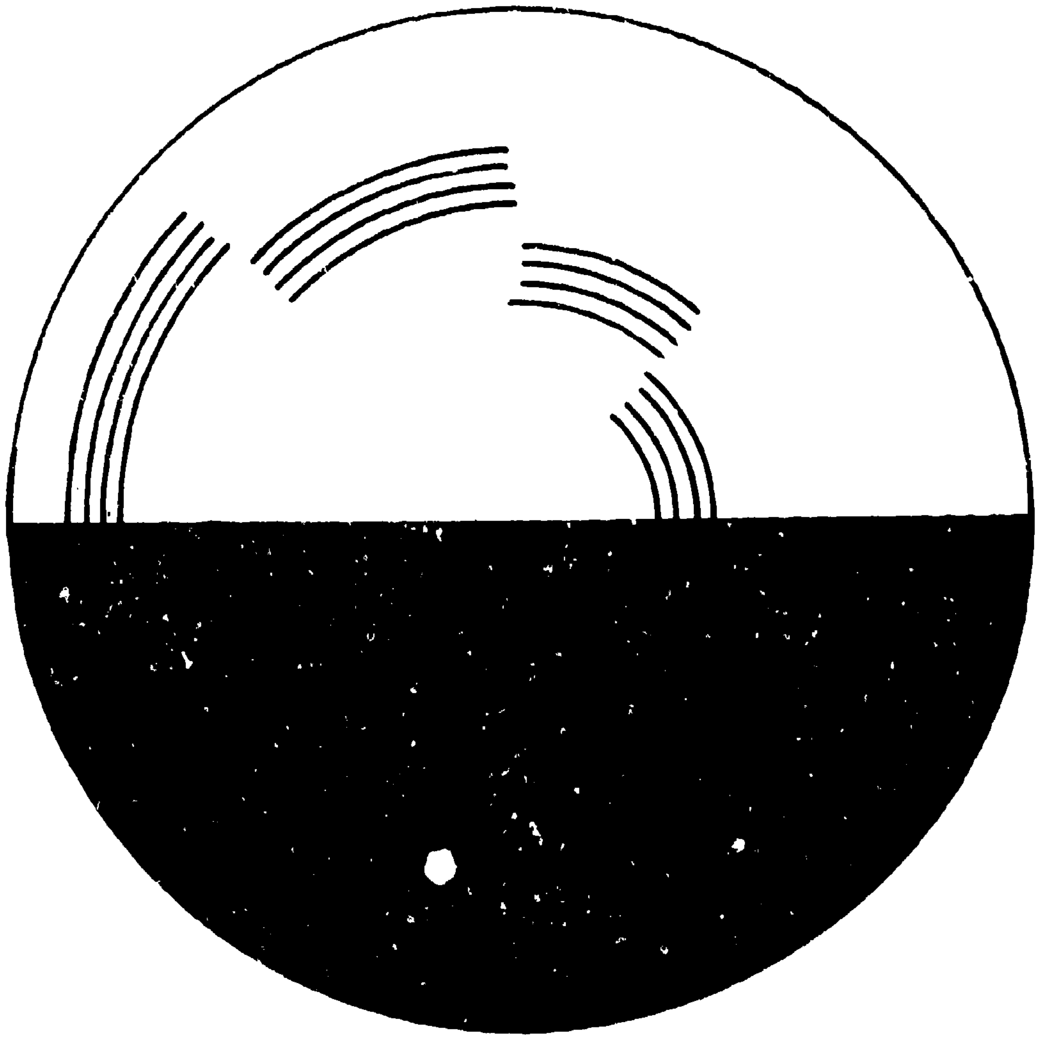

Figure 62. Benham's top (from Sheppard, 1968).

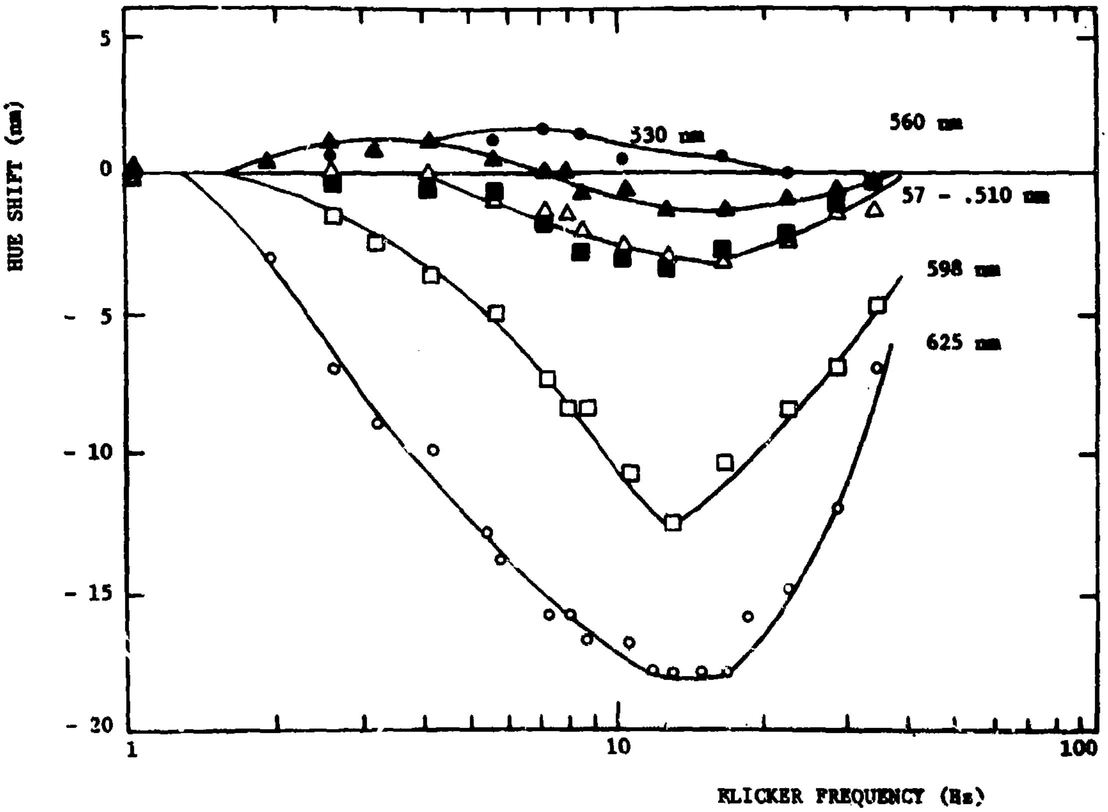

Figure 63. The hue shift as a function of flicker frequency for several wavelengths. Retinal illuminance 4800 td (from van der Horst and Muis, 1969).

GLOSSARY

Absolute motion threshold: the minimum velocity of an object at which an observer can tell that the object is moving.

Adaptation level: the observer's sensitivity to light, determined by the mean luminance of the display and by how long the observer has been exposed to this mean luminance. It takes only five to ten minutes to adapt to photopic luminance, but 20 to 40 minutes to adapt to scotopic luminance. This term is often used interchangeably with "mean luminance", but in these cases it is assumed that the observer has adapted to the mean luminance level.

Ansbacher effect: the apparent shrinkage of a bright, rotating arc.

Apparent motion: the illusion of motion between two sequentially presented, spatially separated objects.

Aubert-Fleischl phenomenon: a moving object appears faster when tracked with the eyes than when the observer fixates on some stationary object in the display.

Autokinetic effect: a small light viewed in an otherwise dark room will appear to move in small random steps, presumably as a consequence of eye movements.

Benham's disk (or top): a disk with a black and white pattern on it that appears colored when rotated (see Figure 62).

Bloch's law: Below some critical duration, the percept is controlled by energy (the product of duration and luminance). Consequently, luminance and duration can be interchanged without changing the percept. Usually this law refers to the detection of a flashed target, but may refer to several other types of visual function (i.e., acuity, color naming, etc).

Broca-Sulzer effect: With increase in the duration of a flash, brightness increases up to a maximum and then declines with further increase. The "enhancement" of brightness at a particular duration is the Broca-Sulzer effect.

Brücke-Bartley effect: The brightness of an intermittent (flickering) light is enhanced over that of a steady light of the same mean luminance when the intermittency is on the order of 8 - 13 Hz.

CFF (Critical flicker frequency): the frequency of a flickering light above which the light appears to glow steadily.

Contrast: for a patterned display, the ratio between the bright and dark parts of the pattern. Several formulas for contrast are given in Appendix B.

Difference limen or threshold: the minimum perceptible change in a stimulus.

Extended source: a luminous object that is larger than about 20' of arc.

Ferry-Porter law: The critical flicker frequency (CFF) increases with the log of the luminance of the flickering object.

Ganzfeld: from the German meaning "whole field"; a homogeneous field that fills the entire visual field of the observer. Standing in very dense fog would produce a Ganzfeld.

Granit-Harper law: The critical flicker frequency (CFF) increases with the log of the area of the flickering object.

Illuminance: the effectiveness of a source of light such as a light bulb in stimulating the human eye. The standard measure is the lumen.

Induced motion: the illusory motion produced in a stationary object by the motion of other objects around it, or the modification of the perceived motion of a moving object by those around it.

Korte's Laws: a set of simple equations that relate various determinents of apparent movement and predict, somewhat imperfectly, the conditions under which apparent movement ought to be seen most strongly.

Landolt ring or "C": A common stimulus for measuring acuity, it is a high contrast circle with a small gap in one of four locations -- up, down, left, or right. The observer's task is to indicate the position of the gap. The tester uses rings with various size gaps to measure the observer's acuity.

Linearvection: the illusion of self-movement when moving contours stimulate an observer's peripheral field of view.

Luminance: the ability of an <u>extended</u> light source such as reflective paper to stimulate the human eye. The most common measure is candelas per square meter (cd/m^2).

Mach bands: the illusory enhancement of contrast near the border between two areas of different luminance.

MAE (Motion aftereffect): the illusion of motion of a stationary object after prolonged observation of moving contours. The illusory motion is in a direction opposite that of the previously seen motion.

Mesopic luminance: the luminance range between photopic and scotopic.

Photopic luminance: luminances above about 10 cd/m^2 or 100 td.

Point source: as a rule of thumb (although there is no universal agreement), a source smaller than about 20 minutes of arc.

Scotopic luminance: luminances below about 10^{-3} cd/m² or 5 X 10^{-2} td.

Suprathreshold: above the minimum signal strength needed to detect, this term usually denotes that the object or signal is easily detected.

Talbot's law: At frequencies above flicker fusion, brightness is proportional to time-average luminance. Usually it assumed that the brightness of the "Talbot level" and that of a steady light of the same time-average luminance are equal.

Troland (td): a unit of retinal illuminance that takes into account the area of the pupil through which the stimulus is viewed. On the assumption that the light passing through the pupil is proportional to its area, the product of luminance and pupillary area describes retinal illuminance. One troland is produced when a luminance of 1 cd/m² is viewed through a pupil of 1 mm² (see Appendix A).

Visual angle: the arc tangent of the target size divided by the distance of the observer from the target. This provides a standard unit for the size of the image of an object on the retina.

Visual masking: the decrement in the visibility of a target due to the presence of another target in close spatial and/or temporal proximity to it.

Visual persistence: the extension of the visual effects of a flash beyond the offset of the flash itself.

Weber's law: used to describe the case when difference threshold along some stimulus dimension is proportional to the strength of the signal (i.e., $\frac{\Delta I}{I}$ = a constant, where ΔI is the difference threshold of I, the signal level).

APPENDIX A

The troland (td) is the unit of illuminance on the retina. It is often preferred to measures of luminance for experiments that examine the effects of changes in stimulus luminance because it eliminates variation in the effective stimulus which come from changes in pupil size. The formula for computing trolands is

$$\text{Trolands} = (\text{luminance in cd/m}^2) \times (\text{area of pupil in mm}^2)$$

where area $= 1/4 . \pi . D^2$ (D denotes the diameter of the pupil).

In most experiments which use the troland unit, the pupil diameter is controlled by placing a small aperture very close to the observer's eye. This "artificial" pupil is always smaller than that of the natural pupil so that effective pupil size remains constant across changes in light level, or the momentary physiological state of the observer.

It is difficult to compare two sets of data when the luminance in one case is in troland units and in the other case is in units of stimulus luminance, because in the latter case the size of the pupil, in this case the natural pupil, is unknown. Yet the data collected in units of luminance may be more valuable to the applied scientist because artificial pupils are unlikely to occur in the applied setting. One way around the problem of comparing data given in units of retinal illuminance to those given in luminance units is to take advantage of tables which give the average expected pupil diameters for observers of different ages at various luminance levels.

APPENDIX B

Contrast is the ratio of luminance in the brightest and darkest parts of the visual field, but this ratio is calculated in several different ways depending on the nature of the stimulus. For displays consisting of one or a group of separate objects, such as letters, spots, figures, etc., the most common formula for contrast is:

$$\text{contrast} = \frac{L_t - L_b}{L_b} \qquad (1)$$

where L_t is target luminance and L_b is background luminance.

If the pattern is repetitive, such as sinusoidal or square-wave bars, the contrast of the pattern is represented by:

$$\text{contrast} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \qquad (2)$$

where L_{max} is the maximum luminance in the pattern and L_{min} is the minimum luminance. This ratio is sometimes multiplied by 100 and called the "percent modulation" of the pattern. Notice that this ratio varies only between zero and one, while the ratio calculated by equation (1) can assume any value.

APPENDIX C

Our primary data base has been Robert Sekuler's index file of several thousand articles. Also, Commander Robert Kennedy of the Naval Biodynamics Laboratory (now of the Canyon Research Group) allowed us the use of his article files. In addition, we searched through Ergonomics Abstracts from 1969 to the present, Psychological Review and Psychological Bulletin from 1968 to the present, and all of Human Factors. We also searched two more data bases through Northwestern University's computer-assisted information service. The first was Psychological Abstracts data base (1967-present), and the search yielded 679 printouts at a cost of $74.40. The other was the U. S. National Technical Information Service data base (1964-present), which yielded 67 printouts at a cost of $74.60. We estimate that the proportion of these articles that actually were incorporated into this review was less than ten percent. Many of the articles that were used in the final version of this review were not found in the search phase of this project, but were referenced by the articles we initially started to read.

Our main difficulty was obtaining articles of an applied orientation. Many had to be ordered through NTIS on microfilm, and others were difficult to obtain because they were University or corporation in-house reports. Luckily, Commander Robert Kennedy's files provided us with some of this material.

BIBLIOGRAPHY

Aarons, L. Visual apparent movement research: Review, 1935-1955, and Bibliography, 1955-1963. Percept. Mot. Skills, 1964, 18, 239-274.

Ailslieger, R. E., & Dick, R. D. The influence of an intermittent visual stimulus on perceptual motor skills in aviation. Human Fact., 1966, 8, 569-572.

Alderson, G. J. K., & Whiting, H. T. A. Prediction of linear motion. Human Fact., 1974, 16, 495-502.

Alexander, K. R. Intermittency in presentation increases identification of masked figures. Percept. & Psychophys., 1970, 7, 223-224.

Allan, L. G., Kristofferson, A. B., & Wiens, E. W. Duration discrimination of brief visual stimuli. Report N71-28068, 1970.

Anglin, J. M., & Mansfield, R. J. W. On the brightness of short and long flashes. Percept. & Psychophys., 1968, 4, 161-162.

Anstis, S. M. Visual adaptation to gradual change in intensity. Science, 1967, 155, 710-712.

Anstis, S. M., Gregory, R. L., Rudolf, N., & MacKay, D. M. Influence of stroboscopic illumination on the aftereffect of seen movement. Nature, 1963, 199, 99-100.

Arend, L. E. Spatial factors in the Broca-Sulzer phenomena. J. Op. Soc. Am., 1973, 63, 879-883.

Asnbacher, H. L. Distortion in the perception of real movement. J. Exp. Psych., 1944, 34, 1-23.

Baker, K. E. Threshold exposure duration as a function of luminance for visual recognition. Percept. & Psychophys., 1969, 6, 147-152.

Ball, K. Effects of stmulus uncertainty and external noise on mechanisms of motion perception. Masters Thesis at Northwestern University, 1977.

Ball, R. J., & Bartley, S. H. Changes in brightness index, saturation, and hue produced by luminance-wavelength-temporal interactions. J. Op. Soc. Am., 1966, 56, 695-699.

Banks, W. P., & Kane, D. A. Discontinuity of seen motion reduces the motion aftereffect. Percept. & Psychophys., 1972, 12, 69-72.

Baron, W. S., & Westheimer, G. Visual acuity as a function of exposure duration. J. Op. Soc. Am., 1973, 63, 212-219.

Bartlett, N. R., & MacLeod, S. Effect of flash and field luminance on human reaction time. J. Op. Soc. Am., 1954, 44, 306-311.

Bartley, S. H. Subjective flicker rate with relation to critical flicker frequency. Percept. & Psychophys., 1938, 22, 388-394.

Bartley, S. H. Brightness enhancement in relation to target intensity. J. Psych., 1951, 32, 57-62.

Bartley, S. H., & Nelson, T. M. A further study of pulse-to-cycle fraction and critical flicker fusion: A decisive theoretical test. J. Op. Soc. Am., 1961, 51, 41-45.

Bartley, S. H., Nelson, T. M., & Soules, E. Visual acuity conditions of intermittent illumination productive of paradoxical brightness. J. Psych., 1963, 55, 153-163.

Bartley, S. H., Paczewitz, G., & Valsi, E. Brightness enhancement and the stimulus cycle. J. Psych., 1957, 43, 187-192.

Basler, A. [Motion perception Report I.: Perception of minute movements. Report] (translated from Pflugers Archive Fur Die Gesamte Physiol, 1906, 115, 582-601) #NASA-TT-F-16186, 1975, 25 pp.

Baumgardt, E., & Hillman, B. Duration and size as determinants of peripheral retinal response. J. Op. Soc. Am., 1961, 51, 340-344.

Beck, J., & Stevens, A. An aftereffect to discrete stimuli producing apparent movement and succession. Percept. & Psychophys., 1972, 12, 482-486.

Benson, A. J., & Guedry, F. E. Comparison of tracking task performance and nystagmus during sinusoidal oscillation in yaw and pitch. Aerospace Med., 1971, 42, 593-601.

Biederman-Thorson, M., Thorson, J., & Lange, G. D. Apparent movement due to closely spaced sequentially flashed dots in the human peripheral field of vision. Vis. Res., 1971, 11, 889-903.

Bird, J. F., & Mowbray, G. H. Visual transient phenomenon: its polarity and paradox. Science, 1969, 165, 583-589.

Bird, J. F., & Mowbray, G. H. Analysis of transient visual sensations about the flicker fusion frequency. Vis. Res., 1973, 13, 673-687.

Bonnet, C. A tentative model for visual motion detection. Psychologia, 1975, 18, 35-50.

Bonnet, C., & Pouthas, V. Interactions between spatial and kinetic dimensions in movement aftereffect. Percept. & Psychophys., 1972, 12, 193-200.

Boring, E. G. Sensation and Perception in the History of Experimental Psychology. New York: Appleton-Century-Crofts, 1942.

Borkenhagan, J. M. Rotary acceleration of a subject inhibits choice reaction time to motion in peripheral vision. J. of Exp. Psych., 1974, 102, 484-487.

Bourassa, C. M., & Bartley, S. H. Some observations on the manipulation of visual acuity by varying the rate of intermittent stimulation. J. Psych., 1965, 59, 319-328.

Boynton, R. M. Discrimination of homogeneous double pulses of light. In D. Jameson, & L. M. Hurvich, (Eds.), Handbook of Sensory Physology, Vol. VII/4, New York: Springer-Verlag, 1972.

Bracewell, R. The Fourier Transform and Its Applications. McGraw-Hill Electrical and Electronic Engineering Series. New York: McGraw-Hill, 1965.

Braddick, O. The masking of apparent motion in random-dot patterns. Vis. Res., 1973, 13, 355-369.

Braddick, O. A short-range process in apparent motion. Vis. Res., 1974, 14, 519-527.

Bradley, D. R. The apparent size of the path traversed by a rotating target during saccadic and smooth pursuit: New data on the shrinking circle illusion. Percept. & Psychophys., 1977, 22, 183-190.

Brandalise, B. B., & Gottsdanker, R. M. The difference threshold of the magnitude of visual velocity. J. Exp. Psych., 1959, 57, 83-88.

Brandt, T., Dichgans, J. & Koenig, E. Differential effects of central versus peripheral veision on egocentric and exocentric motion perception. Exp. Brain Res., 1973, 16, 476-491.

Braunstein, M. L. Interaction of flicker and apparent motion. J. Op. Soc. Am., 1966, 56, 835-836.

Breitmeyer, B., Love, R., & Wepman, B. Contour suppression during stroboscopic motion and metacontrast. Vis. Red., 1974, 14, 1451-1456.

Bridgeman, B., Mayer, M., & Glenn, L. Figure distortion accompanying pursuit eye movement. Vis. Res., 1976, 16, 431-433.

Brink, van den, G., & Bouman, M. A. Variation of integrative actions in the retinal system: An adaptation phenomenon. J. Op. Soc. Am., 1965, 44, 616-626.

Brooke, R. T. The variation of critical flicker frequency with brightness at various retinal locations. J. Op. Soc. Am., 1951, 41, 1010-1016.

Brosgole, L., Cristal, R. M., & Carpenter, O. The role of eye movements in the perception of visually induced motion. Percept. & Psychophys., 1968, 3, 166-168.

Brown, B. Dynamic visual acuity, eye movements and peripheral acuity for moving targets. Vis. Res., 1972, 12, 305-321. (a)

Brown, B. The effect of target contrast variation on dynamic visual acuity and eye movements. Vis. Res., 1972, 12, 1213-1224. (b)

Brown, B. Resolution thresholds for moving targets at the fovea and in the peripheral retina. Vis. Res., 1972, 12, 293-304. (c)

Brown, H. C. The relation of flicker to stimulus area in peripheral vision. Arch. Psych., 1945, #298, 41, 1-61.

Brown, J. F. Thresholds for visual movement, In I. M. Spigel (Ed.). Readings in the study of visually perceived movement. New York: Harper and Row, 1965. (a)

Brown, J. F. The visual perception of velocity, In I. M. Spigel (Ed.). Readings in the study of visually perceived movement. New York: Harper and Row, 1965, 64-107. (b)

Brown, J. L. Flicker and intermittent stimulation, In C. H. Graham (Ed.). Vision and Visual Perception. New York: John Wiley & Sons, 1965.

Brown, J. L., & Black, J. E. Critical duration for resolution of acuity targets. Vis. Res., 1976, 16, 309-315.

Brown, R. H. Influence of stimulus luminance upon the upper speed threshold for the visual discrimination of movement. J. Op. Soc. Am., 1958, 48, 125-128.

Brown, R. H. Visual sensitivity to differences. Psych. Bull., 1961, 58, 89-103. (a)

Brown, R. H. Visual estimate of airplane speed. Human Factors, 1961, 3, 284-285. (b)

Brown, R. H., & Conklin, J. E. The lower threshold of visible movement as a function of exposure time. Am. J. of Psychol., 1954, 67, 104-110.

Burns, B. D., Mandl, G., Pritchard, R., & Webb, C. The perception of briefly exposed point sources of light. Quart. J. Exp. Psych., 1969, 21, 299-311.

Campenhausen, Von, C. Detection of short time delays between photic stimuli by means of pattern induced flicker color (PIFCs). Vis. Res., 1973, 13, 2261-2272.

Carpenter, P. A., & Ganz, L. At attentional mechanisms in the analysis of spatial frequency. Percept. & Psychophys., 1972, 12, 57-60.

Carter, R. C. Visual search with color (Doctoral dissertation, Pennsylvania State University, 1979). (Monograph NBDL-M005). New Orleans: Naval Biodynamics Laboratory, 1980.

Cheatham, P. G., & White, C. T. Temporal numerosity: Perceived number as a function of flash number and rate. J. Exp. Psych., 1952, 44, 447-451.

Cohen, J., & Gordon, D. A. The Prevont-Fechner-Benham subjective colors. Psych. Bull., 1949, 46, 47-136.

Cohen, R. L., & Bonnet, C. Movement detection thresholds and stimulus duration. Percept. & Psychophys., 1972, 12, 269-272.

Collyer, C. E. Discrimination of spatial and temporal intervals defined by three light flashes: Effects of spacing on temporal judgments and or timing on spatial judgments. Percept. & Psychophys., 1977, 12, 357-364.

Coren, S., Bradley, D. R., Hoenig, P., & Girgus, J. S. The effect of smooth tracking and saccadic eye movements on the perception of size: The shrinking circle illusion. Vis. Res., 1975, 15, 49-55.

Croft, T. A. Failure of visual estimation under strobe. Nature, 1971, 231, 397.

Dawson, W. W., & Harrison, J. M. Bloch's law for brief flashes of large angular subtense. Percept. Mot. Skills, 1973, 36, 1055-1061.

Day, R. H. The effect of small brightness differences on the aftereffect of seen movement. Quart. J. Exp. Psych., 1958, 10, 166-170.

Day, R. H. Apparent contraction and disappearance of moving objects in the peripheral visual field. Vis. Res., 1973, 13, 959-975.

Day, R. H., & Strelow, E. R. Visual aftereffect of movement: Partial or complete reduction in the absence of a patterned surround. Nature, 1971, 230, 55-56.

Dichgans, J., & Brandt, T. The psychophysics of visually induced perception of self-motion and tilt. In I.D. Schmidt & F. G. Worden (Eds.), The Neurosciences. Cambridge, Mass.: MIT Press, 1973.

Diener, H. C., Wist, E. R., Dichgans, J., & Brandt, T. The spatial frequency effect on perceived velocity. Vis. Res., 1976, 16, 169-176.

Dillon, D. J. Variability of flicker fusion thresholds. Percept. Mot. Skills, 1963, 17, 666. (a)

Dillon, D. J. Wavelength, area, and intensity as determinants of the flicker-fusion threshold. Percept. Mot. Skills, 1963, 17, 659-661. (b)

Domey, R. G. Statistical properties of foveal CFF as a function of age, bright dark ratio and surround. J. Op. Soc. Am., 1964, 54, 394-398.

Duncker, K. Induced motion. Originally in Psychol. Forch., 1929, 12, 180-259, as reprinted In W. Ellis (Ed.), Source Book of Gestalt Psychology. New York: Humanities Press Inc., 1955.

Dureman, I. Factors influencing the apparent velocity of visual movement after-effects. Scand. J. Psychol., 1962, 3, 132-136.

Efron, R. The duration of the present. Annals N.Y. Academy of Science, 1967, 138, 713-729.

Ellingstad, V. S., & Heimstra, N. W. Velocity-time estimation as a function of target speed and concealment extent. Human Fact., 1969, 11, 305-312.

Eriksen, C. W., & Colgate, R. L. Identification of forms at brief durations when seen in apparent moton. J. Exp. Psych., 1970, 84, 137-140.

Eriksen, C. W., & Collins, J. F. Some temporal characteristics of visual pattern perception. J. Exp. Psych., 1967, 74, 476-484.

Eriksen, C. W., & Collins, J. F. Sensory traces versus physiological movement in the temporal organization of form. J. Exp. Psych., 1968, 77, 376-382.

Eriksson, E. S. Visual disappearance of a motion, pattern. Psychonomic Science, 1969, 17, 85-86.

Erlebacher, A., & Sekuler, R. Perceived length depends on exposure duration: Straight lines and Muller-Lyer stimuli. J. Exp. Psych., 1974, 103, 724-738.

Ettinger, G. The fusion frequency of flicker in the central and peripheral field with photopic levels of surround luminance. Quart. J. Exp. Psych., 1959, 47, 317-330.

Fankhauser, R., & Schmidt, T. Die Optimalen Bedingungen fur die Untersuschung der Raumlichen Summation mit Stehender Reizmarke nach der Methode der Quantitativen Lichtsinnperimetric. Ophthalmologica, 1960, 139, 409-415.

Favreau, O. P., Emerson, V. F., & Corballis, M. C. Motion perception: A color-contingent after-effect. Science, 1972, 176, 78-79.

Fergenson, P. E., & Suzansky, J. W. An investigation of dynamic and static visual acuity. Perception, 1973, 2, 343-356.

Festinger, L., Allyn, M. R., & White, C. W. The perception of color with achromatic stimulation. Vis. Res., 1971, 11, 591-612.

Festinger, L., & Eastman, M. Inferences about the efferent system based on a perceptual illusion produced by eye movements. Psych. Review, 1974, 81, 44-58.

Foley, P. J. Interrelationships of background area, target area and target luminance in their effect on the initial flicker frequency of the human fovea. J. Op. Soc. Am., 1961, 51, 737-740.

Foley, P. J., & Kazdan, J. Area - intensity relations within the fovea for flickering whte and part-spectrum targets. J. Op. Soc. Am., 1964, 55, 547-550.

Ford, A., White, C. T., & Lichtenstein, M. Analysis of eye movements during free search. J. Op. Soc. Am., 1959, 49, 287-292.

Forsyth, D. M., & Brown, C. R. Non-linear property of the visual system at fusion. Science, 1961, 134, 612-614.

Forsyth, D. M., & Chapanis, A. Counting repeated light flashes as a function of their number, their rate of presentation and retinal location stimulated. J. Exp. Psych., 1958, 56, 385-391.

* Ganz, L. Temporal factors in visual perception. In E. D. Carterett, & M. P. Friedman, (Eds.), Handbook of Perception, Vol. V, New York: Academic Press, 1975.

Gebhard, J. W., Mowbray, G. H., & Byham, C. L. Difference-limens for photic intermittence. Quart. J. Exp. Psych., 1955, 7, 49-55.

Gerathewohl, S. J. Conspicuity of steady and flashing light signals: Variation of contrast. J. Op. Soc. Am., 1953, 43, 567-571.

Gerathewohl, S. J. Conspicuity of flashing light signals of different frequency and duration. J. Exp. Psych., 1954, 48, 247-251.

Gerathewohl, S. J., & Taylor, W. Effect of intermittent light on the readability of printed matter under conditions of decreasing contrast. J. Exp. Psych., 1953, 46, 278-282.

Gerhard, D. J. The judgment of velocity and prediction of motion. Ergonomics, 1959, 2, 287-304.

Gibbons, K., & Howarth, C. I. The effect of intermittent illumination on the visual acuity threshold. Quart. J. Exp. Psych., 1962, 14, 167-175.

Gibson, J. J. The visual perception of objective motion and subjective movement. Psych. Rev., 1954, 61, 304-314.

Gibson, J. J., Smith, O. W., Steinschneider, A., & Johnson, C. The relative accuracy of visual perception of motion during fixation and pursuit. Am. J. Psych., 1957, 70, 64-68.

Gillingham, K. K., & McNaughton, G. B. Visual field contraction during G stress at 13°, 45°, and 65° seatback angles. Aviat. Space & Environ. Med., 1977, 48, 91-96.

Gilson, R. D. Lighting factors affecting the visibility of a moving display. Percept. & Psychophys., 1971, 10, 400-402.

Ginsburg, A. P. The perception of visual form: a two dimensional filter analysis. The IV Symposium on Sensory Systems in Visual Systems, Leningrad, USSR, 1976.

Ginsburg, N. Ascending - descending in CFF measurement as a function of eccentricity and starting point. J. Psych., 1967, 67, 161-167.

Ginsburg, N. Flicker fusion bibliography 1953-1968. Percept. Mot. Skills, 1970, 30, 427-430.

Giorgi, A. Effect of wavelength on the relationship between critical flicker frequency and intensity in foveal vision. J. Op. Soc. Am., 1963, 53, 480-486.

Glad, A., & Magnussen, S. Darkness enhancement in intermittent light: An experimental demonstration. Vis. Res., 1972, 12, 111-115.

Gogel, W. C., & Koslow, M. The adjacency principle and induced movement. Percept. & Psychophys., 1972, 11, 309-314.

Goldstein, A. L. Judgments of visual velocity as a function of length of observation time. J. Exp. Psych., 1957, 54, 457-461.

Goldstein, D. A., & Lamb, J. C. Visual coding using flashing light. Human Fact., 1967, 9, 405-408.

Goldstein, J., & Weiner, C. On some relations between the perception of depth and of movement. J. Psych., 1963, 55, 3-23.

Goodson, J. E., & Miller, J. W. Dynamic visual acuity in the applied setting. AD 620326, 1959.

Gordon, D. A. The relation between the thresholds of form, motion, and displacement, In Parafoveal and peripheral vision at a scotopic level of illumination. Am. J. Psych., 1947, 60, 202-225.

Gottsdanker, R. M. The ability of human operators to detect acceleration of target motion. Psych. Bull., 1956, 53, 477-487.

Gottsdanker, R. M. How the identification of target acceleration is affected by modes of starting and of ending. Brit. J. Psych., 1961, 52, 155-160.

Gottsdanker, R. M. Assessment of motion as influenced by structure of background. Scand. J. Psych., 1962, 3, 122128.

Gottsdanker, R. M., & Edwards, R. V. The prediction of collision. Am. J. Psych., 1957, 110-113.

Gottsdanker, R. M., Frick, J. W., & Lockard, R. B. Identifying the acceleration of visual targets. Brit. J. Psych., 1961, 52, 31-42.

Graham, C. H. Visual Perception. In S. S. Stevens, (Ed.), Handbook of Experimental Psychology, New York: John Wiley & Sons, 1951.

Graham, C. H. Perception of movement. In C. H. Graham (Ed.), Vision and Visual Perception. New York: John Wiley & Sons, 1965.

Graham, C. H. Depth and movement. Am. Psychologist, 1968, 23, 18-26.

Graham, C. H., Brown, R. H., & Smith, J. K. Brightness discrimination from varying durations of the just discriminable increment. Psychol. Record, 1937, 1, 229-233.

Granit, R. On inhibition in the after-effect of seen movement. Brit. J.Psych., 1928, 19, 147-157.

Grether, W. F. Visual search in the space environment. Human Fact., 1963, 5, 203-209.

van de Grind, W. R., Grüsser, O. J., & Lunkenheimer, H. U. Temporal transfer properties of the afferent visual system. In R. Jung (Ed.), Handbook of Sensory Physiology, Vol. VII/3, Springer-Verlag: Berlin, 1973.

Grindley, G. C., & Wilkinson, R. T. The after-effect of seen movement on a plain field. Quart. J. Exp. Psych., 1953, 5, 183-184.

Grossberg, M. The latency of response in relation to Bloch's law at threshold. Percept. & Psychophys., 1968, 4, 229-232.

Grossberg, M. Frequencies and latencies in detecting two-flash stimuli. Percept. & Psychophys., 1970, 7, 377-380.

Haber, R. H., & Hershenson, M. The psychology of visual perception. Ch. 6: Temporal Factors, In Visual Perception. New York: Rinehart & Winston, 1973.

Haber, R. H., & Standing, L. G. Direct estimates of apparent duration of a flash followed by visual noise. Canad. J. Psych., 1970, 24, 216-229.

Haines, R. F. A review of peripheral vision capabilities for display layout designers. Proceedings of the S.I.D., 1975, 16, 238-249.

Hamerman, J. A. Choice reaction time to movement of eccentric visual targets during concurrent rotary acceleration. Percept. & Psychophys., 1979, 26, 369-373.

Harmon, L. D. The recognition of faces. Image, object and illusion, Readings from Scientific American, W. H. Freeman & Co.: San Francisco, 1974, 100-112.

Harmon, L. D., & Julesz, B. Masking in visual recognition: Effects of two-dimensional filtered noise. Science, 1973, 180, 1194-1197.

Harvey, L. O., Jr., & Michon, J. A. Detectability of relative motion as a function of exposure duration, angular separation, and background. J. Exp. Psych., 1974, 103, 317-325.

Hecht, S., & Shlaer, S. Intermittent stimulation by light. V. The relation between intensity and critical frequency for different parts of the spectrum. J. Gen. Physiol., 1936, 19, 965-979.

Held, R., Dichgans, J., & Bauer, J. Characteristics of moving visual scenes influencing spatial organization. Vis. Res., 1975, 15, 357-366.

Held, R., & White B. Sensory deprivation and visual speed: An analysis. Science, 1959, 130, 860-861.

Hempstead, C. F. Motion perception using oscilloscope display. IEEE, 1966, 3, 128-135.

Henderson, D. C. The relationships between time, distance, and intensity as determinants of motion discrimination. Percept. & Psychophys., 1971, 10, 312-320.

Henderson, D. C. Visual discrimination of motion: Stimulus relationships at threshold and the question of luminance-time reciprocity. Percept. & Psychophys., 1973, 13, 121-130.

Henderson, R. L., & Burg, A. Vision and audition in driving. DOT Hs-801 265, 1974.

Herrick, R. M. Foveal luminance discrimination as a function of the duration of the decrement or increment in luminance. J. Comp & Physiol. Psych., 1956, 59, 437-443.

Herrick, R. M. Foveal increment thresholds for multiple flashes. J. Op. Soc. Am., 1973, 63, 7, 870-878. (a)

Herrick, R. M. Increment thresholds for multiple identical flashes in the peripheral retina. J. Op. Soc. Am., 1973, 63, 1261-1265. (b)

Herrick, R. M. Detection of short-duration light pulses presented in the periphery. NADC 73115-40, 1973. (c)

Herrick, R. M. Foveal light-detection thresholds with two temporally spaced flashes: A review. Percept. & Psychophys., 1974, 15, 361-367.

Herrick, R. M., & Theisen, C. J., Jr. Increment thresholds for two non-identical flashes. J. Op. Soc. Am., 1972, 62, 583-593.

Hick, W. E. The threshold for sudden changes in the velocity of a seen object. Quart. J. Exp. Psych., 1950, 2, 33-41.

Holland, H. C. The archimedes spiral. Nature, 1957, 179, 432-435.

Holmgren, S. On searching for Mach band type phenomena in the visual perception of spatial velocity distributions. Report. 151, Dept. of Psych., U. of Uppsala, Sweden, 1973.

van der Horst, G. J. C., & Muis, W. Hue shift and brightness enhancement of flickering light. Vis. Res., 1969, 9, 953-963.

Hylkema, B. S. Examination of the visual field by determining the fusion frequency. Acta ophthalmologica, 1942, 20, 181-193.

Ikeda, M. Temporal summation of positive and negative flashes in the visual system. J. Op. Soc. Am., 1965, 1527-1534.

Ikeda, M., & Takeuchi, T. Influence of foveal load on the functional visual field. Percept. & Psychophys., 1975, 18, 255-260.

Jerison, H. J., & Pickett, R. M. Vigilance: A review and re-evaluation. Human Fact., 1963, 5, 211-238.

Johansson, G. Configurations in event perception. Uppsala, Sweden: Almqvist & Wiksell, 1950.

Johansson, G. Studies on visual perception of locomotion. Dept. of Psych., U. of Uppsala, Sweden, Report 206, 1977. Also Perception, 1977, 6, 365-376. (a)

Johansson, G. Visual perception of locomotion elicited and controlled by a bright spot moving in the periphery of the visual field. Dept. of Psych., U. of Uppsala, Sweden, Report 210, 1977. (b)

Johnson, C. A., & Leibowitz, H. W. Velocity-time reciprocity in the perception of motion: foveal and peripheral determinations. Vis. Res., 1976, 16, 177-180.

Johnston, A. W., Cole, B. L., Jacobs, R. J., & Gibson, A. J. Visibility of traffic control devices: Catering for the real observer. Ergonomics, 1976, 14, 591-609.

Julesz, B. Foundations of Cyclopean Perception. Chicago: The University of Chicago Press, 1971.

Kabrisky, M., Tallman, O., Day, C. M., & Radoy, C. M. A theory of pattern recognition based on human physiology. Ergonomics, 1970, 13, 129-147.

Kahneman, D. Time-intensity reciprocity under various conditions of adaptation and backward masking. J. Exp. Psych., 1966, 71, 543-549.

Kahneman, D., & Norman, J. The time-intensity relation in visual perception as a function of observer's task. J. Exp. Psych., 1964, 68, 215-220.

Kahneman, D., Norman, J., & Kubovy, M. Critical duration for the resolution of form: Centrally or peripherally determine? J. Exp. Psych., 1967, 73, 323-327.

Kahneman, D., & Wolman, R. E. Stroboscopic motion: Effects of duration and interval. Percept. & Psychophys., 1970, 8, 161-164.

Kaiser, P. K. Color names of very small fields varying in duration and luminance. J. Op. Soc. Am., 1968, 58, 849-852.

Kalfin, K., & Locke, S. Evaluation of long-term visual motion aftereffect following monocular stimulatin. Vis. Res., 1972, 12, 354-361.

Kaufman, L. Sight and mind. New York: Oxford University Press, 1974.

Keck, M. J., Palella, T. D., & Pantle, A. Motion after-effect as a function of the contrast of sinusoidal gratings. Vis. Res., 1976, 16, 187-191.

Keesey, V. T. Variables determining flicker sensitivity in small fields. J. Op. Soc. Am., 1970, 60, 390-398.

Kelly, D. H. Effects of sharp edges in a flickering field. J. Op. Soc. Am., 1959, 49, 730-732.

Kelly, D. H. Visual Response to Time-Dependent Stimuli.I.Amplitude Sensitivity Measurements. J. Opt. Soc. Amer., 1961, 51, 422-429. (a)

Kelly, D. H. Flicker Fusion and Harmonic Analysis. J. Opt. Soc. Amer., 1961, 51, 917-918. (b)

Kelly, D. H. Frequency doubling in visual response. J. Op. Soc. Am., 1966, 56, 1628-1633.

Kelly, D. H. Flickering patterns and lateral inhibition. J. Opt. Soc. Amer., 1969, 59, 1361-1370.

Kelly, D. H. Flicker. In D. Jameson, & L. M. Hurvich (Eds.), Handbook of Sensory Physiology, VII/4, New York: Springer-Verlag, 1972.

Kelly, D. H. Spatio-temporal frequency characteristics of color-vision mechanisms. J. Op. Soc. Am., 1974, 64, 983-990.

Kelly, D. H. Spatial, temporal, and chromatic relations. In H. Spekreijse & L. H. Van der Tweel (Eds.), Spatial Contrast: Report of a Workshop held in Amsterdam, January 4-9, 1976.

Kelly, D. H. Visual contrast sensitivity. Optica Acta, 1977, 24, 107-129.

Kennedy, R. S., Yessenow, M. D., & Wendt, G. R. Magnitude estimation of visual velocity. J. Psych., 1972, 82, 133-144.

Kimball, K. A. Estimation of intersection of 2 converging targets as a function of speed and angle of target movement. Percept. Mot. Skills, 1970, 30, 303-310.

Kinchla, R. A. Visual movement perception: A comparison of absolute and relative movement discrimination. Percept. & Psychophys., 1971, 9, 165-171.

Kinchla, R. A., & Allan, L. G. A theory of visual movement perception. Psych. Rev., 1969, 76, 537-558.

Kinchla, R. A., & Allan, L. G. Visual movement perception: A comparison of sensitivity to vertical and horizontal movement. Percept. & Psychophys., 1970, 8, 399-405.

Kinney, J. A. S. Changes in appearance of colored stimuli with exposure duration. J. Op. Soc. Am., 1965, 55, 738-739.

Kintz, R. T., & Witzel, R. F. Role of eye movements in the perception of apparent motion. J. Op. Soc. Am., 1972, 62, 1237-1238.

Kirkwood, B. Temporal and spatial factors in the fading of diffuse visual images. Percept. & Psychophys., 1968, 4, 110-112.

Kitchel, J. M., & Jenney, L. L. Electronic and optically generated aircraft displays. JANAIR 680505, 1968.

Kitterle, F. L. The effects of inducer duration on successive brightness contrast. Vis. Res., 1975, 15, 273-275.

Kitterle, F. L., & Corwin, T. Enhancement of apparent contrast in flashed sinusoidal gratings. Vis. Res., 1979, 19, 33-39.

Kitterle, F. L., & Rysberg, J. A. The effect of exposure duration on the apparent contrast of sinusoidal gratings. Perception & Psychophys., 1976, 19, 335-338.

Klein, G. S. The relation between motion and form acuity in parafoveal and peripheral vision and related phenomena. Arch. Psych., 1942, 39, 1-70.

Kolers, P. A. Aspects of motion perception. New York: Pergamon Press, 1972.

Krauskopf, J. Effect of target oscillation on contrast resolution. J. Op. Soc. Am., 1962, 52, 1306.

Kugelmass, S., & Landis, C. The relation of area and luminance to the threshold for critical flicker fusion. Am. J. Psych., 1955, 68, 1-9.

Kulikowski, J. J. Apparent fineness of briefly presented gratings: Balance between movement and pattern channels. Vis. Res., 1975, 15, 673-680.

Landis, C., & Hamwill, N. Critical flicker fusion, age, and intelligence. Am. J. Psych., 1956, 69, 459-461.

deLange, H. Research into the Dynamic Nature of the Human Fovea-Cortex Systems with Intermittent and Modulated Light. Attenuation Characteristics with White and Colored Light. J. Opt. Soc. Am., 1958, 48, 777-784.

Lappin, J. S., Bell, H. H., Harm, J. O., & Kottas, B. On the relation between time and space in the visual discrimination of velocity. J. Exp. Psych., Human Percept. & Perf., 1975, 1, 383394.

Layton, B. Perceptual Noise and Aging. Psych. Bull., 1975, 82, 875-883.

LeGrand, Y. Light, colour and vision. Ch. 13, time effects, London: Chapman & Hall, 1968.

Leibowitz, H. W. Effect of reference lines on the discrimination of movement. J. Op. Soc. Am., 1955, 45, 829-830. (a)

Leibowitz, H. W. The relation between the rate threshold for the perception of movement and luminance for various durations of exposure. J. Exp. Psych., 1955, 49, 209-214. (b)

Leibowitz, H. W., Johnson, C. A., & Isabelle, E. Peripheral motion detection and refractive error. Science, 1972, 177, 1207-1208.

Levinson, J. Z. Flicker fusion phenomena. Science, 1968, 160, 21-28.

Lichtenstein, M. Spatio-temporal factors in cessation of smooth apparent motion. J. Op. Soc. Am., 1963, 53, 304-306.

Link, J. M., & Valerie, L. L. Differential thresholds for motion in the periphery. N69-36925 (1969).

Loomis, J. M., & Nakayama, K. A velocity analogue of brightness contrast. Perception, 1973, 2, 425-428.

Ludvigh, E. Effect of reduced contrast in visual acuity as measured with Snellen test letters. Arch. Ophthal., 1941, 25, 469-474.

Ludvigh, E., & Miller, J. W. Study of visual acuity during ocular pursuit of moving test objects, I: Introduction. J. Op. Soc. Am., 1958, 48, 799-802.

Luria, S. M. Color-name as a function of stimulus intensity and duration. Am. J. Psych., 1967, 80, 1427.

Mack, A., & Herman, E. A new illusion: the underestimation of distance during pursuit eye movements. Percept. & Psychophys., 1972, 12, 471-473.

MacKay, D. M. Perceptual stability of a stroboscopically lit visual field containing self-luminous objects. Nature, 1958, 181, 507-508.

Mackie, J. B., & Beck, E. C. Relations among age, intelligence and critical flicker fusion. Percept. Mot. Skills, 1965, 21, 875-878.

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

Magnussen, S., & Glad, A. Effects of steady surround illumination on the brightness and darkness enhancement of flickering lights. Vis. Res., 1975, 15, 1413-1416. (a)

Magnussen, S., & Glad, A. Temporal frequency characteristics of spatial interaction in human vision. Exp. Brai. Res., 1975, 23, 519-528. (b)

Mandriota, F. J., Mintz, D. E., & Notterman, J. M. Visual velocity discrimination: effects of spatial and temporal cues. Science, 1962, 138, 437-438.

Mansfield, R. J. Brightness function: Effect of area and duration. J. Op. Soc. Am., 1973, 63, 913-920.

Markowitz, J. Optimal flash rate and duty cycle for flashing visual indicators. Human Fact., 1971, 13, 427-433.

Marks, L. E. Brightness as a function of retinal locus in the light adapted eye. Vis. Res., 1968, 8, 525-535.

Marks, L. E. Apparent depth of modulation as a function of frequency and amplitude of temporal modulation of luminance. J. Op. Soc. Am., 1970, 60, 970-977.

Marks, L. E. Brightness and retinal locus: Effects of target size and spectral composition. Percept. & Psychophys., 1971, 9, 26-30.

Marshall, A. J., & Gordon, S. The apparent length of rotating arcs under con ditions of dark adaptation. Percept. & Psychophys., 1973, 14, 349-352.

Mashour, M. A study of motion preferences. Scand. J. Psych., 1969, 10, 299-305.

Masland, R. H. Visual motion percepton: Experimental modification. Science, 1969, 165, 819-821.

Mates, B. Effect of reference marks and luminance on discrimination of movement. J. Psych., 1969, 73, 209-221.

Mates, B., & Graham, C. H. Effect of rectangle length on velocity thresholds for real movement. Proceedings Nat'l Academy of Sciences, 1970, 65, 516-520.

Mattson, D. L. Stimulus length and orientation variables interact in peripheral motion perception. Percept. Mot. Skills, 1976, 43, 95-98.

Mayhew, E. W., & Anstis, S. M. Movement after-effects contingent on color, intensity, and pattern. Percept. & Psychophys., 1972, 12, 77-85.

McColgin, F. H. Movement thresholds in peripheral vision. J. Op. Soc. Am., 1960, 50, 774-779.

McFarland, J. H. The influence of eye movements on a new type of apparent visual movement. Psychon. Sci., 1966, 4, 51-52.

McKee, M. E., Allan, L. C., & Kristofferson. Duration discrimination of brief visual off-flashes. N71-28136, 1970, 80 pp.

Mertens, H. W., & Lewis, M. F. Discrimination of short duration (2 pulse) flashes as a functon of signal luminance and method of measurement. FAA Civil Aeromedical Inst. FAA-AM-71-42.

Miller, J. W. Study of visual acuity during the ocular pursuit of moving test objects II. Effects of direction of movement relative movement, and illumination. J. Op. Soc. Am., 1958, 48, 803-808.

Misiak, H. R. The decrease in critical flicker frequency with age. Science, 1951, 113, 551-552.

Morin, R. E., Grant, D. A., & Nystrom, C. D. Temporal predictions of motion inferred from intermittently viewed light stimuli. J. Gen. Psych., 1956, 55, 59-71.

Mowbray, G. H., & Gebhard, J. W. Differential sensitivity of the eye to intermittent white light. Science, 1955, 121, 173-175.

Mowbray, G. H., & Gebhard, J. W. Differential sensitivity of peripheral retina to intermittent white light. Science, 1960, 132, 672-674.

Nachmias, J. Effect of exposure duration on visual contrast sensitivity with square wave gratings. J. Opt. Soc. Am., 1967, 57, 421-427.

Nelson, T. M., & Bartley, S. H. The role of PCF in temporal manipulations of color. J. Psych., 1961, [illegible]2, 457-477.

van Nes, F. L. Enhanced visibility by regular motion of retinal images. Am. J. Psych., 1968, 81, 367-374.

van Nes, F. L., Koenderink, J. J., & Bouman, M. A. Spatiotemporal modulation transfer in the human eye. J. Op. Soc. Am., 1967, 57, 1082-1088.

Notterman, J. M., & Page, D. E. Weber's law and the difference threshold for the velocity of a seen object. Science, 1957, 126, 652.

Osaka, N. Perceived brightness as a function of flash duration in the peripheral visual field. Percept. & Psychophys., 1977, 22, 63-69.

Owen, W. G. Spatio-temporal integration in the human peripheral retina. Vis. Res., 1972, 12, 1011-1026.

Pearson, L. A., & Tong, S. E. Two-flash fusion threshold: The influence of age, psychophysical method, instructions, viewing conditions, sex and subject variability. Brit. J. Psych., 1968, 59, 4, 407-414.

Peterson, H. E., & Dugas, D. J. The relative importance of contrast and motion in visual detection. Human Fact., 1972, 14, 207-216.

Pirenne, M. H. Flicker and after-images. In H. Davson (Ed.), The Eye, Vol. 2, The visual process. New York: Academic Press, 1962.

Pollack, W. T. The visibility of a target as a function of its speed of movement. J. Exp. Psych., 19[illegible], 15, 449-454.

Pomerantz, J. R. Eye movements effect the perception of apparent (beta) movement. Psychon. Sci., 1970, 19, 193-194.

Raab, D. H. Magnitude estimation of brightness of brief foveal stimuli. Science, 1962, 135, 42-43.

Raab, D. H., & Fehrer, E. Supplementary report: The effect of stimulus duration and luminance on visual reaction time. J. Exp. Psych., 1962, 64, 326-327.

Rabelo, C., & Grusser, O. J. Die Abhangigkeit der subjektiven helligkeit intermittierender lichtreize von der flimmerfreque (Brucke-effekt,,, brightness enchancement): Untersuchungen bei verschiedener leuchtdichte una feldgrobe. Psych. Forsch., 1961, 26, 299-312, (In German).

Rachlin, H. C. Scaling subjective velocity, distance, and duration. Percept. & Psychophys., 1966, 1, 77-82.

Ramachandran, F. S., Madhysudhan, R. V., & Vidyasgar, T. R. Apparent movement with subjective contours. Vis. Res., 1973, 13, 1399-1401.

Ratliff, F. Mach Bands: Quantitative studies on neural networks in the retina. Holden-Day, Inc., 1965.

Remole, A. Luminance thresholds for subjective patterns in a flickering light: Effect of wavelength. J. Op. Soc. Am., 1971, 61, 1164-1168.

Remole, A. Extended border enhancement during intermittent illumination: binocular effects. Vis. Res., 1973, 1289-1295. (a)

Remole, A. Subjective patterns in a flickering field: Binocular vs. monocular observation. J. Op. Soc. Am., 1973, 63, 745-748. (b)

Remole, A. Luminance thresholds for perceived movement in a flickering field. J. Op. Soc. Am., 1974, 64, 1133-1135.

Richards, W., & Felton, T. B. Spatial frequency doubling: Retinal or central? Vis. Res., 1973, 13, 2129-2137.

Riley, T. M. Multiple images as a function of LED's viewed during vibration. Human Fact., 1977, 19, 79-82.

Roehrig, W. C. The influence of area on the critical flicker-fusion threshold. J. Psych., 1959, 47, 317-330. (a)

Roehrig, W. C. The influence of the portion of the retina stimulated on critical flicker-fusion thresholds. J. Psych., 1959, 48, 57-63. (b)

Rogers, J. G. Peripheral contrast thresholds for moving images. Human Fact., 1972, 14, 199-205.

Rosenbaum, D. A. Perception and extrapolation of velocity and acceleration. J. Exp. Psych., Human Percept. & Perf., 1975, 1, 395-403.

Roufs, J. A. J. Dynamic properties of vision I. Experimental relationships between flicker and flash thresholds. Vis. Res., 1972, 12, 211-278.

Roufs, J. A. J. Dynamic properties of vision III. Twin flashes, single flashes, and flicker/fusion. Vis. Res., 1973, 13, 309-323.

Runeson, S. Constant velocity: Not perceived as such. Psych. Res., (Psychologische Forschung), 1974, 37, 3-23.

Runeson, S. Visual prediction of collision with natural and non-natural motion functions. Percept. & Psychophys., 1975, 18, 261-266.

Saucer, R. T., & Coppinger, N. W. Standard stimulus-conditions for thresholds of apparent movement. Am. J. Psych., 73, 435-439.

Saugstad, P., & Lie, I. Training of peripheral visual acuity. Scand. J. Psych., 1964, 5, 218-224.

Scanlan, L. A., Roscoe, S. N., & Williges, R. C. Time-compressed displays for target detection. Aviat. Res. Mono., 1971, 1, pt. 3.

Schafer, W. D., Immich, H., & Sipp, H. V. Der Einfluss von Alter und Geschlewt auf das Erkennen begwegter Objekte. Albrecht v. Graefes Arch. klin. exp. Ophthal., 1973, 188, 253-262.

Schmerler, J. The visual perception of accelerated motion. Perception, 1976, 5, 167-185.

Scott, T. R., Karras, H. G., & Milligan, W. L. Effect of prior seen motion on sequential size discrimination. Percept. Mot. Skills, 1968, 27, 619-622.

Scott, T. R., Jordan, A. E., & Powell, D. A. Does the visual aftereffect of motion add algebraically to objective motion in the test stimulus. J. Exp. Psych., 1963, 66, 500-506.

Scott, T. R., Lavender, A. D., McWhirt, R. A., & Powell, D. A. Direction asymmetry of motion aftereffect. J. Exp. Psych., 1966, 71, 806-815.

Sekuler, R., & Ball, K. Mental set alters visibility of moving targets. Science, 1977, 198, 60-62.

Sekuler, R., & Pantle, A. A model for after-effects of seen movement. Vis. Res., 1967, 7, 427-440.

Sekuler, R., & Tynan, P. Rapid measurement of contrast-sensitivity functions. Am. J. Optom., & Physiol. Optics, 1977, 54, 573-575.

Sen, T. K. Visual responses to two alternating trains of high-frequency intermittent stimuli. J. Op. Soc. Am., 1964, 54, 386-398.

Sgro, F. J. Beta motion thresholds. J. Exp. Psych., 1963, 66, 281-285.

Sharpe, C. R. The contrast sensitivity of the peripheral visual field to drifting sinusoidal gratings. Vis. Res., 1974, 14, 905-906.

Sheppard, J. J., Jr. Human color percepton. New York: American Elsevier Publishing Co., 1968.

Shinar, D., Mayer, R. E., & Treat, J. R. Reliability and validity assessments of a newly developed battery of driving related vision tests. From Proceed. of the 19th Conference of the Amer. Assoc. for Automotive Medicine, 1975.

Siegel, M. H., & Siegel, A. B. Color name as a function of surround luminance and stimulus duration. Percept. & Psychophys., 1971, 9, 140-144.

Singer, W., Zihl, J., & Poppel, E. Subcortical control of visual thresholds in humans: Evidence of selective attention. Exp. Brain Res., 1977, 29, 173-190.

Smith, R. L., & Kennedy, R. S. Predictor displays: A human engineering technology in search of a manual control problem. Airtask A3400000/054B/5F55-525-400, Pacific Missile Test Center, Point Mugu, CA., 1976.

Smith, S. L., & Goodwin, N. C. Blink coding for information display. Human Fact., 1971, 283-290.

Smythies, J. R. A preliminary analysis of the stroboscopic patterns. Nature, 1957, 179, 523-524.

Sperling, G. Movement perception in computer-driven visual displays. Beh. Res. Meth. & Instr., 1976, 8, 144-151.

Sperling, G., & Jolliffe, C. L. Intensity-time relationship at threshold for spectral stimuli in human vison. J. Op. Soc. Am., 1965, 55, 191-199.

Spigel, I. M. Contour absence as an initial factor in the inhibition of the decay in a movement aftereffect. J. Psych., 1962, 54, 221-228.

Spigel, I. M. Readings in the study of visually perceived movement. New York: Harper & Row, 1965.

Springer, R. M., Deutsch, J. A., & Stanley, G. Double flashes from single pulses of light. Percept. & Psychophys., 1975, 18, 398-401.

Stanley, G. Apparent shrinkage of a rotating arc as a function of luminance relations between figure and surround. Acta Psychol., 1966, 25, 357-364.

Stanley, G. Apparent brightness of a rotating arc-line as a function of speed of rotation. Acta Psychologica, 1967, 26, 17-21.

Stanley, G. Apparent length of rotatng arc-line as a function of speed of rotation. Acta Psychologica, 1968, 28, 398-403.

Stanley, G. Static visual noise and the Ansbacher effect. Quart. J. Exp. Psych., 1970, 22, 43-48.

Stanley, G., & Dua, J. K. The effect of dark gaps on the apparent length of a moving light line. Acta Psychologica, 1969, 31, 189-193.

Stecher, S. Discrimination of luminance differences between temporally separated paired flashes. J. Op. Soc. Am., 1967, 57, 1271-1272.

Stevens, S. S. On the Psychophysical Law. Psych. Rev., 1957, 64, 153-180.

Stevens, S. S. The surprising simplicity of sensory metrics, Am. Psych., 1962, 17, 29-39.

Taylor, J. H. Practice effects in simple visual detection tasks. J. Op. Soc. Am., 1964, 201, 691-692. (a)

Taylor, J. H. Use of visual performance data in visibility prediction. Applied Optics, 1964, 3, 562-569. (b)

Teichner, W. H., & Krebs, M. J. Estimating the detectability of target luminances. Human Fact., 1972, 14, 511-519.

Thalman, W. A. The after-effect of seen movement when the whole visual field's filled by a moving stimulus. Am. J. Psych., 1921, 31, 429-441.

Theodor, L. H. The detectability of a brief gap in a pulse of light as a function of its temporal location within the pulse. Percept. & Psychophys., 1971, 12, 168-170.

Thompson, P. G. Velocity after-effects and the perception of movement, Dissertation: University of Cambridge, England, 1976.

Thorson, J., Lange, G. D., & Biederman-Thorson, M. Objective measure of dynamics of a visual movement illusion. Science, 1969, 164, 1087-1088.

Tolhurst, D. J. Reaction times in the detection of gratings by human observers: a probabilisic mechanism. Vis. Res., 1975, 15, 1143-1149.

Tolhurst, D. J., Sharpe, C. R., & Hart, G. The analysis of the drift rate of moving sinusoidal gratings. Vis. Res., 1973, 13, 2545-2555.

Tyler, C. W. Temporal characteristics in apparent movement: Omega movement vs. Phi movement. Quart. J. Exp. Psych., 1973, 25, 182-192.

Tyler, C. W. Observations on spatial-frequency doubling. Perception, 1974, 3, 81-86.

Tyler, C. W., & Torres, J. Frequency response characteristic for sinusoidal movement in the fovea and periphery. Percept. & Psychophys., 1972, 12, 232-236.

Tynan, P., & Sekuler, R. Perceived spatial frequency varies with stimulus duration, J. Op. Soc. Am., 1974, 64, 1251-1255.

Tynan, P., & Sekuler, R. Moving sual phantoms: A new contour completion effect, Science, 1975, 188, 951-952. (a)

Tynan, P., & Sekuler, R. Simultaneous motion contrast: Velocity sensitivity and depth response. Vis. Res., 1975, 15, 1231-1238. (b)

Uetsuki, T., & Ikeda, M. Study of temporal visual response by summation index. J. Op. Soc. Am., 1970, 60, 377-381.

Valerie, L. L. Display for seeing without looking. Human Fact., 1960, 8, 507-514.

Virsu, V., & Nyman, G. Monophasic temporal modulation increases apparent spatial frequency. Perception, 1974, 3, 337-353.

Virsu, V., Nyman, G., & Lehjio, P. K. Diphasic and polyphasic temporal modulations multiply apparent spatial frequency. Perception, 1974, 3, 323-326.

Walker, J. T. A new rotating gradient disk: Brightness, flicker, and brightness aftereffects. Vis. Res., 1974, 14, 223-228.

Walker, J. T. Visual texture as a factor in the apparent velocity of objective motion and motion aftereffects. Percept. & Psychophys., 1975, 18, 175-180.

Walker, P., & Powell, D. J. Lateral interaction between neural channels sensitive to velocity in the human visual system. Nature, 1974, 252, 732-733.

Wasserman, G. S. Brightness enhancement in intermittent light: Variation of luminance and light-dark ratio. J. Op. Soc. Am., 1966, 56, 242-250.

Waygood, M. The visibility of rate of change of luminance in the presence or absence of a boundary. Optica Acta, 1969, 16, 61-64.

Weale, R. A. The aging eye, London: H. K. Lewis Co., 1963.

Webster, R. G., & Haselrud. Influence on extreme peripheral vision of attention to a visual or auditory task. J. Exp. Psych., 1964, 68, 269-272.

Weiner, E. L. Motion prediction as a function of target speed and duration of presentation. J. Applied Psych., 1962, 46, 420-424.

Weisstein, N., Maguire, W., & Berbaum, K. A phantom-motion aftereffect. Science, 1977, 198, 955-958.

Welde, W. L., & Cream, B. W. Variables influencing the perception of flicker in wide angle CRT displays. AD-766-443 (1472) (microfilm), 1972.

White, C. T. Catoptic images and the peripheral movement illusion. J. Op. Soc. Am., 1960, 50, 1116-1117.

White, C. T., & Eason, R. G. Evoked cortical potentials in relation to certain aspects of visual perception. Psych. Mono., 1966, 80, 1-14.

White, C. T., & Ford, A. Eye movements during simulated radar search. J. Op. Soc. Am., 1960, 50, 909-913.

White, J. W., Collins, S. B., & Rinalducci, E. J. The Broca-Sulzer effect under scotopic viewing conditions. Vis. Res., 1976, 16, 1434-1443.

White, K. D. Foveal CFF during the course of dark adaptation. J. Op. Soc. Am., 1976, 66, 70-73.

Whittle, P., & Challands, D. D. L. The effect of background luminance on the brightness of flashes. Vis. Res., 1969, 9, 1095-1110.

Wienke, R. E. The effect of flash distribution and illumination level upon the detection of low intensity stimuli. Human Fact., 1964, 6, 305-311.

York, M. Behavioral efficiency in a visual monitoring task as a function of signal rate and observer age. Percept. Mot. Skills, 1962, 15, 404.

Young, R. S., Cole, R. E., Gamble, U., & Rayner, M. D. Subjective patterns elicited by light flicker. Vis. Res., 1975, 15, 1291-1293.

AUTHOR INDEX

SUBJECT INDEX

DISTRIBUTION

1 US ARMY WESTERN COMMAND ATTN: APPE
1 DEPARTMENT OF THE NAVY TRAINING ANALYSIS AND EVALUATION GROUP
1 HQDA ATTN: DAAG-ED
1 HQ, ICATA ATTN: ATCAT-OP-Q
2 HQDA RESEARCH AND STUDIES OFC
1 MILITARY OCCUPATIONAL DEVELOPMENT DIV DAPC-MSP-O, RM 852C HOFFMAN BLDG 1
4 OASD (MRA AND L)
1 HQDA ATTN: DAMO-RQR
1 HQ TCATA TECHNICAL LIBRARY
1 HQDA ODCSPER
1 USRADCO, STC
1 HQDA ATTN: DAMI-ISI
1 USA AVIATION SYSTEMS COMD ATTN: DRSAV-ZDR
1 USA CORADCOM ATTN: AMSEL-PA-RH
1 USA ARRADCOM ATTN: ATFE-LO-AC
1 HEADQUARTERS, US MARINE CORPS ATTN: CODE MPI-20
2 US ARMY EUROPE AND SEVENTH ARMY
1 1ST INFANTRY DIVISION AND FT. RILEY ATTN: AFZN-DPT-T
1 USA INTELLIGENCE AND SECURITY COMMAND ATTN: IAOPS-TNG-T
2 HQ TRADOC TECHNICAL LIBRARY
1 NAVAL TRAINING EQUIPMENT CEN ATTN: TECHNICAL LIBRARY
1 MILITARY OCCUPATIONAL DEVELOPMENT DIRECTORATE ATTN: ATZI-NCR-MS-M, RM 3N33 HOFFMAN BLDG II
1 DATA ANALYSIS DIVISION ATTN: ATZI-NCR-MD, HOFFMAN BLDG II
1 USA MILPERCEN ATTN: DAPC-POO-T
1 USAFACFA CHIEF, ORGANIZATIONAL EFFECTIVENESS BRANCH
1 8TH INFANTRY DIVISION
1 HQDA ARMY FORCE MODERNIZATION COORDINATION OFFICE
1 NAVAL AIR SYSTEM COMMAND /
1 DCSOPS (DIST 4) ATTN: DAMO-ROT
1 123D USARCOM RESERVE CENTER
1 US ARMY SOLDIER SUPPORT CENTER /
1 DIRECTORATE OF ARMOR AVIATION ATTN: ATZK-AAD
1 USAARMC + FT. KNOX AVIATION DIVISION
1 USA FORCES COMMAND AFIN - DEPUTY C OF S FOR INTELLIGENCE
1 USA FORCES COMMAND AFOP - DEPUTY CHIEF OF STAFF FOR OPERATIONS
1 US ARMY AIR DEFENSE SCHOOL ATTN: ATSA-DTD
1 DIRECTORATE OF TRAINING ATTN: ATZQ-T
1 DIRECTORATE OF COMBAT DEVELOPMENTS ATTN: ATZQ-D
1 HQDARCOM MARINE CORPS LIAISON OFC
1 DEPARTMENT OF THE ARMY US ARMY INTELLIGENCE + SECURITY COMMAND
1 US ARMY SAFETY CENTER ATTN: LIBRARIAN, BLDG 4905
1 USA MISSILE COMMAND ATTN: DRS I-NTN
1 US ARMY CECOM ATTN: DRSEL-ATI D
1 USA FORCES COMMAND
1 PM TRADE /
1 US MILITARY DISTRICT OF WASHINGTON OFC OF EQUAL OPPORTUNITY
1 NAVAL CIVILIAN PERSONNEL COMD SOUTHERN FLD DIV
22 ARI LIAISON OFFICE
1 7TH ARMY TRAINING COMMAND
1 HQ USAREUR ATTN: DCSOPS
1 I A. OCS STUDY OFFICE
1 U... NAVY TRAINING ANALYSIS EVALUATION GROUP
1 USACDEC ATTN: ATEC-EX-E HUMAN FACTORS
1 USAFAGOS/TAC SENIOR ARMY ADVISOR
1 INTER-UNIV SEMINAR ON ARMED FORCES + SOC
1 USA ELECTRONIC PROVING GROUND ATTN: STEEP-MT-ES
1 OASA (RDA) DEPUTY FOR SCIENCE AND TECHNOLOGY
1 OFC OF NAVAL RESEARCH /
1 AFHRL/LRT
1 AFHRL/LRLG
1 AIR FORCE HUMAN RESOURCES LAB ATTN: AFHRL/TSR

1 FEDERAL AVIATION ADMINISTRATION CENTRAL REGION LIBRARY, ACE-66
1 AFAMRL/BB
1 AFAMRL/HE
1 NAVAL PERSONNEL R AND D CENTER COMMAND AND SUPPORT SYSTEMS
1 NAVY PERSONNEL R AND D CENTER /
1 NAVY PERSONNEL R AND D CENTER DIRECTOR OF PROGRAMS
1 NAVY PERSONNEL R AND D CENTER /
1 US ARMY AVN ENGINEERING FLIGHT ACTIVITY ATTN: DAVTE-TD
2 OFC OF NAVAL RESEARCH PERSONNEL AND TRAINING RESEARCH PROGRAMS
1 NAVAL PERSONNEL R + D CENTER /
1 OFC OF NAVAL RESEARCH PROJECT OFFICER, ENVIRONMENTAL PHYSIOLOGY
1 DEPT. OF NATIONAL DEFENCE DEFENCE AND CIVIL INSTITUTE OF ENVIR MED
1 NAVAL AEROSPACE MEDICAL RSCH LAB AEROSPACE PSYCHOLOGY DEPARTMENT
1 USA TRADOC SYSTEMS ANALYSIS ACTIVITY ATTN: ATAA-TCA
1 HEADQUARTERS, COAST GUARD CHIEF, PSYCHOLOGICAL RSCH BR
1 USA RESEARCH AND TECHNOLOGY LAB /
1 USA ENGINEER TOPOGRAPHIC LABS ATTN: ETL-GSL
1 USA ENGINEER TOPOGRAPHIC LABS ATTN: STINFO CENTER
1 USA ENGINEER TOPOGRAPHIC LABS ATTN: ETL-TD-S
1 USA MOBILITY EQUIPMENT R AND D COMD ATTN: DRDME-TQ (SCHOOL)
1 NIGHT VISION LAB ATTN: DRSEL-NV-SDD
1 USA TRAINING BOARD ATTN: ATTG-ATB-TA
1 USA HUMAN ENGINEERING LAB
1 USAHEL LIAISON REP, USAAVNC /
1 USA MATERIEL SYSTEMS ANALYSIS ACTIVITY ATTN: DRXSY-C
1 USA RESEARCH OFC /
1 NAFEC HUMAN ENGINEERING BRANCH
1 BATTELLE-COLUMBUS LABORATORIES TACTICAL TECHNICAL OFC
1 USA ARCTIC TEST CEN ATTN: AMSTE-PL-TS
1 USA COLD REGIONS TEST CEN ATTN: STECR-OP
1 USA CONCEPTS ANALYSIS AGCY ATTN: CSCA-RQP
1 USA CONCEPTS ANALYSIS AGCY ATTN: CSCA-JF
1 HQ WRAIR DIV OF NEUROPSYCHIATRY
1 USACACDA ATTN: ATZL-CAC-IC
1 USACACDA ATTN: ATZL-CAC-IM
1 USACAC ATTN: ATZL-CAC-IA
1 USACACDA ATTN: ATZL-CAC-A
1 USA ELECTRONIC WARFARE LAB CHIEF, INTELLIGENCE MATER DEVEL + SUPP OFF
1 USA RSCH DEVEL + STANDARDIZA GP, U.K.
1 USA RESEARCH AND DEVELOPMENT LABS CHIEF, BEHAV SCIENCES DIV, FOOD SCI LAB
1 TRAJANA ATTN: SAJS-OR
1 NAVAL AIR SYSTEMS COMMAND ATTN: AIR-5313
1 ECOM ATTN: AMSEL-CT-O
1 USACDEC TECHNICAL INFORMATION CENTER
1 USAARL LIBRARY
1 HUMAN RESOURCES RSCH ORG (HUMRRO) /
1 SEVILLE RESEARCH CORPORATION
1 USA TRADOC SYSTEMS ANALYSIS ACTIVITY ATTN: ATAA-SL (TECH LIBRARY)
1 UNIFORMED SERVICES UNIT OF THE HEALTH SCI DEPARTMENT OF PSYCHIATRY
1 USA COMPUTER SYSTEMS COMMAND ATTN: COMMAND TECHNICAL LIBRARY H-9
1 HUMAN RESOURCES RSCH ORG (HUMRRO)
1 HUMRRO LIBRARY
1 EUSTIS DIRECTORATE, USAAMRDL TECHNICAL LIBRARY
1 RAND CORPORATION /
1 RAND CORPORATION ATTN: LIBRARY D
1 FEDERAL AVIATION ADMINISTRATION ATTN: CAMI LIBRARY ACC-44D1
1 NAFEC LIBRARY, ANA-64
1 GRONINGER LIBRARY ATTN: ATZF-RS-L BLDG 1313
1 CENTER FOR NAVAL ANALYSIS
1 NAVAL HEALTH RSCH CEN LIBRARY
1 NAVAL ELECTRONICS LAB ATTN: RESEARCH LIBRARY
1 NAVAL PERSONNEL R AND D CEN LIBRARY ATTN: CODE P106

1 AIR FORCE HUMAN RESOURCES LAB ATTN: AFHRL/OTS
1 HQ. FT. HUACHUCA ATTN: TECH REF DIV
1 USA ACADEMY OF HEALTH SCIENCES STIMSON LIBRARY (DOCUMENTS)
1 SCHOOL OF SYSTEMS AND LOGISTICS /
1 USAMERDC TECHNICAL LIBRARY
1 DEPARTMENT OF THE NAVY TRAINING ANALYSIS AND EVALUATION GP
1 NATIONAL CENTER FOR HEALTH STATISTICS /
1 USMA DEPT OF BEHAVIORAL SCI AND LEADERSHIP
1 OLD DOMINION UNIVERSITY PERFORMANCE ASSESSMENT LABORATORY
1 USA COMMAND AND GENERAL STAFF COLLEGE ATTN: LIBRARY
1 USA TRANSPORTATION SCHOOL USA TRANSP TECH INFO AND RSCH CEN
1 NASA HQ /
1 NMRDC PROGRAM MANAGER FOR HUMAN PERFORMANCE
1 NAVAL MEDICAL R AND D COMMAND (44)
1 USA ADMINCEN TECHNICAL RESEARCH BRANCH LIBRARY
2 HQDA USA MED RSCH AND DEVEL COMMAND
1 USA FIELD ARTY BD /
1 NAT CLEARINGHOUSE FOR MENTAL HEALTH INFO PARKLAWN BLDG
1 U OF TEXAS CEN FOR COMMUNICATION RSCH
1 INSTITUTE FOR DEFENSE ANALYSES
1 USA TRAINING SUPPORT CENTER ATTN: ATIC-DST-PA
1 AFHRL TECHNOLOGY OFC (H)
1 PURDUE UNIV DEPT OF PSYCHOLOGICAL SCIENCES
1 USA MOBILITY EQUIPMENT R AND D COMMAND ATTN: DRDME-ZG
1 HQ. USA MDW ATTN: ANPE-OE
1 DA US ARMY RETRAINING BDE RESEARCH + EVALUATION DIVISION
1 CALSPAN HUMAN FACTORS AND TRAINING CENTER
1 USA AEROMEDICAL RESEARCH LAB SCIENTIFIC INFORMATION CENTER
1 USAF SCHOOL OF AEROSPACE MEDICINE AEROMEDICAL LIBRARY (TSK-4)
1 US MILITARY ACADEMY DEPT. OF HISTORY, BLDG 601
1 USA INTELLIGENCE CEN AND SCH ATTN: SCHOOL LIBRARY
1 USA INTELLIGENCE CEN AND SCH ATTN: ATSI-DP
1 MARINE CORPS INSTITUTE
1 NAVAL SAFETY CENTER /
1 USAAVNC AND FT. RUCKER ATTN: ATZQ-ES
1 US ARMY AVN TNG LIBRARY ATTN: CHIEF LIBRARIAN
1 USAAVNC ATTN: ATZQ-D
1 US MILITARY ACADEMY DIRECTOR OF INSTITUTIONAL RSCH
1 USA AIR DEFENSE SCHOOL ATTN: ATSA-CD-MS
1 USAADS-LIBRARY-DOCUMENTS
1 USA AIR DEFENSE BOARD ATTN: FILES REPOSITORY
1 USA INFANTRY BOARD ATTN: ATZB-IB-AE
1 USA INTELLIGENCE CEN AND SCH ATTN: ATSI-DT-SFL
1 USA ORDNANCE CEN AND SCH ATTN: ATSL-TD-TAC
1 USA ARMOR SCHOOL ATTN: ATZK-TD
1 USA ARMOR CENTER DIRECTORATE OF COMBAT DEVELOPMENTS
1 NAVAL POSTGRADUATE SCH ATTN: DUDLEY KNOX LIBRARY (CODE 1424)
1 USA TRANSPORTATION SCHOOL DEPUTY ASST. COMMANDANT EDUCA. TECHNOLOGY
1 USA SIGNAL SCHOOL AND FT. GORDON ATTN: ATZH-ET
1 USA ARMOR CENTER + FT. KNOX OFFICE OF ARMOR FORCE MGT + STANDARDIZATION
1 CHIEF OF NAVAL EDUCATION AND TNG /
1 USA SIGNAL SCHOOL + FT. GORDON EDUCATIONAL TECHNOLOGY DIVISION
1 HQ ATC/XPTD TRAINING SYSTEMS DEVELOPMENT
5 USA INTELLIGENCE CEN AND SCH ATTN: ATSI-ERM
1 US ARMY ARMOR CENTER ATTN: ATZK-TD-PMO
1 USA QUARTERMASTER SCHOOL DIRECTORATE OF TRAINING DEVELOPMENTS
1 US COAST GUARD ACADEMY /
1 USA TRANSPORTATION SCHOOL DIRECTORATE OF TRAINING + DOCTRINE
1 USA INFANTRY SCHOOL LIBRARY /
1 USA INFANTRY SCHOOL ATTN: ATSH-I-V
1 US ARMY INFANTRY SCHOOL ATTN: ATSH-CD
1 USA INFANTRY SCHOOL ATTN: ATSH-DOT-LRD

1 USA INFANTRY SCHOOL ATTN: ATSH-EV
1 USA MP + CHEM SCH/TNG CEN + FT. MCCLELLAN ATTN: ATZN-PTS
1 USA MP + CHEM SCH/TNG CEN + FT. MCCLELLAN DIR. COMBAT DEVELOPMENT
1 USA MP + CHEM SCH/TNG CEN + FT. MCCLELLAN DIR. TRAINING DEVELOPMENT
1 USA MP + CHEM SCH/TNG CEN + FT. MCCLELLAN ATTN: ATZN-MP-ACE
1 USA INSTITUTE OF ADMINISTRATION ATTN: RESIDENT TRAINING MANAGEMENT
1 USA FIELD ARTILLERY SCHOOL MORRIS SWETT LIBRARY
1 USA INSTITUTE OF ADMINISTRATION ACADEMIC LIBRARY
1 USA WAR COLLEGE ATTN: LIBRARY
1 USA ENGINEER SCHOOL LIBRARY AND LEARNING RESOURCES CENTER
1 USA ARMOR SCHOOL (USARMS) ATTN: LIBRARY
1 ORGANIZATIONAL EFFECTIVENESS CEN + SCH ATTN: LIBRARIAN
1 US ARMY INTELLIGENCE CENTER + SCHOOL ATTN: ATSI-TP
1 US ARMY INTELLIGENCE CENTER + SCHOOL ATTN: ATSI-RM-M
1 US ARMY INTELLIGENCE CENTER + SCHOOL ATTN: ATSI-TD-PM
1 US ARMY INTELLIGENCE CENTER + SCHOOL ATTN: ATSI-CD-CS
1 US ARMY INTELLIGENCE CENTER + SCHOOL ATTN: ATSI-ES
1 DEPARTMENT OF THE AIR FORCE AIR UNIVERSITY LIBRARY (ATC)
1 HQ TRADOC TRAINING DEVELOPMENT INSTITUTE
2 BRITISH EMBASSY BRITISH DEFENCE STAFF
2 CANADIAN JOINT STAFF
1 COLS (W) LIBRARY
1 FRENCH ARMY ATTACHE
1 AUSTRIAN EMBASSY DEFENSE, MILITARY AND AIR ATTACHE
3 CANADIAN DEFENCE LIAISON STAFF ATTN: COUNSELLOR, DEFENCE R AND D
1 ROYAL NETHERLANDS EMBASSY MILITARY ATTACHE
1 CANADIAN FORCES BASE CORNWALLIS ATTN: PERSONNEL SELECTION
2 CANADIAN FORCES PERSONNEL APPL RSCH UNIT
1 ARMY PERSONNEL RESEARCH ESTABLISHMENT
1 NETHERLANDS EMBASSY OFFICE OF THE AIR ATTACHE
6 LIBRARY OF CONGRESS EXCHANGE AND GIFT DIV
1 DEFENSE TECHNICAL INFORMATION CEN ATTN: DTIC-DDA-2
140 LIBRARY OF CONGRESS UNIT DOCUMENTS EXPEDITING PROJECT
1 US GOVERNMENT PRINTING OFC LIBRARY, PUBLIC DOCUMENTS DEPARTMENT
1 US GOVERNMENT PRINTING OFC LIBRARY AND STATUTORY, LIB DIV (SLL)
1 THE ARMY LIBRARY ATTN: ARMY STUDIES SEC
3 / /

NUMBER OF ADDRESSEES 222

TOTAL NUMBER OF COPIES 406

*U.S. GOVERNMENT PRINTING OFFICE: 1981--361-662/2804

SUPPLEMENTARY

INFORMATION

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Corrected Copy

AD-A109 907

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report 540	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SOURCEBOOK OF TEMPORAL FACTORS AFFECTING INFORMATION TRANSFER FROM VISUAL DISPLAYS		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. Sekuler & P. D. Tynan R. S. Kennedy		8. CONTRACT OR GRANT NUMBER(s) N61756-76-M-5961
9. PERFORMING ORGANIZATION NAME AND ADDRESS Psychology Department, Northwestern University, Evanston, Illinois; Canyon Research Group, Westlake Village, CA		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2Q162722A777
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Research Institute for the Behavioral and Social Sciences, 5001 Eisenhower Avenue, Alexandria, VA 22333		12. REPORT DATE June 1981 13. NUMBER OF PAGES 177
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

This report was funded as a collaborative effort by the U.S. Army Research Institute with the U.S. Naval Pacific Missile Test Center, Point Mugu, California and U.S. Naval Biodynamics Laboratory, New Orleans, Louisiana.

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

Temporal factors	Vision	Illusions
Human Engineering Design Criteria	Vection	Dynamic Visual Acuity
Visual Displays	Motion Perception	Display Design
Military Standards	Flicker	
Contract Sensitivity	Brightness Enhancement	

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

This report collects in one document the important research literature on temporal factors in vision. Over 350 scientific articles are cited herein and this represents approximately 10 percent of the data base which was consulted. The literature searched was comprised of the following: 1) several thousand articles (under the general rubric <u>temporal factors</u> and <u>information processing</u>) from existing reprint files of the authors and others; 2) <u>Ergonomics Abstract</u>, <u>Psychological Bulletins</u>, <u>Psychological</u>

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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)		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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)

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

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(Item 19 Continued)

Spatio Temporal Interactions

(Item 20 Continued)

Reviews and Human Factors for the last 12 years; 3) a listing from two automated look-up systems (Psychological Abstracts 1967-present and National Technical Information System 1964-present). An integrative review of the literature is provided and three chapters are included which deal with application of these findings to display design. The subject matter is perception of temporal events--specifically motion perception (real and apparent) and flicker/flash sensitivity. A small chapter covers some temporally based phenomena which distort or degrade perception. Features of these phenomena may be observed in visual displays. Only studies which report findings which are robust enough to be expected to be important outside the laboratory are included. Where sufficient data were available, equations are provided to the engineer for the calculation of design criteria (e.g., peripheral motion threshold, contrast thresholds, contrast thresholds and age, etc.). Where gaps exist in our scientific knowledge, recommendations are provided for applied research. General guidelines are offered for incorporating design criteria into Military Standard 1472 for perceptions due to temporal events.

SUPPLEMENTARY

INFORMATION

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Corrected Copy

AD-A109907

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report 540	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SOURCEBOOK OF TEMPORAL FACTORS AFFECTING INFORMATION TRANSFER FROM VISUAL DISPLAYS		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. Sekuler & P. D. Tynan R. S. Kennedy		8. CONTRACT OR GRANT NUMBER(s) N61756-76-M-5961
9. PERFORMING ORGANIZATION NAME AND ADDRESS Psychology Department, Northwestern University, Evanston, Illinois; Canyon Research Group, Westlake Village, CA		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2Q162722A777
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Research Institute for the Behavioral and Social Sciences, 5001 Eisenhower Avenue, Alexandria, VA 22333		12. REPORT DATE June 1981
		13. NUMBER OF PAGES 177
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

This report was funded as a collaborative effort by the U.S. Army Research Institute with the U.S. Naval Pacific Missile Test Center, Point Mugu, California and U.S. Naval Biodynamics Laboratory, New Orleans, Louisiana.

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

Temporal factors	Vision	Illusions
Human Engineering Design Criteria	Vection	Dynamic Visual Acuity
Visual Displays	Motion Perception	
Military Standards	Flicker	Display Design
Contract Sensitivity	Brightness Enhancement	

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

This report collects in one document the important research literature on temporal factors in vision. Over 350 scientific articles are cited herein and this represents approximately 10 percent of the data base which was consulted. The literature searched was comprised of the following: 1) several thousand articles (under the general rubric temporal factors and information processing) from existing reprint files of the authors and others; 2) Ergonomics Abstract, Psychological Bulletins, Psychological

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

(Item 19 Continued)

Spatio Temporal Interactions

(Item 20 Continued)

Reviews and Human Factors for the last 12 years; 3) a listing from two automated look-up systems (Psychological Abstracts 1967-present and National Technical Information System 1964-present). An integrative review of the literature is provided and three chapters are included which deal with application of these findings to display design. The subject matter is perception of temporal events--specifically motion perception (real and apparent) and flicker/flash sensitivity. A small chapter covers some temporally based phenomena which distort or degrade perception. Features of these phenomena may be observed in visual displays. Only studies which report findings which are robust enough to be expected to be important outside the laboratory are included. Where sufficient data were available, equations are provided to the engineer for the calculation of design criteria (e.g., peripheral motion threshold, contrast thresholds, contrast thresholds and age, etc.). Where gaps exist in our scientific knowledge, recommendations are provided for applied research. General guidelines are offered for incorporating design criteria into Military Standard 1472 for perceptions due to temporal events.

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)		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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)

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

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)