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SYSTEMS RESEARCH
JOHNS HOPKINS UNIVERSITY

LECTURES ON MEN AND MACHINES

166-I-19

SYSTEMS RESEARCH

operates under

Contract N5-ori-166, Task Order I

between

SPECIAL DEVICES CENTER

OFFICE OF NAVAL RESEARCH

and

THE JOHNS HOPKINS UNIVERSITY

Studies are conducted at

Systems Research Field Laboratory, Jamestown, Rhode Island
Electrical Engineering Laboratory, The Johns Hopkins University
Psychological Laboratory, The Johns Hopkins University

and under subcontract with

Industrial Engineering Laboratory, New York University
Motion-and-Time Study Laboratory, Purdue University
Applied Psychology Laboratory, Purdue University
Psychophysical Research Unit, Mount Holyoke College

concerning

Basic psychological, physical, and motion-and-time studies relevant to military information systems and devices

Lectures on

MEN AND MACHINES

An Introduction to Human Engineering

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Lectures on MEN AND MACHINES

An Introduction to Human Engineering

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1947

FOREWORD

Human engineering is the application of human factors to engineering design. Before there can be much human engineering, however, there must be basic research to discover more about these human factors: the capabilities and limitations of normal adults as seeing, hearing, manipulating, talking, and understanding mechanisms. With this knowledge, the linkage between men and their machines can eventually be improved, and the combination of several men and machines into any type of efficient system can eventually be bettered.

Only within the last few years have most of us realized how little of practical value is known about the coordination between man's senses and his muscles. During the war, this ignorance frequently cost us much in both men and materials. To fill some of the specific gaps in our knowledge, a great deal of psycho-physical research was started. One of the resulting efforts was the Harvard "Systems Research" contract -- sponsored by the Navy's Bureau of Ships and financed by the Office of Scientific Research and Development -- a project to improve the complex information systems which made up our shipboard Combat Information Centers.

At the end of hostilities, "Systems Research" was continued through a contract between The Johns Hopkins University and the Special Devices Center, Office of Naval Research. It was as a part of this contract that the ten excellent lectures, reprinted in this pamphlet, were delivered to the Naval Postgraduate School, Annapolis, in the spring of 1947.

The four men who wrote and delivered these lectures are a remarkable group. All of them are quite young, but each has made significant contributions in research and publication in his field of competence. Dr. Clifford T. Morgan, Chairman of the Department of Psychology and Director of Systems Research, is the author of "Physiological Psychology," the most widely accepted text in its field. His concept of the analysis of psychophysical (man-machine) systems in Chapter V makes a distinct contribution on that subject.

Before joining Systems Research, Dr. Alphonse Chapanis, of Johns Hopkins, was associated with the Army Air Forces Aero-Medical Laboratory for four years. There he conducted a number of researches on psycho-physical problems in flying and on visual factors in aircraft design. Now, his principal activities are in the field of visual displays, the design of experiments and the statistical treatment of data. His use of formulae for analysis of variance in Chapter II marks real progress in developing procedures for the quantitative separation of human and mechanical factors in man-machine operations.

Dr. Wendell R. Garner, of Johns Hopkins, has several researches to his credit before joining the Systems Research Laboratory. First, at Harvard, he worked on counter-measures problems at the Radio Research Laboratory, and later on communications problems at the Psycho-Acoustic Laboratory. He became a member of Systems Research when it began at Harvard and transferred with it to The Johns Hopkins University. He is now doing research on auditory signaling systems and on the visual display of radar information. In Chapters VI and VII he gives a brief summary of our present knowledge, both basic and practical, of the psychophysics of communications and auditory signals.

Dr. Fillmore H. Sanford, of the University of Maryland, the fourth psychologist of the group, is by specialty a semanticist. It was he who took the technical academic phrasings of the three research scientists and helped present their data in more easily readable form. He has "dumbed down" a highly specialized professional terminology to the level of general non-professional appreciation.

These lectures, the first coherent public discussion of their subject, show the work which has been done and, even more vividly, the work which still needs doing. The physiological psychologists, whose study is normal man (as opposed to the study of the more highly publicized abnormal), are now beginning to discover this needed basic knowledge -- knowledge to be applied by the mechanical and electrical and industrial engineers in their problems of design and installation.

The Navy has sponsored this project because the Navy expects to profit from it -- profit in terms of machines and systems of machines better designed to fit the men who operate them. But the full value of the work in the years to come will be in civil life, wherever men build tools for other men to work with.

J. C. Wylie
Commander, U. S. Navy
Technical Officer, Systems Research

PREFACE

For years experimental psychologists have worked diligently in academic laboratories studying man's capacities to perceive, to work and to learn. Only very slowly, however, have the facts and methods which they have assembled been put to use in everyday life. A particularly glaring gap in modern technology, both industrial and military, is the lack of human engineering -- engineering of machines for human use and of engineering human tasks for operating machines. Motion-and-time engineers have been at work for years on many of these problems, but the experimental psychologist is also needed for his fundamental knowledge of human capacities and his methods of measuring human performance.

The recent war put the spotlight on this gap. The war needed, and produced, many complex machines, and it taxed the resources of both the designer and the operator in making them practical for human use. The war also brought together psychologists, physiologists, physicists, design engineers and motion-and-time engineers to solve some of these problems. Though much of their work began too late to do any real good, it has continued on a rather large scale into the peace.

Today there are many groups busy with research on man-machine problems. They use different names to describe the work in its various aspects: Biotechnology, Biomechanics, Psycho-Acoustics, Human Engineering, Psychophysical Research, and Systems Research. Other names might also be appropriate and may appear in the future. In these lectures, we have used two terms, Psychophysical Systems Research and Human Engineering. But whatever the name, the objective is the same -- to develop, through fundamental research and applied tests, a science which can deal adequately with the design and operation of machines for human use.

Human engineering, being a young field, has no textbooks. One cannot even compile a short bibliography which will give a reasonably complete view of the field. In addition to our research effort, we are still in the stage of compiling information and methods from all sorts of places: from textbooks of experimental psychology, physiology, physics, and motion-and-time engineering; from the journals of these professions; and from many previously classified reports which have not yet seen the light of day. As a consequence, we, who are in human engineering research, are hampered by a lack of well-compiled reference material, and we have a hard time telling our potential customers, the design engineers, what we are about.

We therefore jumped at the invitation of the Naval Postgraduate School to give a series of lectures on human engineering to the postgraduate engineering students at the school. This let us tell a large group of well-selected engineering officers -- men who, in the future, will be responsible for putting human engineering to work in the Navy -- what human engineering is all about. It also made us make the first attempt at digging out and compiling information for our own use and that of our colleagues in the field.

These lectures, we know perfectly well, are only a first attempt. We had only a few weeks notice, and we had to work them out hurriedly while engaged nearly full time on other activities. They have many shortcomings in thoroughness, in balance, in accuracy and in exposition. Now, in order to get copies into the hands of those who want them, we are publishing them within six weeks after the last lecture was given. Naturally there has been no time to revise them or to make the many improvements which we, the authors, know are needed. We hope that you who read them will accept our apologies for the errors you may find, for the imperfect reproduction and arrangement of illustrations, or for any other shortcomings of the text.

To the Head of the Naval Postgraduate School and his staff, we express our appreciation for their splendid cooperation in the various details of preparing and presenting these lectures. We are also grateful to the officers who listened to them and who made many constructive comments about their weaknesses and good points. We also commend the splendid efforts of our staff members who worked so hard to prepare them for publication on schedule: Mrs. Elizabeth Behenna and Mrs. Marion Chapanis, who typed the manuscript; Mr. John Spurbeck and his assistant Mrs. Helen Battams, who drew or photographed all of the illustrations; Mrs. Dorothy Reed, Editorial Assistant, who worked many hours overtime to prepare the manuscript for the lithographers; and Miss Helene Kuhn, Administrative Assistant, who has coordinated the efforts of the authors, the artist, the editor and the lithographers.

Baltimore, Md.
20 June 1947

Clifford T. Morgan, Director
Systems Research

CONTENTS

I: DEFINITIONS, HISTORY AND PURPOSE

OBJECTIVES OF LECTURES

This is the first of a series of ten lectures -- ten lectures on psychophysical systems research.

Whenever somebody is bold enough to barge into a series of lectures, there ought to be some purpose behind his behavior. Even if he is giving only one small lecture it sometimes helps if there is a definite objective in mind. Tea-time small-talk can get along nicely, though bare naked of purposes -- dignified or scientific purposes, that is -- but somehow lectures ought to do better. They ought not only to have purposes. It is also nice if the people who have to listen to the lectures know what the purposes are. This series of lectures does have a purpose. In fact, it has three purposes.

Definition. The first of the three objectives is to give you some notion as to just what psychophysical systems research is. You are probably scratching around intellectually to find some meaning to bring to this imposing term. We will join you in hunting for a precise definition, for we at present do not possess or know of one. Probably the main reason the topic lacks clear definition is that it is such a new field. You could not rightfully call it more than four or five years old.

We are not at this point going to try to make a nice clear statement about the definition of the field we are going to look at. Being realistic individuals, we will not attack, except under explicit orders, unless there is at least a small chance of victory. But even though a happy definition cannot be stated, those of us who have been working in this field have the comforting impression that we know what we are working on. In addition, we can point to our work and our problems, even though we may hem and haw when we try to describe and define. Here we are going to try to give you mainly a pointing definition -- a definition by example -- of psychophysical systems research. That is purpose one.

Methods. The second objective of the series of lectures is to give you a good look at the methods used in this type of research -- a look at the ways people have devised for getting good answers to good questions in this field. We will pay particular attention to these methods as they apply to life in the Navy. This field has, to a large extent, grown out of wartime research. While we can not say this field has value only for military problems, still we can say that one of the major interests of this type of research is, and probably will continue to be, problems of naval warfare. The research methods used in this research are in many respects different from methods used in other scientific branches. These methods are not new. But they have been applied in new ways to new problems. The second lecture of this series will wrestle mainly with these methods. We need to understand the methods before we can really come to grips with the facts. So presenting methods is objective two.

Facts. The third objective of this series of lectures is to survey the field of knowledge about psychophysical systems. This survey will cover the last eight lectures of the series, dealing with facts of two general types. In the first place, wherever possible, we shall state general facts. General facts are facts that apply to general cases and general situations. This field is so new, however, that such generalizations of facts are difficult to find.

In the second place, we will state specific facts people have busily accumulated during the war, and to some extent in years prior to the late war. There is an abundance of specific facts applying to specific situations. Whenever these specific facts seem to have some general application, we of course will look at them closely, whether they come from our chosen field or from some other type of research. In most cases the specific facts will be concerned with the effective operation of systems of transferring information and combat information centers. Problems in these areas are of primary interest to us at the present time. But we do not want to get ahead of our lectures, and you will be hearing more of that sort of material later in the series.

THE FIELD OF PSYCHOPHYSICAL SYSTEMS RESEARCH

Definitions

A moment ago, we dodged the problem of defining Psychophysical Systems Research. But I am afraid we cannot get along permanently without facing the problem of definition. A good definition of any term should surely tackle the meaning of every word in that term.

Research. First let us take the last word in the total phrase, psychophysical systems research. And let us start out along a familiar path, following the worn words of Webster. According to Webster, who claims to define anything, research is "the careful or critical examination in seeking facts or principles; diligent investigation." In general, that definition will do for now, with the possible exception that we would like to say "seeking new facts or principles." Thus research is a diligent search for facts or principles -- particularly, facts or principles which are new.

Systems. Again according to our man Webster, a system is an "assemblage of objects united by regular interaction or interdependence." And again that definition will, in general, suffice for our purposes here. Particularly if we give it say, three minutes, to sink in. But it should be pointed out that there are systems and then, again, there are systems; in other words, there are various kinds of systems. We might, for example, speak of the nervous system or of a transportation system. It is neither of these systems with which we are concerned, but they are systems, and they have something in common with the systems we are to deal with. That leads us to the third word in our phrase.

Psychophysical Systems. We are concerned here with psychophysical systems. A system is a scheme or arrangement of objects, but since we are here concerned with psychophysical systems, we are concerned with the scheme or arrangement of some fairly peculiar objects. On the one hand, those objects are physical, and on the other, they are "psycho" -- in other words, equipment and people. Thus we are interested in the interaction between the human being and the environment in which he moves. This environment, for our purposes, is mainly the equipment which he works -- or which works him. That is essentially the meaning which the term psychophysical adds to the general term systems research.

We have to make that distinction between psychophysical systems research and plain systems research because there are so many things which are called systems research. During the war we had systems of radar, we had systems of sonar, and we had systems of practically anything anyone can think of, including even, systems of system. For practical reasons during the war, the laboratory which we represent was called the Systems Research Laboratory. That name has stuck. It should be clear to you, however, that we are here concerned with psychophysical systems, and not just any system. We are concerned with systems of people and things.

Kinds of Psychophysical Systems

Even when we have resolved to worry only about psychophysical systems, we must still recognize that there are various kinds of psychophysical systems.

Aircraft Systems. We might, for example, speak of aircraft psychophysical systems. By that we would mean the system or interaction between aircraft crews and the instruments with which they must work. We might be interested in the pilot and his gadgets, or we might be interested in the tail gunner and the controls he uses or the instruments with which he works. We mentioned aircraft psychophysical systems because it is one area about which we now know a good deal. A large number of competent people tackled that problem during the war.

Communications Systems. To go off in another direction, we might be interested in communications systems. That is, we might be interested in the physical or the psychophysical systems needed to get good communication, spoken or otherwise, out of one human being at one place and into another human being somewhere else.

Information Systems. Our specific interest, however, is in informational transfer systems, specifically in combat information centers. Since radar played such a large part in the operation of a CIC, or combat information center, we have become interested to a large extent in radar systems. And we are interested from all points of view. We are also curious about systems of displaying information, and systems of getting information from one locale to another. And certainly not the least of our interests is the problem of the general coordination of various sources of information. In CIC, for example, information is received from many sources, displayed, classified, and retransmitted to other areas.

It should be made perfectly clear, however, that although these are our primary interests, they are not our only interests, since the method used in attacking many of these problems is to obtain basic and general information, which will apply to systems other than the one in which we happen to be working at the moment.

Human Engineering

In order to keep our vocabulary straightened out during these lectures, we should point out about here that the term human engineering is becoming more and more common in this field. The term human engineering, as we understand it, means essentially the same thing that we mean when we say psychophysical systems research. Since human engineering is somewhat easier to say than the slightly more accurate and definitely more cumbersome term we have been using, we will talk from now on as if the two terms are synonymous.

Other terms which have been applied to this type of work are: biomechanics, psychological problems in equipment design, and applied psychophysics. The many terms used are evidence of the newness of this field, and they all mean essentially the same thing.

So we, as human engineers, are concerned with man as a worker-with-machines. We are concerned on one hand with how the man works, and on the other with the equipment he uses in his work. If any brief definition can be given of psychophysical systems research, (or human engineering, or biomechanics, or any of the other terms) it would be that this is the branch of science which busies itself with man as a worker of machines, and with machines as things that man must work.

Relations between Men and Machines

In the actual working of experiments in this field, we quite frequently find that we are interested essentially in three different types of relations between men and equipment.

Man and Machine. In the first place, we primarily want to know about the interrelation between a man and a machine. We want to know what is the best way for a man to work with a particular machine, and we also want to know what is the best way to design a particular machine or instrument in order to get the most and the best out of it when it is used by a human operator.

Man and Man. In the second place, we are quite frequently concerned with relations between human beings when more than one of them is working in a machine or equipment environment. As equipment becomes more and more complicated, and more and more cumbersome, two or more individuals working together have a greater chance of getting in one another's hair. Thus, while the necessity for cooperation is greatly increased, the ability to cooperate is greatly decreased. The increased complexity of the area in which the men must work often makes it hard to tell what is cooperation and what is merely confusion happening to two people at the same time.

Machine and Machine. In the third place, we are interested, although not so frequently, in the relation of a machine to another machine. We must always remember, of course, that these machines have human beings in their environment. Thus, we are interested in physical systems insofar as those physical systems need to be modified to fit the men who are still necessarily around as operators. For example, from the purely physical point of view, a radio transmitter may work perfectly well as a transmitter. It does the things a good transmitter should. But when it is used as part of an elaborate system -- say some ground control approach system for controlling aircraft -- it may clutter up the works pretty seriously. Perhaps the use of any transmitter, however noble an instrument it is, is a poor idea. Maybe voice communications had better be left entirely out of aircraft control systems. That is the sort of curiosity we have about machines.

HISTORY OF PSYCHOPHYSICAL SYSTEMS RESEARCH

As an aid to getting the best slant on the type of problem involved in psychophysical systems research (or human engineering) and as a help in sizing up the present status of this branch of science, it seems desirable to dig a little into history. No new branch of science suddenly springs from nowhere to become a full-fledged member of the scientific world. Science grows. Usually its growth can be traced, and its ancestors can be pointed out with some reasonable certainty. And almost always, unlike some cases of alleged paternity you may know about, the father of a new branch of science rarely claims that he was in Salt Lake City or some such place at the time of conception. In the case of human engineering of the sort that concerns us here, there are three quite distinct lines of development which have led to the present status of this science.

One of these developments stems from the engineering sciences. The other two developments are rooted in psychology. We should like to go over with you briefly the history of each of these three developments in an attempt to show how this branch of science got the way it is today.

Time-and-motion Engineering

One of the scientific developments which has led to the growth of human engineering, or psychophysical systems research, is that of time-and-motion study. Time-and-motion study grew out of the engineering sciences, and the people who started it were engineers. There is a general distinction made between time studies and motion studies, in theory at least, although in practice it is quite difficult to separate the two types of studies.

Time Study. This involves the time-relation of motion and sequences of motion. The primary effort has been to find the best working rate, in order to set the base rate on which pay should be scaled. Credit for the beginning of time study usually goes to Frederick W. Taylor. Time study originated in the machine shop, and had its first application in 1881. At the present time, management uses time study in determining wage rates in industry. It does not have too good a general reputation, because people have made the ready assumption that the primary function of a time engineer in any industry is to get more work for less money out of the worker.

Motion Study. Credit for the development of motion study is usually given to Frank B. Gilbreth and his wife, Lillian M. Gilbreth. Motion study, unlike time study, is concerned primarily with the manipulations or movements which a human operator must make in performing any job. It usually consists of an analysis of those movements and an attempt to get at the best way of doing a particular job by studying the various possible ways it can be done. Several techniques have been developed from motion study, some of which have been very useful during the past war.

Micromotion Study. One of these techniques, for example, is the micromotion study. This technique consists of taking very high speed motion pictures of men doing a particular job. Then, in the analysis, the motions which cannot easily be seen as they actually occur can be very easily seen by slowing down the camera.

Such analyses of slowed-down movement have resulted in considerably improved performance on a great many different types of tasks.

While we are still on the topic of time-and-motion studies, we should remember that time-and-motion studies involve a very specific philosophy toward the worker and the machine. With time-and-motion study, it is assumed that the machine is already there, and that the task at hand is to determine the individual's best way of operating that machine. Thus, time-and-motion engineers, as they are called, are concerned with the human being in relation to the physical environment in which he must work. But they are primarily concerned with the human being, and not the machine. The machine is a given, a fixed entity. Time-and-motion engineers do not want to redesign equipment, do not want to make over systems of equipment. They are simply attempting to determine the best way to work in a given situation. And "the one best way to work," to use the Gilbreths' phrase, means the most efficient way to work in terms of total time and output.

Personnel Selection

One ancestral root of human engineering, then, goes back into time study, motion study, and time-and-motion study. Personnel Selection, a second historical feeder, reaches back into psychology.

Human Similarities and Differences. We might say that psychologists, in terms of their interests, fall into two general groups. Some are curious about human similarities. Others are interested mainly in human differences. Those who choose to worry about similarities work to find out what the average person can see, feel, hear or do under various conditions. To such investigators, the fact that people are not precisely alike is a major inconvenience. Those who wrestle with human differences do not look upon variability as a nuisance. It is the problem. We do not mean to say that psychologists belong to one or the other of two belligerent camps over this matter. In fact many psychologists are interested in both similarities and differences. But the two emphases, the two types of problem, can be discussed. The two emphases have led to two different developments in psychology. The interest in individual differences has given us the field of personnel selection as we know it today.

Selection of Intelligence. From its official birth around 1860 to the turn of the century, psychology was primarily a science of individual similarities. Individual differences were not considered much of a problem until a psychologist named Cattell, a fairly radical fellow in his day, came down with a worry about the rather wide differences among people. Cattell got interested in the way people differ in reaction time, in the ability to see, hear, smell and move, in the ability to solve problems. This curiosity about individual differences really blossomed during the first World War. For the first time, psychologists were able to get at vast numbers of people to see precisely how and how much they differed in various abilities. You are familiar with the intelligence tests born out of this research and used on a large scale in World War I.

Development of Tests. Intelligence Selection was the only selection used during that war, but the science got the impetus it needed. Psychologists did a tremendous amount of work on Selection problems between the two wars. Industry began using personjel selection techniques more and more. New tests were devised, tried out, revised, found good, and put to use. There were performance tests and paper and pencil tests, ability tests and interest tests, long tests and short tests, big tests and little tests. Almost any one of these tests, if properly used, could be shown to have a useful selective function. You have undoubtedly encountered some of these tests or some of the newer and better ones used during the recent war.

Selection of Operators. The development of selection techniques pointed out another aspect of the general problem of human beings working with machines. This branch of science or branch of psychology, developed because it was recognized that there is a best man for every job. Some men can do the same job better than other men, and there is not necessarily a correlation between how well a man can perform one job and how well he can perform anther job. By the time World War II had started, selection techniques were fairly mature. You are familiar with the tremendous number and variety of tests used for the selection of men for military jobs.

The philosophy involved in the technique of personnel selection is a little different from that involved in time-and-motion engineering. While time-and-motion engineers are interested in the one best way of work, the personnel selection men are interested in the best man for work.

Selection vs. Designed Jobs. There is no denying the very great significance of selection. In the general trend toward studying and doing something about the human being in his working environment, the studying of, and the doing something about, personnel selection has been, and is, of outstanding importance. We in the Systems Research Laboratory, however, are not primarily interested in this aspect of the total problem. We are interested in the man and the equipment with which he must work: we are interested in the design of the job, and we are interested in the design of the machine.

We have chosen not to engage in systematic worry about the fact that one man may be better than another on a given job. There are many other people who are very competently worrying in this area. Personnel selection has developed to such an extent that it is now a relatively complete and independent branch of psychology. Our attention is directed in the main toward a less well cultivated area. We want to study the average man and his performance rather than differences between men.

Experimental Psychology

The third development which has led to psychophysical systems research is experimental psychology. In case you are wondering why we call one sort of psychology 'experimental' psychology it might be well to point out that there are various kinds of psychology.

Non-experimental Psychologists. Unfortunately for those of us who are interested in the human being and his working habits, the kind of psychology which has become popularized and with which the average person is most familiar is not the kind of psychology in which we are interested. Just as the engineers have different kinds of engineer -- electrical engineers, mechanical engineers, civil engineers, chemical engineers, and so forth, so have psychologists divided themselves into various kinds of psychologist. Thus we have people whose primary interest is in personality and abnormal personality. We call this type of fellow a clinical psychologist to distinguish him from the laboratory experimental psychologist, and from other sorts of psychologist which we shall mention. The clinical psychologist is interested primarily in how people behave, how they develop, and why certain people do not behave in a normal fashion.

Another kind of psychologist which we have already mentioned is the personnel psychologist. He is primarily interested in individual differences and in selecting a man for a particular job in the selection problems we talked about a moment ago. This type of psychologist is employed primarily by industry in their personnel selection bureaus, and quite frequently the personnel manager of a large industry will have had his training in psychology.

Still another kind of psychologist is interested in the social interaction of human beings, in his social behavior, or his group behavior. These social psychologists do business with such things as public opinion polls, scales for measuring attitudes, propaganda devices, group morale and racial prejudice. We also have people who are interested primarily in educational problems, and we call them educational psychologists, or occasionally, school psychologists.

Experimental Psychologists. And last, but not least, we have what is called the experimental psychologist. Historically, the experimental psychologist has been around longer than any of the other types. The usual date given for the birth of experimental psychology is approximately 1878. This date, as in the case of most dates, is not exact, but will serve to give the general time when experimental psychology began to stand on its own feet. The experimental psychologist has in the past been interested primarily in the normal man, in the normal man as a perceiver and doer. Thus, the experimental psychologist has been interested in vision, in hearing, in tactual sensitivity, and in motor behavior. Because of these interests, the experimental psychologist has in the past worked mostly in university laboratories.

Shortly before the war this type of psychologist began to do some applied work in such fields as the design of lighting arrangements, design of instrument panels, and so forth. It was during the past war, however, that most of us were not-too-gently forced out of the laboratory and rather pointedly requested to become practical in our research. The demands during this past war were so great that they could not be ignored, and it was during the last war that experimental psychology merged with time-and-motion engineering to produce what today is called psychophysical systems research, or human engineering.

WARTIME DEVELOPMENTS

It was war, and the military problems which came along with that war, which brought psychophysical systems research to at least its adolescence. It has been possible for a long time pretty much to ignore the fact that every piece of equipment nearly always has a human being of some sort attached to it. In fact, the attached human being himself can forget that fact when the task is simple. Any human being can do a very simple task, and any human being can do it in almost any way. When, however, the task becomes more and more complex, and the equipment more and more intricate and far-reaching, the human being becomes more noticeable, more important, more demanding of alteration. He stands out because of his limitations.

Human Limitations

It was this last war which so increased the complexity of many of the tasks normally required of man that something had to be done to make the man more efficient. Or, to change the perspective 180 degrees, something had to be done to make the machinery more efficient, since it so often did not do what it was supposed to do because of the limitations of the human being who operated it. We can make a machine do almost anything, given enough development engineers, and enough time. The human being has, however, reached pretty much the limits of his development, at least the limits of his development as we ourselves can see it. There is not much that can be done about changing the human being now. We will have to leave that to Darwin. And it is conceivable that another war may happen before Darwin has evolved a superman to operate supermachines.

When we stop to think how much a single radar can do in a fraction of a second, and then stop to think also that even the simplest form of reaction for a human being requires approximately 1/5 of a second, we realize the limitations we are up against. This simple comparison of a machine's reaction time with a man's reaction time furnishes us with a clear cut example of what we are up against. The human factor in any system must be studied. Machines that demand super-human performance will fail because the human is not yet in a super stage. Jobs that push man beyond his limits of skill, speed, sensitivity and endurance will not be done -- cannot be done.

Physiological Limitations. One line of physical development which has thrown plenty of problems into the lap of psychophysical systems research is the modern aircraft. It has taken only about 40 years since Kitty Hawk to get an airplane so complex that we now are not only worried about whether a man can fly it, but are considerably uncertain as to whether he can even live in it. With the tremendous speeds now being obtained in modern aircraft, the purely physiological limitations of the human organism become a cardinal consideration for designers and engineers -- and for the organism with no wings who personally flirts with these limitations and Arlington Cemetery when he flies the aircraft of the future.

Psychological Limitations. Already there is much concern and some research devoted to finding what a man can bear and still live. A more immediate problem is what a man can bear and still work. It will hardly be enough that a man merely survives in an aircraft. He must also fly it. With this tremendously increased complexity of equipment during the past war came an increased recognition of the fact that something had to be done to make the human being a little more efficient in this environment We are now reaching a point where it is no longer of such prime necessity to develop better and better equipment. Better and better equipment does not insure better and better performance -- as long as man demonstrates a perverse disinclination to behave like a superman. Even now, it is surprising to remember that not until 1934 was anything done concerning the design of an airplane from the point of view of the individual who was to fly it. Before then considerable attention was paid to the selection of the pilot. This was sufficient since there were so few aircraft that pilots could be selected to fit the plane and the job.

But when more and more pilots are required, then the selection cannot be so rigid any longer, and the time comes when we must change from selecting the pilot for the plane or job and start selecting the plane or job for the pilot. The procedure had been: here is a bright and eager plane. Let us find a man who can get the most out of it. It has become more like this: here is a bright and eager young man. Let us find -- or design -- a plane that will get the most out of him.

In order to define more accurately the general field of psychophysical systems research, we will go through several specific types of development which have occurred during the war. For each, we shall attempt to point out briefly the nature of the problem involved, and the sort of solution which can be found. We are not attempting, in any of these cases, to present the wide variety of available facts. The time during this lecture is much too short for that, and they will be the subject of most of the future lectures.

Radar

With the exception of that well-known bomb, radar is probably the most surprising and rapid development of the past war. At the beginning of the war, radar was practically unknown in this country. It developed rapidly, however, due primarily to the organization of several very large laboratories where work was devoted exclusively to the development of new radar systems. What are some of the problems which were brought about by the development of radar?

A-scope Operation. In the first place, if you can remember back to the early part of the war, radar started out using only an A-scope -- a horizontal sweep on which appeared a vertical blip indicating the presence of a target. While the operator was looking for this blip, there was usually a large amount of noise, known as grass, and the operator was required to detect the presence of a pip in a lot of random grass. As many of you know, this game of pip-in-the-grass was not a relaxing sort of pastime. Later developments required the operator not only to find such pips but to match such pips in height. These were visual tasks which operators had not been required to do before, and it was essential that the operator do as well as was humanly possible. In jobs such as this, it is necessary to know the optimal working conditions for the operator; to know how long the operator can work and still tell pip from grass; to know under what conditions of lighting the operator can best work, and so forth.

Intensity-modulated Scopes. Later developments produced what is called the intensity-modulated scope -- the B-scope and the PPI. With developments of these scopes came still another visual task for the operator. He had to make a visual discrimination of a very small pattern against a dimmer, rather sketchy background pattern. Later in the war, another problem concerned with radar arose. If a radar can send out a signal and receive it, that radar can also receive some signals it does not want. This jamming, as it came to be known, made it even harder to see the right thing at the right time. The operator had to distinguish not only when a target appeared but also whether or not it was a legitimate target, or whether it was some enemy produced target being put in to confuse him

Fire-control Radar. Radar also required a form of coordination hitherto unnecessary. Radar as used in fire control, for example, quite frequently required two or three men to position the director, and consequently the gun. Previously a gun could be positioned pretty much by one man. But now we have a case where one man positions in bearing, another positions in range and still another positions in elevation. This is one of the problems we were referring to when we said that we are interested in man-to-man relations when working with physical systems.

It is in problems like this that the psychophysicist, or the human engineer, begins to go to work. He must determine what are the limits of visual discrimination. He must determine the optimal level of discrimination, and he must determine the work habits necessary to get the most efficient cooperation.

Communications

Communication was another field of development during the war which led to considerable interest in the problem of human efficiency in operation of equipment. The best communication happens when certain noises emanate from the mouth of one person, travel a short distance through air, and impinge on the ear of another person. Such communication seemed to satisfy people until fairly recently. But it has been found not to work too well when the listener is two hundred miles away in another ship or two feet away in the same PBM. So electronics comes in, bringing astounding feats of communication, and confounding problems of human engineering.

Noise Interference. Even when two people are talking with each other through air, there is always the problem of noise interference. It is well understood that if your listener is in the engine room you have to talk louder than if he were on the bridge at midnight. The same principle holds if your listener is on the receiving end of an intercom system. The system generally helps you talk louder but with the use of electronic means of communication a new source of noise is introduced -- that of electrical noise. Even though electronic means of communications enable people to talk over greater and greater distances that same development has made new noise reduction problems.

Sources of Interference. Electrical noises, of course, are not the only new noises that clutter up communications. The greater and greater speeds of aircraft, for example, mean greater and greater noise levels. Thus the faster a man flies through the air the more difficult it becomes for him to understand what other people are saying. One other communication problem that ties in with the development of newer and better aircraft is that of speech at high altitudes. Speech sounds are made by blowing air across vocal cords. When, at high altitudes, you start to blow, there seems to be very little to blow with. You have to blow abnormally hard to pick up enough air pressure to move a microphone diaphragm. Special microphones have to be developed to take into account decreased pressure at high altitudes. You might say that such microphones keep high altitude flyers from becoming blow-hards.

To do anything about these problems you have to improve radio telephone equipment, improve transmitters and improve receivers. We also have discovered during the war such surprising things as the fact that under conditions of considerable noise very badly distorted speech can be more clearly understood than high-fidelity speech. This is due to the fact that with a certain form of controlled distortion, you get more speech power out of the system.

Sonar

A third development, entirely new during this past war was that of underwater sound or sonar. A sonar system sends out a short pulse of very high frequency in sound, and picks up the returning impulse to indicate the presence of a target under water. Sonar does essentially under water what radar does in the air, although at much slower rate. Usually when the sonar signal, or reflection of a target is received, it is heterodyned to produce an audible tone. These tones are, however, of very short duration, and this short duration is one of the things which presents a problem. Offhand, it seems as though there is no particular problem with sonar -- it is a very simple matter to send out a pulse, to receive the pulse, heterodyne it, and listen to it. If you hear something, something is there. And, by judging the time it took for this tone to reappear, a very good estimate of the range of the target can be obtained.

Auditory Discrimination. That, however, is not all of the problem. When the pulse goes out, echoes are returned all the time -- some from water, some from seaweed, and some from objects on the surface of the water. Also, we know that all sorts of sounds come back from strictly neutral but often uncooperative fish. Out of all this mass of sound coming back, the operator is required to distinguish one particular sound, and to make a judgment about that sound. This distinction is usually made in terms of a difference in intensity. Furthermore, if the sound is reflected from the moving target, the frequency of the sound as it comes back will be either higher or lower than the frequency that was transmitted. This change in frequency gives rise to an indication of direction of movement of the target. If, however, the direction of the target is to be detected, the operator must be able to tell which direction the frequency has changed, and also how much the frequency has changed.

Psycho-Acoustic Research. All of these things present problems of hearing, problems which can be solved with normal experimentation. For example, as the duration of a tone is decreased, it begins to lose pitch character; therefore, the duration of the tone must be long enough that it can have a definite pitch character, but, on the other hand, it should be short enough to allow reasonable estimation of range. Also, the ear is more sensitive to changes in intensity with some intensities than with other intensities; thus, it seems reasonable that the equipment should be operated at an intensity level such as to give maximum sensitivity. The same phenomenon exists in the case of pitch, or frequency. The frequency should be heterodyned to give a range of frequencies in which the ear is most sensitive to changes in frequency, so that the operator can catch most quickly changes in direction of movement of target.

Aircraft Development

The advent of modern aircraft has produced a wide variety of psychophysical problems. With higher and higher speeds, pilots, and other members of the crew, must react faster and faster. The pilot cannot afford to take five or ten seconds to make a decision, for in that five or ten seconds he may have traveled several miles. Also, with the increased equipment on modern aircraft, the pilot and other members of the crew must attend to more and more instruments. Sometimes it is fatal to the pilot, if he happened to read a particular instrument wrong -- and he will very frequently read an instrument wrong if there are so many instruments around that he cannot spot the correct one. Still another aspect of aircraft development, is the fact, mentioned previously, that extremely high altitudes cause changes in the reactions of human beings, as well as changes in their physiological mechanisms.

Combat Information Centers (CIC)

The major development in which our laboratory is interested at the present time is the combat information center on war ships. In this one room, information must be collected, it must be displayed, it must be coordinated, and it must be retransmitted to many different areas. In CIC we not only have deposits of radar display and operation, but also display systems which are peculiar to CIC. One of the most serious problems, involved in the operation of CIC, is the coordination of information, and the cooperation of various individuals in providing that coordination. Out of the wrestling with these problems new systems for display have been developed. There are remote indicators with large screens on which to display polar coordinate information. We also have vertical plots and electromechanical systems of target designation. All these will be talked about later.

TYPES OF RESEARCH

In conclusion, we should like to point out briefly the various types of research which tend to get done in psychophysical systems research. Our long range aim is to provide a basic source of information which will be available for engineers in designing new equipment. If this information exists, new equipment may be designed according to principles of human engineering, rather than according to somebody's hunches. We also should like to design to a certain extent certain types of human tasks, again in terms of psychological principles which need not be immediately practiced. There is, however, a practical side to research, and much of our research at the present time is along very practical lines. By practical we do not mean to say that long range programs are not practical, but rather we simply mean that their value is not so much for the present as it is for the future. The problems on which we work can be divided roughly into five types.

Optimal Methods of Work. The determination of optimal methods of work with equipment that is already around is one type of research we undertake. It is the classical time-and-motion approach. That is, it assumes that the equipment is already there, and that the only task is to determine the best way for a man to perform a task with that equipment. This type of research is practical. It is immediately useful. And it also tends to be specific -- specific in the sense that the information obtained does not have the general application that we would like it to have. This type of research is, however, necessary -- especially when one considers how long it takes to completely design, build and install new equipment. A change in the method of operation can be made immediately while a change in equipment would probably take three years to bring about.

Appraisal. A second type of study we do, which is also very practical, is the appraisal of new systems or new pieces of equipment. In these types of problems what we usually attempt to do is simply to determine whether the new equipment performs a given function better than existing systems or equipment. This type of research is even more practical and more specific than the first type mentioned.

Improved Design of Instruments. This type of research is more basic and more long range. What we try to do is to establish general principles for the design of equipment. We may want to determine the optimal size of letters on dials, the optimal location of dials, the optimal location of cranks and other types of control, and the correct pressure which would have to be exerted on them. We also want to determine general principles for the design of display systems, and for the design of radar systems from the psychological point of view.

Improved Design of Tasks. With this type of work we hope to be able to classify various kinds of jobs, and to establish certain principles for the classification of such jobs. In such a way we can make the assignment of jobs more efficient. For example, it can be determined that certain types of operations should not be combined in the same person, since these operations conflict and would better be performed by two different individuals. Likewise we should be able to determine whether certain types of task can be better performed by machines alone or by inserting a man into the system to work in the machines.

Design of Systems. This last type of research is one of the most difficult to perform. With this we should like to determine the overall design of systems -- of systems of equipment and systems of men operating these equipments. For example, we should be able to design the optimal system for transmitting radar information to either guns or fire control directors. We should also be able to determine the best systems for displaying and coordinating various types of information. We likewise should be able to do something about the design of purely physical systems such as radar systems -- to keep the design in line with sound psychological principles.

Solutions to all these types of problems should be possible. We who work in psychophysical systems research believe solutions are possible. At least these are the kinds of problems we attack and the kinds of problems we make noises about.

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II. METHODS IN PSYCHOPHYSICAL SYSTEMS RESEARCH

In the first lecture of this series you had a look at some of the ancestors of psychophysical systems research, you were exposed to a definition of the field, and you saw a sample of the sort of problem this branch of science considers its own.

In this lecture we snould like to build upon that background. We want to build upon it by talking about (1) science and scientific method in general and (2) science and scientific method in particular as it is applied to, or exemplified by, psychophysical systems research. What is science? What is scientific method? What sort of science is psychophysical systems research? What sort of methods does it use in getting at its problems?

SCIENCE AND TECHNOLOGY

A good place to start, perhaps, is with the question of the difference between science and technology, a question that people have been thinking about a good deal recently. Though science and technology -- or basic science and applied science -- are pretty much birds of a feather, we can find fairly definite differences between them. If we can put our finger on these differences, we will be in a better position to see where psychophysical systems research is going and how it plans to get there.

Characteristics of Science

First let us consider the purpose of science. The general purpose of science is to discover basic relationships between phenomena. Examples of this principle are familiar to all of you. Scientists, for example, have been interested in discovering the relationships between voltage, resistance, and current flow in electrical circuits; the relationships between atoms in various sorts of chemical elements; the effect of extreme temperature on human behavior; the effects of x-rays on the growth of living cells; and so on. All along the line, the purpose is to uncover basic relationships.

Scientific Laws. In accomplishing this purpose, the scientist assembles a great multitude of observations on the phenomena he is interested in. He then attempts to catalogue them and sort them into meaningful groups. Finally he tries to deduce from these observations scientific laws or generalizations which describe the relationships he has observed. A famous scientific law of this sort is Newton's Universal Law of Gravitation. He stated, "Every particle of matter in the physical universe attracts every other particle with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them."

Generality of Scientific Laws. A very important thing about this type of scientific generalization or scientific law is its great generality. It applies to practically everything. It applies not only to the gravitational force between stars but also to the gravitational force between bodies of matter anywhere in the physical universe. (If the bodies are of the sort that have such things as motives and glands, the law of gravity may seem, upon occasion, to work itself out very peculiarly. But we can be reasonably sure that any human defiance of this law is only apparent. The law stands, inviolate.) From the basic law we can make all sorts of deductions about specific problems. We can, for example, account for the rise and fall of the tides. We can explain the behavior of falling bodies and we use the law as an important part of our calculations about the flight of projectiles.

Timelessness of Scientific Laws. Not only does the law have this remarkable generality but it is also, and just as importantly, possessed of timelessness. It applies not only anywhere but any time. It enables us to explain things which have already happened, things which are happening now, things about to happen and things that will happen in the distant future. Astronomers, who are generally pretty well checked out on the law of gravity, can use it to predict with an error of only a very few minutes -- they hope -- the appearance of Halley's comet in 1986.

We may summarize the approach of the basic or so-called pure scientist, then, as follows: (a) he makes many observations of whatever it is he is interested in, (b) he collects and arranges his data, (c) he pores over these data with the idea of hitting upon (d) some generalization which, he at least hopes, will describe once and for all the general relationships he has been studying.

Technology Equals Applied Science. The applied scientist or technologist or engineer usually does not worry about the discovery of basic and everlasting relationships in the field of natural or biological science. More usually he has a down-to-earth interest in applying basic laws, already around, to specific problems that confront him. The electronics engineer, for example, uses basic laws of electricity, basic knowledge about the entrails of electronic tubes, etc. He assembles these items of information so that he can work out electronic circuits for various specific purposes. He does not get himself excited about discovering basic relationships merely for the sake of discovering basic relationships.

Functions of Science

Let us apply this distinction between the basic and applied scientist to psychophysical systems research. As the first lecture pointed out, in somewhat different words, there are three essential classes of problems which can be attacked in this complex field.

Testing. One of these involves comparing two or more given systems with the very earthy purpose of finding out which one does better at its appointed job. In carrying out this kind of work, the scientist performs essentially what is the function of a testing laboratory, and the answers he obtains from this kind of approach are extremely specific. All that he can say is that System A is better or is worse than System B. Which often is a very handy sort of statement to make. But there are no generalizations obtained from such work. As a rule the results have very limited applicability. If somebody comes along with a new system, C, the comparisons have to be made all over again.

Engineering. The second approach to the problem of psychophysical systems research has more in common with the way the technologist or engineer goes about his business. This involves the application of basic knowledge to the design or evaluation of systems. For example, if we own a lot of sound, basic knowledge about the way human arms and legs work, we can probably do a better job when we set out to design radar or aircraft controls. Basic information regarding the visual acuity of human observers under certain conditions may also be applied to the design of various types of work compartments, dials, and display systems. It is important to point out, however, that the technologist or engineer depends primarily on the basic principles discovered by the "pure" scientist. He may sometimes "poo poo" basic research, but in his actual work he can go no further than available basic knowledge permits him to go. He is hogtied if the basic knowledge is not at hand. And when he applies this information to various types of systems, he discovers no new generalizations, no new basic knowledge.

Fundamental Research. The third approach to the problems of systems research is that of basic or fundamental research: that is, the discovery of bed-rock relationships between variables involved in the system. The emphasis here is on discovery rather than application of basic principles. This is probably the most important approach to these problems because the generalizations and the knowledge obtained are timeless and can be applied to systems which have not yet been made or which have never even passed through the gadget-filled dreams of designers. The principles are, furthermore, universally applicable. They can be used for various types of systems: aircraft systems, tank systems, or radar systems. This is, in short, the most efficient method from the standpoint of long range objectives in systems research. In the long run, the research-dollar buys more results this way.

"Pure" Facts. It is important to note, however, that in many cases the basic knowledge discovered in scientific investigations may lie dormant for decades before useful applications can be found for it. A good illustration of this is the use of red illumination for "ready rooms" and "dark-adapting rooms." The basic information about the sensitivity of the eye, upon which this application rests, was discovered 50 years ago. At the time it was considered to be purely a basic bit of knowledge, having nothing much to do with anything that mattered. When the war came along, however, and a problem arose, the hoary, "useless" old facts were dragged out and put to important use.

Science and Human Variability

The discussion of the various methods of attacking the problem of systems research has been presented in fairly simplified terms; but let us go back to the simplest procedure, that of comparison or evaluation of systems, and have a closer look at it. It turns out to be not quite so simple after all. It is not as simple as putting a meter onto an electronic circuit and determining the voltage output. It is not that simple because, as we have seen, psychophysical systems research involves people. And people cause all sorts of trouble. For one thing, they differ. How they differ and the sorts of trouble they cause by differing can be illustrated by a problem that arose 150 years or so ago -- a problem that we might regard as the first systems research problem to be tackled by scientists.

The Astronomer's "Error." For a long time astronomers have been trying to build more and more accuracy into their instruments. They soon discovered, however, that the limiting factor was inherent inaccuracy of the human observer. In one standard type of observation a telescope was pointed straight north or south; a star hove into sight and passed over a grid of vertical hair lines, the middle line being the exact meridian of the observatory. The problem for the astronomer was to decide at exactly what time the star passed this middle line. Great precision was important because this measurement constituted the time standard for clocks and watches throughout the world.

The first hint that something was wrong with this method came in 1795, whan a man named Maskelyne, head of the Greenwich Observatory in England, discharged an assistant for recording all star transits about a half second too late. Maskelyne estimated the error of his assistant by comparison with his own observations which he, being a chief and being human, naturally assumed to be correct.

Human Error Variability. Some decades later a German astronomer named Bessel ran across the Greenwich report containing an account of this incident. Bessel, for some reason, got curious. He began to test astronomers against each other. The results of this experiment showed that no two astronomers agreed precisely on the time of a given transit, although usually the difference between two skilled observers was well under a second. It seemed at first that there might be a constant difference between any two given individuals so that their measurements could be made to agree by the use of a constant correction factor. Further investigation, however, showed that the differences were by no means constant. The difference between any two astronomers varied with the magnitude of a star and with its rate of movement across the telescope field. So no two astronomers agreed with each other for long. As a result of these early investigations, more precise methods were gradually evolved for the measurement of star transit across telescopes -- methods that took into account individual differences.

Man vs. Machine Error. The moral of this story is clear.

In this early systems research project, the astronomers saw quite clearly that the limiting factor in the combination of man and machine is the man and not the machine. Man is the source of greater error. The second important point to notice about this historical incident is that it very clearly illustrated the magnitude of individual differences. Differences between individuals can be found in all sorts of capabilities. We know now, for example, that even in as simple a job as lifting a finger in response to a sound, the very fastest man is about twice as fast as the slowest man. Men with good night vision require only about one tenth as much light to see at night as do men with poor night vision. Individuals with good memory and intelligence can learn a series of numbers about ten times faster than individuals with poor capacity in this regard. And so it goes, through the entire gamut of human capabilities. People persist in differing -- from one another and often from themselves.

The "Average" Man. In psychophysical systems research, therefore, we cannot use a single man as a meter or test of a piece of equipment. We must use many individuals, selected at random, so that we have an adequate sample of the kinds of people who will be using these systems. We are primarily interested in similarities and not differences among men. Our generalizations and our findings, therefore, are usually stated in terms of what the average man can do with the type of system or machine he will have to work with.

THE DESIGN OF EXPERIMENTS

With this brief background, then, how does the investigator proceed when he attacks problems in psychophysical systems research? The methods of science are fairly clear cut. And in this sort of research, as in any other research you know about, the basic technique is controlled observation, or, as it is usually referred to, "the method of experiment." It is important to notice the use of the word "controlled" in the term "controlled observation." Mere observation is not enough. A man could observe a radar system for days and days on end and might come out with nothing more useful than the exclamation, "Ain't science wonderful?" or, "What will they think of next?" The complexity of radar systems and the variety of behaviors exhibited by individuals operating the systems may serve only to confuse the investigator. It has happened

Controlled Experiments

Traditionally, an experiment happens when you arrange conditions so that all factors are held constant except the one you are investigating. You then vary just what you want to vary, and watch. But let us see how we would apply this to an actual experimental situation. We talked a moment ago about dark adaptation. You know that if you go into a theater after leaving a brightly lit street, you cannot at first see the difference between an empty seat and a fat lady. Gradually as you sit in the theater, having felt that it was an empty seat, your eyes become more and more adjusted to the darkness until finally, after a half hour or so, you can see quite well. Many people observed this phenomenon in a general sort of way, but the scientist is interested in formulating more precise quantitative relationships for this function. How exactly would he proceed in setting down precise statements about dark adaptation?

Methods. First of all, he would formulate the problem carefully. In this case, he is interested in the relationship between the sensitivity of the eye and the length of time the eyes have been in the dark. These are the two variables which are to be studied systematically; everything else will be held constant. What does that mean? It means that he will do his experiment in a completely dark room. Extraneous sources of light, of course, would mess up his results. Next, the size of the test light must be held constant. The same color of test light must be used all the time because we know that the color of the test light makes a difference in the dark adaptation process. Then, too, we know that if you have just been looking at the sun, your eyes are blinded for quite a long time; whereas if you step into a dark room from a dimly lit room you can see fairly well. So, obviously the amount of previous exposure to light must be controlled. Finally, we must make some attempt to control a lot of other factors which concern the individual. The subjects should be fairly well rested, not fatigued, and they should be fairly normal observers with respect to their visual apparatus.

Results. Having thus arranged and controlled all of these various conditions, the completely dark room, the size of the light to be tested, the color of light, the previous exposure of the subject, and so on, the experimenter can now proceed to investigate the nature of this process known as dark adaptation. He does this by letting each subject record the least amount of light that is just barely visible at various times after going into a dark room. The results of such an experiment yield a curve such as is shown in Fig. 1. We see that the process of dark adaptation is really two processes. The sensitivity of the eye increases fairly rapidly (that is, it can see much dimmer lights) during the first few minutes; it then levels off, and in about ten minutes it suddenly shows another very sharp increase in sensitivity. This kind of experiment has been repeated many times, and in many laboratories. We know now that it accurately represents the increase of sensitivity of the eye as a function of time in the dark. This is what is meant by a scientific generalization. This kind of information has been extremely important during the war in furnishing us with the basic knowledge necessary for the solution of many problems concerned with seeing at night.

Let us stop a minute and underline what we said about the essential method of science being that of controlled observation. The scientist has to control his conditions in order to be sure of what he is getting. If our test at ten minutes were made with a pin point of light and at twenty minutes with a large lamp, our results would be, to put it mildly, contaminated by this extra variable. Obviously, the size of the light is an important variable which can be, and has been, studied in its own right. But in order to get meaningful data we must control this factor so as to discover its precise contribution to the total effect.

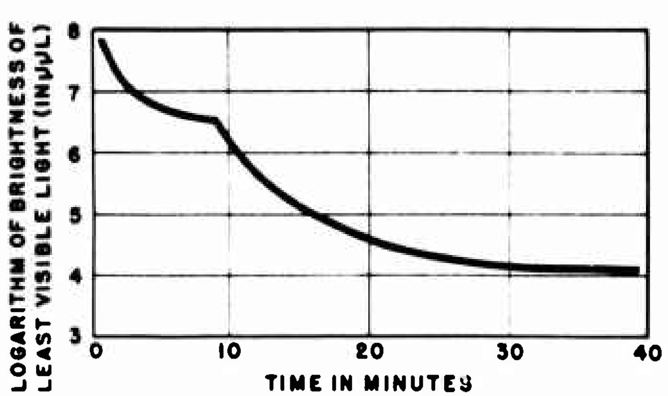


Fig. 1. Curve of normal dark adaptation measured with a 1/2° violet light, 7° peripherally in the visual field. (From Chapanis, 1945.)

Experiments with Several Variables

Newer types of experimental design have recently been evolved however, which have a number of advantages over this traditional type of experiment. The simple, traditional experiment controls every variable but one. That one is made to vary. The newer experimental designs involve the simultaneous, controlled variation of several factors. This makes them more applicable to problems in systems research. They are considerably harder to plan, however, and it would not be unfair to say that the scientist, in using this method, is like an architect -- except that in this case he is building an experiment instead of a house.

Experimental Design. Let us look at one of these experimental designs to see what the structure is like. Shown in Table I is a fairly simple design used in an experiment to measure the time required by operators to read bearing and range information from

Table I

Experimental Design Used in Studying the Speed of Reading Target Information from Various Types of Bearing and Range Indicators
(From Chapanis, 1946.)

OPERATOR	EQUIPMENT				
	SG	SR	VF	VJ	X
A	17(4)*	13(1)	14(5)	15(3)	23(2)
B	11(3)	5(5)	1(2)	18(1)	25(4)
C	20(5)	4(4)	9(3)	19(2)	6(1)
D	7(2)	21(3)	22(1)	8(4)	2(5)
E	3(1)	16(2)	12(4)	10(5)	24(3)

* The entries are the serial orders in which equipment and operators were tested. The numbers in parentheses designate the target list used in each test.

four types of standard Navy radar equipment, the SG and SR radars, and VF and VJ remote indicators, and from a direct-reading, counter-type bearing and range indicator of experimental design, indicated here by an X. Five operators were tested on each of these pieces of equipment and they are represented by the letters A, B, C, D, and E in the left-hand column on this table. The numerical entries in the table, those not in parentheses, represent the order in which the various combinations of operators and equipment were tested. You will notice that these numbers are randomized; that is, they follow no logical or coherent order.

Balancing Human Errors. There is a reason for this. If, for example, we were to test each operator on the SG radar first, you would not consider it a fair trial when we came to the SR because each of the operators might have learned something in going from the SG to the SR radar. Or, if we always tested the experimental counter last, that might not be fair because the operators might be tired out by the time they came to that test and hence would not give representative results. We must always worry about and do something about such things when our experiments deal with that most troublesome of all experimental animals, the human being. You will notice, for example, that each piece of equipment gets tested first once, each gets tested second once, and so on.

Balancing Testing Errors. Then, in this experiment, there were five separate target lists used. These are shown by the numbers 1, 2, 3, 4, 5, in parentheses in this table. It would obviously not be fair to test the SG radar with target list number one for all subjects, because target list one might conceivably be prejudiced in some way. It might, for example, contain difficult targets or very easy targets and in that way the results that we got from this piece of equipment would not be representative. Similarly it would not be fair to test operator A with one target list for all pieces of equipment because if we were to use the same target list time and time again, he would eventually get to recognize some of the targets and hence his results would not be representative. For this reason, the target lists are also randomized throughout the experiment.

We can see from an examination of this table that each piece of equipment gets tested once, and only once with each target list; and that each operator gets tested once, and only once with each target list. Each operator, however, gets tested with all the target lists; and each piece of equipment gets tested with all the target lists before the experiment is through. By such planning we are able to control certain factors concerned in an experiment of this sort, even though we vary systematically several other factors.

Analysis of Results. Let us look now at the results obtained from this experiment. Shown in Table II are the average times required by the various operators to read one bearing and one range from each of the pieces of equipment. If we average all these times across the table, that is, for all the pieces of equipment together, our averages shown in the right-hand column are the averages obtained for the operators. Differences between these averages represent individual differences in speed of reading targets from the scales and dials tested. If, on the other hand, we average our data down the columns, that is, for each piece of equipment, then our averages represent the average times required by the five operators to read a bearing and range from the particular set of dials and scales in each piece of equipment.

Table II

Average Times (in seconds) Required to Read a Target Bearing and Range from Various Types of Indicators
(From Chapanis, 1946.)

OPERATOR	EQUIPMENT					AVERAGE
	SG	SR	VF	VJ	X	
A	3.1	3.3	3.1	3.6	1.7	3.0
B	3.2	3.2	3.4	3.2	1.8	3.0
C	3.4	3.6	3.7	3.2	1.9	3.2
D	2.9	3.0	2.9	3.1	2.0	2.8
E	3.8	3.9	4.3	4.4	1.7	3.6
Average	3.3	3.4	3.5	3.5	1.8	

Differences between Operators. We can now see from the data in the right-hand column of this figure that there are some fairly sizeable differences between observers. Our operator D is the fastest. On the average he requires only 2.8 seconds to read a bearing and range from these various pieces of radar. Operator E, on the other hand, is considerably slower. He takes 3.6 seconds on the average to perform the same kind of job Expressed as a percentage, operator E requires about 29% more time than D.

Differences between Equipment. If we look at the average figures across the bottom of the table, we find that there are also some rather striking differences between the pieces of equipment. The SG, the SR, the VF, and the VJ radars require about the same amount of time in order for the average operator to read a bearing and range. These times are 3.3, 3.4, 3.5, and 3.5 seconds respectively. For the experimental piece of gear, however, we notice that the average time is only 1.8 seconds, which represents a reduction in time of about 47%. By means of a statistical technique called the analysis of variance, it is possible to put all of these values into the hopper and come out with the conclusion that the differences between the various operators are significant and that the differences between the various pieces of gear are also significant. And it might be worthwhile pointing out incidentally that when the statistician says something of this sort is significant he means that the differences are so large that they could not conceivably have arisen by chance.

Value of Experimental Design. The advantages of this type of experimental design are that it permits us to explore several variables simultaneously, and so is more economical. Also, it gives us greater generality of our findings. In this table, for example, we can see that the experimental piece of gear is better not only for operator A but is also better for operators B, C, D, and E. In this way we can feel pretty confident that about the same sort of results would have been obtained had we used a number of other operators. Similarly, if we examined the average times turned in by operator D we find that he is faster than anyone else on the SG, the SR, the VF and the VJ radars. This consistency of findings makes us pretty confident that operator D was probably born faster -- born with a faster reaction time, that is -- than the other four operators.

ANALYSIS OF SYSTEMS ERRORS

The procedures outlined thus far are the methods that the scientist would use were he doing his work in the experimental laboratory. Unfortunately in systems research it is not always possible to maintain the degree of control the scientist would like to have. For instance, if you were doing your experiment on board ship, the skipper might not cooperate completely when, for experimental purposes, it became desirable to have a heavy cruiser stand on beams end while you did a 10 minute study of a "B" scope. Various important factors in a system may escape deliberate manipulation. In investigating sources of error in reading target locations from the PPI on a radar, for example, the investigator discovers that not only is there a human source of error in these readings but the radar itself comes with some built-in error. The final range reading of a target, as given by the operator, is thus a combination of two sources of error: the operator's own error in locating, identifying, and reading the target location, and the inherent error of the instrument itself. Now, in a system of this sort, is it possible to analyze out the two sources of error?

Kinds of Psychophysical Error

In the analysis of errors in a system, it is important to distinguish between two concepts of error: (1) error as an algebraic difference between true and obtained measurements, and (2) error as an arithmetic, or absolute, difference between true and obtained measurements. An illustration will aid in clarifying these concepts. Suppose a radar set is used to obtain a series of range readings on a target. Let us call these ranges R_O, that is, range obtained from the radar. If the true range of the target is R_T, the error of our measurement, ϵ, is $R_O - R_T$. Now, if we obtain a large number of such error measurements and plot them graphically, we will probably find a set of values distributed as shown in Fig. 2.

Constant Error. In general, if the errors of the radar system and the operator are variable and if the radar set is calibrated, the discrepancy between the radar range and the true range will average around zero. This means that the obtained range will be too great as often as it is too short. If we took enough range readings from the radar set, the average obtained range would be a very close approximation to the true range. The plus errors and the minus errors will cancel themselves out. If the average error did not come out to be zero, but came out to be +500 yards, for example, we would have discovered what is known as a constant error in the radar system.

Let us pause for a moment now to summarize the preceding remarks in a slightly different way. The average difference, or average error, between true and obtained measurements tells us the constant error of our system if we take the direction of the errors into account. It is called a constant error because it indicates a consistent tendency for our readings to be too high or too low.

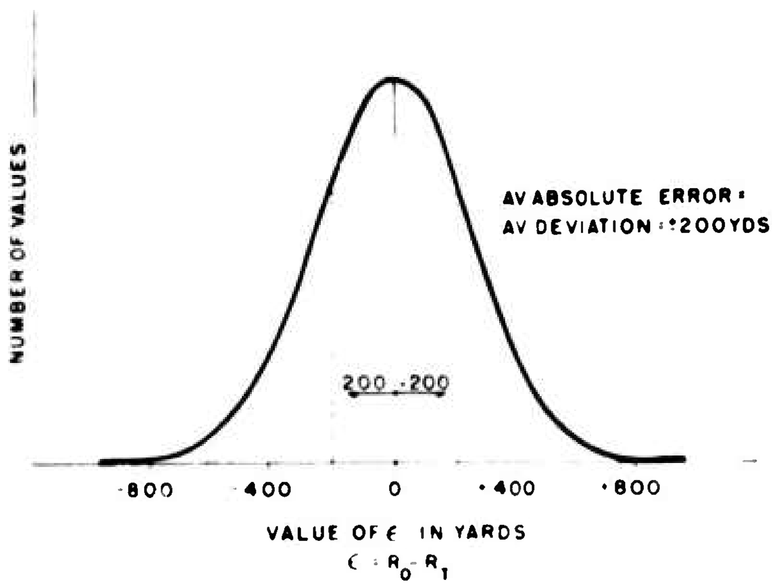


Fig. 2. Theoretical distribution of a large number of discrepancies (ϵ) between ranges obtained from a radar (R_O) and the true range of a target (R_T).

Variable Error. Although it is important to identify and measure the constant errors in systems, it is much more important to study what are known as the variable errors in a system. There are several reasons for this. In the first place, we do not have enough time to make a large number of range readings on a single target, and in the second place, we are not so much concerned with the direction of any error as with the absolute magnitude of it. Or we can put it this way: We have available only single estimates of the true range of a target at any time, and what we really want to know is "how far off" the single estimate is likely to be, irrespective of the direction of the error. In mathematical terms we are concerned with the absolute magnitude of ϵ, that is, $|R_O - R_T|$. The average of a large number of such measurements is equivalent to what the statistician calls the average deviation of the errors. This average deviation is a measure of the variable errors in our system. It tells us the most probable (or average) discrepancy between any one obtained range and the true range. In our previous illustration, the average deviation was 200 yards. This means that, or the average, any single range reading will be off by plus or minus 200 yards.

From a practical standpoint, the constant errors in a system are less important since it is always possible to correct for them. It is the variable errors which are true indicators of the inherent instability or inaccuracy of a system. To illustrate: If operators on a radar set always read ranges as 500 yards short of the true range, we could rectify the error by a simple correction in the electronic circuits or even in the dials.

The real source of difficulty, however, lies in the fact that an operator will give a series of readings, the first of which is 500 yards too short, the next 400 yards too great, the next 100 yards too short and so on. The reduction of these annoying variable errors constitutes one major objective of systems research.

The Accumulation of Psychophysical Error

A moment ago, we referred to the average deviation and defined it as the average absolute difference between the obtained and true range. This is shown as formula (1):

$$\text{A.D.} = \frac{\Sigma\,|R_O - R_T|}{N} \qquad N = \text{No. of Measurements}$$

For a number of good theoretical reasons -- which any chronic statistician would love to elaborate for you -- it is usually easier to work with variances instead of average deviations in analyzing systems errors. The formula for a variance is as follows:

$$\text{(2)} \qquad \sigma^2 = \frac{\Sigma\,(R_O - R_T)^2}{N}$$

It differs from that of an average deviation only in that the deviations are squared. The variance is still a measure of variable error.

Sum of Variance. Now, here is the crux of the matter. The variance of the error in our complete or total system is equal to the sum of the variances of the error contributed by individual parts of the system.

$$\sigma_T^2 = \sigma_{A+B+C+\dots}^2 = \sigma_A^2 + \sigma_B^2 + \sigma_C^2 + \dots \tag{3}$$

A good statistician, in an hour, could give you the proof of the equation. In two hours, perhaps we could give it to you. But since you are busy people, we had better ask you simply to have faith. This equation holds true so long as there is no correlation between errors in one part of the system with errors in other parts of the system. Fortunately for most systems research, this assumption of the random nature of errors appears to be justified.

The basic equation above does two things: First, it gives us some extremely useful information about the way errors accumulate in a system, and second, it enables us to analyze the magnitude of errors in certain parts of our system, if we know certain other errors in the system.

Distribution of Machine Error. In order to see how errors accumulate in a system, let us assume a fairly realistic example that might arise in a systems analysis with the VF remote radar indicator. The upper curve in Fig. 3 is a distribution of a thousand errors contributed to the final range readings by the VF itself. These errors include all sources of inherent inaccuracy in the radar system. This chart tells us that, of our thousand errors, 32 were of zero yards. There were 20 of our thousand measurements in which the actual position of the target was 16 yards less than the position shown on the radar. Similarly, there were 20 measurements in which the actual location of the target was 16 yards more than the position as shown on the radar. In short, this curve is a way of showing the numbers of errors we have at -30 yards, -20 yards, -10 yards, +10 yards, and so on. We have postulated here an average error (that is, an average absolute error) of plus or minus ten yards. On the average, then, the discrepancy between the actual location of a target and what the VF remote indicator says is the range, is plus or minus ten yards.

Man and Machine Error. Now, let us further assume that the average human error in operating the VF remote indicator is plus or minus 20 yards. That is to say, on the average, the operator is twice as inaccurate as the machine. What happens now when we accumulate both sources of error? The resultant error is shown by the lowest curve in Fig. 3. If we accumulate both the

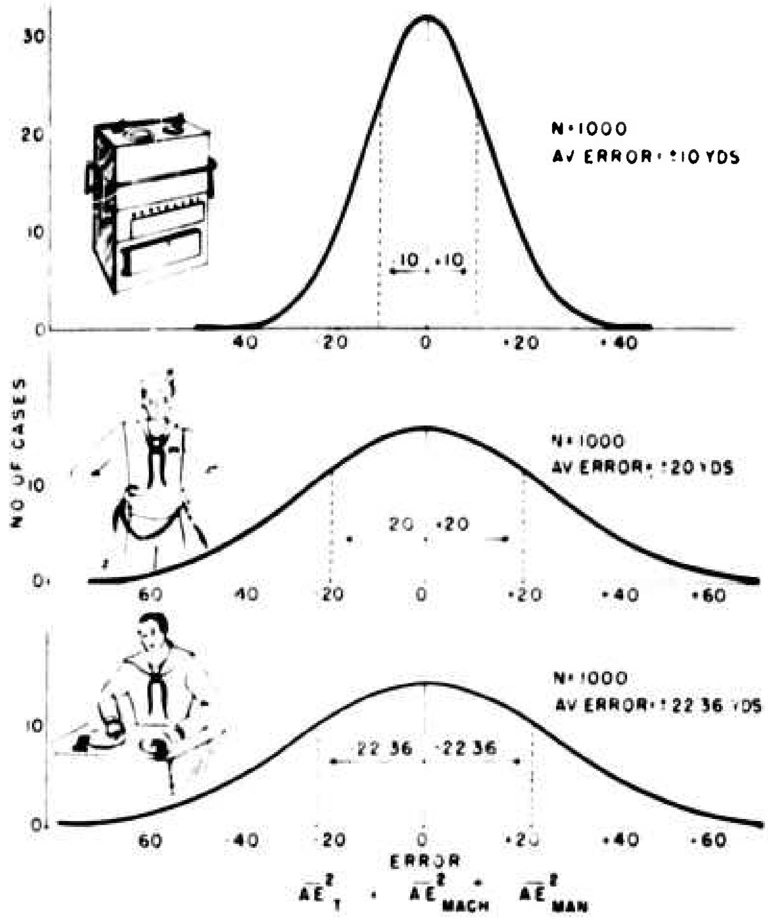


Fig. 3. Theoretical distributions of 1000 range errors made by a VF remote radar indicator (top), by an operator (center), and by the machine and man together (bottom).

inherent errors of the machine and the inherent error of the operator, the resultant error is not a simple sum of the errors from the two sources. The total error must be accumulated in a manner as shown by the equation:

(4) $$\overline{AE}^2_{MAN+MACH.} = \overline{AE}^2_{MAN} + \overline{AE}^2_{MACH.}$$

That is to say, we must square the machine's average error, add to this the square of the man's average error, and then we will have the square of the total average error. Although this method of accumulating errors in a system may not appear reasonable, a large number of studies at the experimental and mathematical level show it to be true. You will also recognize equation (4) as a simple variation of our basic equation (3) above.

Which Error Is Important? This sort of accumulation of error in a system has extremely important implications. In the first place, we notice that when we accumulate errors this way, the machine's errors amount to relatively very little. We have increased the average error of the man from 20 yards to no more than 22.36 yards by adding in the error of the machine.

What does this mean as regards the kind of problem that Systems Research should tackle? Let us look at the problem this way. If we were able to eliminate completely the inherent error of the machine, we would be reducing the average error of the final range readings by only 2.36 yards. This means, in short, that we can make our greatest contribution to increasing the accuracy of the man and machine combination, not by worrying about the accuracy of the machine, but rather by increasing the inherent accuracy of the operator. We are likely to get more for our money if we work on the man.

In the illustration above, it was assumed that the error of the man alone was twice as great as that of the machine alone. Now, see what happens as we increase this differential. If the average error of the man is plus or minus 30 yards and the average error of the machine is still plus or minus 10 yards (a ratio of 3 to 1) the average error of the man and machine is only plus or minus 31.6 yards. The addition of the machine-error to the man-error in this case has increased the total error by 1.6 yards, or five per cent. If the average error of the man is plus or minus 50 yards, and the error of the machine still plus or minus 10 yards (a ratio of 5 to 1), the average error of the man and machine is plus or minus 51 yards. In this case, adding the error of the machine to that of the man has increased the total error of the combination by only one yard or two per cent. Or, to state it another way, if we could make a perfect machine for this combination, we would reduce our final error by only two per cent.

The moral of this story should be clear. If at one point in our system we have an instrument or an operation which has a low inherent error, and if, further, in another location in the system, there is an operation or instrument which is relatively more inaccurate, it would not be economical to attack the operation which has the low source of error since its contribution to the total or resultant error is much smaller than we might at first suppose. Remember that it is not the addition of errors but the addition of squares of errors which makes up the final result.

Analysis of Variance as a Research Tool. This same basic approach provides us with a powerful tool for the determination of the error variance in one part of the system when certain other variances are known. Mathematically speaking, the basic formula is the one which shows that the total variance is the sum of component variances. Consider an experiment performed to measure the agreement between the range reading obtained on two VF remote indicators. The two VFs were operated simultaneously in reading ranges of a moving target. Now a range report obtained from one VF is a combination of the true range of the target plus the error of the VF itself. This is the formula:

(5) $$R_{VF_1} = R_T + \epsilon_{VF_1}$$

The VF error includes both the inherent inaccuracy of the VF and the error of the man who is operating the VF. Similarly, a range report from the second VF is equal to the true range of the target plus the error of the VF. Even if this is the only information we have -- even if we do not know the true range of the target at any time -- we can discover more about the inherent variability of the VF and operator by performing a few algebraic manipulations. First, let us find the difference between the corresponding ranges obtained on the two VFs. This subtraction is shown algebraically in the following formulas:

(6) $$R_{VF_1} - R_{VF_2} = \left(R_T + \epsilon_{VF_1}\right) - \left(R_T + \epsilon_{VF_2}\right)$$

(7) $$R_{VF_1} - R_{VF_2} = \epsilon_{VF_1} - \epsilon_{VF_2}$$

If we have determined a large number of such measurements on the two VFs, we may then write:

(8) $$\sigma^2_{(R_{VF_1} - R_{VF_2})} = \sigma^2_{e_{VF_1}} + \sigma^2_{e_{VF_2}}$$

This formula tells us that the variance of the differences between the range reports given by the two VF indicators is equal to the variance of the error contributed by the first VF, plus the variance of the error contributed by the second VF. In writing this equation (8), we again made use of our basic equation (3). Remember that the value on the left of the equal sign in equation (8) is the only value we measured. In this experiment, however, it is reasonable to assume that the errors of the two VFs are of about the same order of magnitude so that we may write this equation:

(9) $$\sigma^2_{e_{VF_1}} = \sigma^2_{e_{VF_2}} = \sigma^2_{e_{VF}}$$

Now, let us substitute the results of equation (9) into equation (8), in which case we get the following:

(10) $$\sigma^2_{(R_{VF_1} - R_{VF_2})} = 2\sigma^2_{e_{VF}}$$

(11) $$\sigma^2_{e_{VF}} = \frac{\sigma^2_{(R_{VF_1} - R_{VF_2})}}{2}$$

These formulas tell us that the variance of the error of one VF is equal to one half the variance of the differences between the range reports obtained on the two VFs. Thus, if the variance of the differences between range reports on the two VFs was 1500 yards, the variance of the error of one VF is equal to 750 yards. By performing a few other simple calculations we can then translate this variance into an average error and determine that the average error of one VF and its operator amounts to about 22 yards.

It is important to note in this example that it is impossible to determine the magnitude of the constant errors of the two VFs. Let us assume for example that the average difference between the range reports on the two VFs was -10 yards. This tells us that there is some constant error, either physical or psychological or both, in the operation of one or both of the VFs. But we cannot discover the magnitude of this constant error because one VF might be off by 100 yards, the other by 90; or one might be off by -30 yards and the other by -40, and the constant error would still be the same.

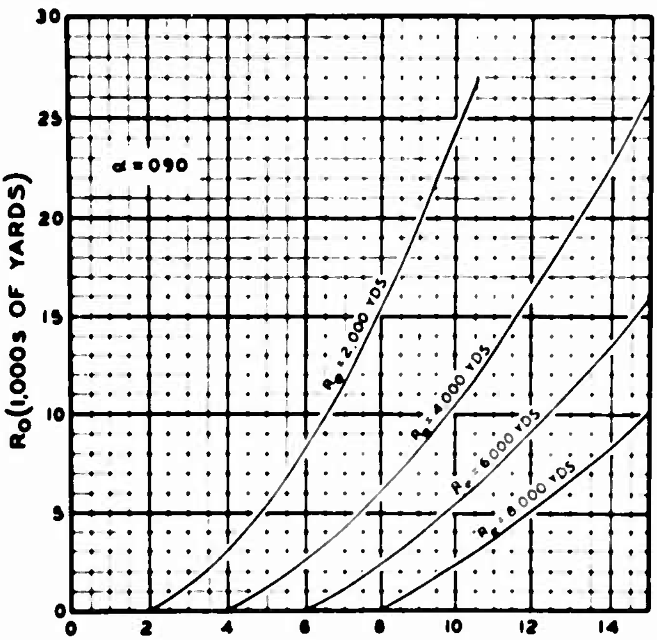
Importance of Time in the Accumulation of Error

Let us go a little further into the method we can use in analyzing systems problems. So far we have been talking only about the accumulation of range errors. But when we turn to a study of such a system as that operating in the Combat Information Center, a new factor enters. Time rears its bothersome, but imperious, head.

Operator's Delay. The tracking of high speed aircraft has become an extremely important problem and, mainly because of the time element, is one of the most difficult jobs faced by the Combat Information Center. We know that when a target pip shows up on a PPI, the bearing and range of the target is correct. However, it takes a while for the radar operator to locate the target, to operate his controls, and to read the bearing and range for the target. During the time that the operator has been performing these various manipulations, the target has not been idly picking its teeth. It is moving -- often with disconcerting speed. By the time the operator has given his bearing and range, the information is old information. It is stale, it no longer tells us where the target really is.

Accumulated Error. Let us see by how much we may be in error in certain practical situations. In Fig. 4 is a series of curves showing the various range errors which we would find as a function of the initial range of detection by the radar and as a function of the speed of the target in knots and the time delay in seconds. In this illustration we have also assumed a target angle of 090°. Suppose, for example, that a VJ remote operator first detects a high speed aircraft at a range of 10,000 yards. Suppose that this aircraft is traveling at about 800 knots. We know from our experimental work that it takes the VJ operator approximately 13 seconds to locate a target, to operate his bearing and range cranks, and to read the two dials associated with these cranks. By reading down the bottom to a speed of 800 knots and then reading across to a time delay of about 13-1/2 seconds, we find that the range report given by this operator will be in error by about 2,000 yards.

It is impossible to overestimate the importance of this point. Even while the radar operator was performing his normal operations at the greatest possible speed, his reading was in error by 2,000 yards by the time he blurted out the bearing and range. We can see from this that it really does not do much good to have a radar which is accurate within one or two hundred yards, if it is going to be used for detecting high speed aircraft; the rest of our system is not capable of handling that kind of precise information. The situation is something like using a Rolls razor to shave a pig.



S (KNOTS)	d (1,000's OF YARDS)						
200 T = 0	180	360	540	720	900	1080	1260
400 T = 0	90	180	270	360	450	540	630
600 T = 0	60	120	180	240	300	360	420
800 T = 0	45	90	135	180	225	270	315
1000 T = 0	36	72	108	144	180	216	252

Fig. 4. Range error (R_e) as a function of initial range of target (S), and time delay in CIC (T) when the target angle is 090°. (From Garner, 1947.)

<u>Systems Error</u>. Obviously as the time delays throughout the rest of the system increase, the error becomes worse and worse. We know that the information proceeds from the radar operator to a plot board, from the plot board to a gunnery liaison officer, from the gunnery liaison officer to the fire director radar, and from the fire director radar to the gun. Each of these steps takes time, and it is not unreasonable to say that the whole process would take at least 30 seconds.

Let us see how much this means in terms of our hypothetical situation. Remember that we postulated an initial pick-up at 10,000 yards, and said that our aircraft was traveling at a speed of 800 knots. Now we know that our system has a time delay of about 30 seconds. If we read across the 800 knot scale to a value of about 30 seconds, we find that as the range report given by the operator is transferred from one point to another throughout the system, it will be in error by nearly 7,000 yards by the time it finally gets to the fire control station. This means, in short, that the aircraft will have traveled nearly three quarters of the way from the point of initial detection to our own location before the information taken from the radar can get to the fire control station. This might be regarded as dangerous.

The moral of this story is so obvious that it hardly needs emphasizing. We are not going to make our greatest contribution to radar systems by attacking the radar or the man *per se*, so long as we have such large inherent delays in the system. By attacking these delays at their sources it may be possible to keep Combat Information Centers up to snuff in an age of supersonic aircraft.

SUMMARY

Let us pause a moment, now, and summarize. We have looked, in the most general way, at the scientist's method. We have talked about "pure" science and "applied" science. We have seen that the systems research scientist, sometimes obviously applied and sometimes touched with purity, earns his living by working on three sorts of problems: (1) he runs tests to compare the effectiveness of two machines or instruments or systems, (2) he applies known psychophysical principles to new problems, and (3) he searches, in his moments of semi-purity, for basic and as yet unknown psychophysical principles of *general* applicability.

We have seen that, even in the simplest of these activities the 'systems researcher,' in order to create trustworthy knowledge, has to contend with complicated sets of circumstances. We saw how individual differences can clutter up an apparently simple problem, how individual differences must so often be controlled or allowed for in systems research. We had a look at other complicating factors that the scientist must handle before he can gain knowledge.

He must analyze out his significant variables, he must control certain of them while letting others vary, he must place the strategy and tactics of his experiment so that he can watch and measure several factors efficiently and at once. In treating his data, he must use suitable, often fairly intricate statistical devices. We have looked at concrete illustrations of most of these points. All this gives us a notion of what sort of procedures are necessary if we are to make reliable declarative sentences about the way the world or any small part of it really works. The next lecture in this series will present a few pretty good such sentences on the results of research into the working environment.

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III. THE WORKING ENVIRONMENT

As some of you may remember, the first lecture of this series dealt, in general terms, with an overall orientation to psychophysical systems research. The second lecture, in terms almost as general, treated the business of approaches and methods. In this, the third lecture, we want to get down to actual cases -- to look at about 50 minutes' worth of fairly concrete problems and facts in the field of human engineering. These problems and facts concern what we may call the working environment.

Industrial Applications. In recent years business and industrial concerns have spent millions of dollars trying to make factories and offices more comfortable, more attractive places in which to work. More, bigger and better lighting fixtures flood our modern factories with light almost as good as natural daylight. Air conditioning plants keep the work area at an even, cool temperature the year round. Sound-absorbing materials keep down the noise levels. In some cases industrial noises have been replaced with other noises -- commonly known as music -- which are supposed to make work pleasanter. For each of these improvements one can find dozens of reports in engineering and trade journals pointing enthusiastically to increased production, decreased accident rates and improved worker morale.

Military Problems. If we are interested in human engineering we cannot ignore these developments. Certainly we ought to examine carefully the scientific studies which show the effects of these various environmental factors on human efficiency. All of us know from experience that most military systems are not located in very comfortable places. Riding inside a tank, for example, is something like being in a boiler factory built on a roller coaster. Modern aircraft hiss and roar through space so fast that sounds can just barely keep up with the plane. In the space of a few minutes a man may be whisked up to an altitude where the air is so thin that a match won't burn. And many of us can testify that a ship in a heavy sea succeeds, with astounding speed, in reducing our work efficiency to zero. These unusual stresses that mechanized war places on man make the problem of systems design much more difficult.

System Design. We have already seen that man is the weak sister in most man-machine combinations. If we put the man-machine combination in an environment unfavorable to the man we can't expect to get as much out of our system. In many cases, the environment is so important -- and so stressful -- that we may have to design an entirely different kind of system just so the man will be able to work in it. Let us give you one illustration. You all know that when it gets dark you cannot read small print. If, therefore, our psychophysical system has to be located in an environment which must be kept fairly dim, then, obviously, the display part of the system, the dials and scales, have to be redesigned so that a man can see them. But again, we should notice that it is necessary to redesign the system, not because the system will not function in darkness, but because the man will not function in darkness -- at least his eyes do not. You cannot get far *feeling* an air-speed indicator.

Beware. Before cataloguing some of the environmental conditions which affect human efficiency, we ought to introduce a note of caution. In our last lecture we described the method of science as being a method of *controlled* observation. The importance of controls in experimentation is probably nowhere better illustrated than in this field. If a production engineer goes into a factory, changes the lighting, and then finds that production goes up, the scientist is not satisfied. He wants to know, "How can you be sure that the lighting had anything to do with the increase in production?" Maybe the workers learned how to do the job better in the meantime. Maybe the new production engineer was a nice guy, so everybody spent less time grumbling. The scientist is not willing to accept the results of any factory experiments, no matter how enthusiastic the author may be, unless he is sure that other factors have been adequately controlled.

Production Up. We can get some idea about how important these other factors can be from the results of an experiment done in the Hawthorne Works of the Western Electric Company. This study extended over a period of two years, during which time various experimental conditions were tried out on a group of five women who were assembling telephone relays. One of the most important findings of this two-year study was that production went up no matter what the experimenter did to these girls. He gave them two 5-minute rest periods -- production went up. He gave them two 10-minute rest periods -- production went up some more. He took away the rest periods -- production still went up some more. He gave them rest periods again -- production went up. He gave them free lunches -- production went up. He took away the free lunches -- production still went up.

The Artifact -- Morale. What was happening here? Well, the five girls were in a separate room. They knew they were being experimented on. They knew that they were being given special consideration and they so enjoyed having this attention that their morale reached a new high. Anything the experimenter did resulted in more production. It is this kind of evidence that should make us very skeptical about most factory experiments. If we look for really good experiments in this field, we find pitifully few of them. There are enough of them, however, for some good general conclusions to come through our screen of adaptive skepticism.

Other Factors. One thing more before we get going. In this lecture we are going to look at the physical work environment. This does not mean that other things are not important, because they are. Morale, good leadership, letters from home, and dozens of other psychological factors play an important role in the efficiency of the working sailor and soldier. But we have only a little time and have to draw the line somewhere. So we will stick to the physical environment.

TEMPERATURE AND HUMIDITY

Almost all of you, we are sure, will agree that the temperature and humidity of the environment seem to affect your performance. In 1940, the British Industrial Health Research Board attempted, after considerable investigation, to set down the chief requirements for satisfactory heating and ventilation in the work space.

Feeling Comfortable. They found very soon that people differed a lot in what they thought was a comfortable environment. After sampling a wide variety of opinions, however, they came up with some recommendations about temperatures and ventilation which seemed to suit the average person. Their recommendations are that in winter the best average temperature for very light work is about 65° Fahrenheit; for active, light work, from 60° to 65° Fahrenheit, and for work involving more muscular exertion, from 55° to 60° Fahrenheit. In hot weather they say that the temperature should be kept as low as possible by thorough ventilation. They further recommend that the supply of fresh air should not be less than about 1,000 cubic feet per person per hour and should preferably be greater. In winter, the rate of air movement should be about 20 to 40 feet per minute, and in warm weather higher velocities are desirable. The relative humidity should not generally exceed 70% and should be less if possible. These are the general requirements for an environment which will make the average person feel comfortable.

But we have to distinguish between comfortable temperatures and temperatures at which we can work, if we have to, without any loss in efficiency. The two are not necessarily the same.

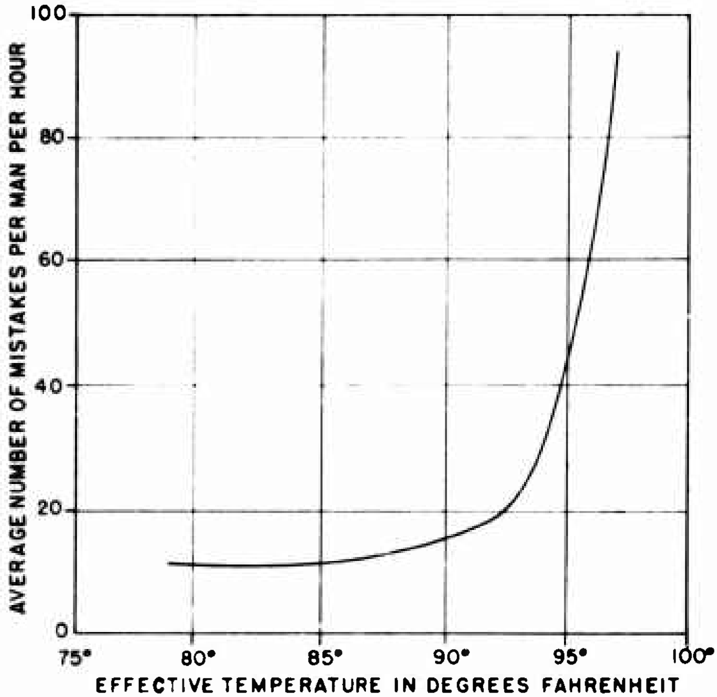

Fig. 5. Average number of mistakes made by eleven wireless operators in recording Morse messages at various room temperatures. (From Mackworth, 1946.)

Temperature and Performance. During the war, a study undertaken by the Applied Psychology Research Unit at the University of Cambridge, England, investigated the effects of heat on wireless telegraph operators who heard and recorded Morse messages for several hours at a clip. This study was undertaken primarily to discover how hot a room could get before the performance of wireless operators began to deteriorate. The experimenter had his subjects sit in a hot room at various temperatures -- 79°, 85°, 87-1/2°, 92°, and 97° Fahrenheit. The results of these experiments are shown in Fig. 5. We see here the average number of mistakes made per man per hour during a three hour work period at the various room temperatures. It is very clear from this study that although the most comfortable working environment may be at a temperature of about 65°, performance does not begin to deteriorate until temperatures of about 87-1/2° or 92° are reached. At the worst temperature -- 97° Fahrenheit -- the number of mistakes increased nearly ten times.

Temperature and Fatigue. It is also interesting to look at these data in another way. Shown in Fig. 6 is the average number of mistakes per man per hour at the various room temperatures, with the data separated into the performance for the first hour and for the third and last hour. It is clear from these data that the performance of the wireless operators deteriorated markedly from the first to the third hours of work and that the amount of deterioration was worst at the extremely hot temperatures.

Humidity. Similar findings were obtained in studies performed by the Armored Medical Research Laboratory at Fort Knox. Their data are a little more complete, however, because they studied one other factor, humidity. The results of this investigation, shown in Fig. 7, prove what most people suspected all along: it is a lot harder to work well if the air is hot and sticky. Conversely, if the air is dry, a man can tolerate a much hotter temperature. Just to see how this works out, let us look at the figures for a temperature of 100° Fahrenheit. At this temperature work becomes impossible when the humidity reaches about 86%. If the temperature goes up to 110° Fahrenheit, then the humidity must be kept down to about 57% or less. It is important to point out that most of the combinations of humidity and temperature tested do not occur in nature. But they do occur very frequently in many of the machines dreamed up by our engineers. One other thing that needs to be pointed out is that in both of these studies just mentioned, the subjects were acclimatized; that is, they lived at these temperatures long enough to let their bodies get used to them. A person who had not been exposed previously to these temperatures would collapse under conditions which the acclimatized person could take with only moderate difficulty.

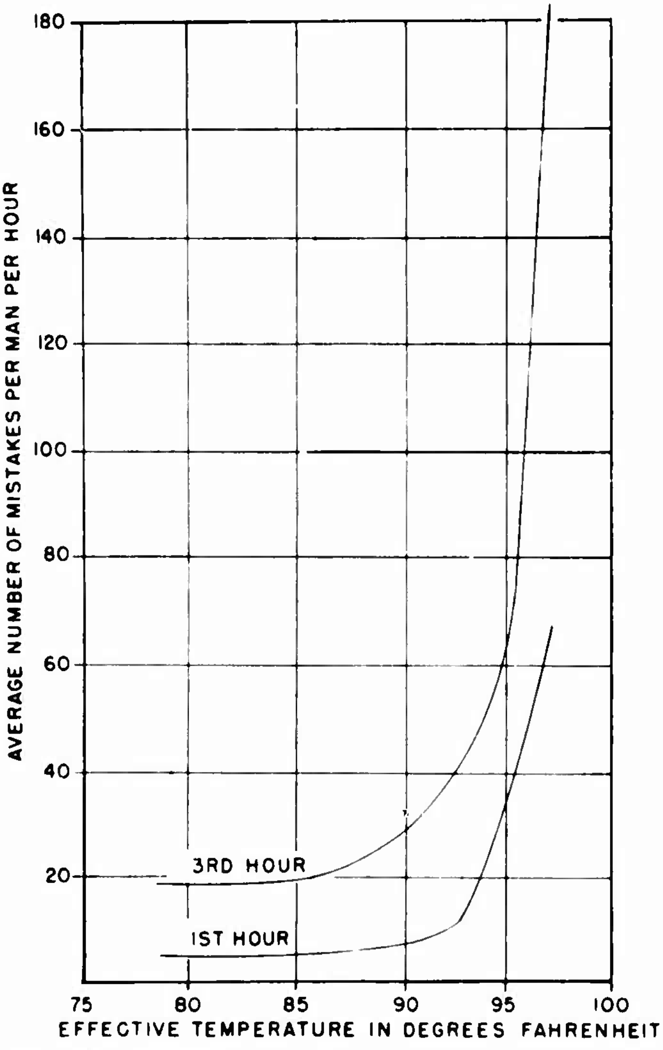

Fig. 6. Average number of mistakes made by eleven wireless operators during the first and third hours of work at various room temperatures. (From Mackworth, 1946.)

"Fresh Air." The temperature of the air around us, however, has nothing to do with whether or not we consider it to be fresh or stale. There are probably a large number of factors which contribute to making the air around us feel and smell stale. Body odors, fumes or exhalations from machinery, and moisture are probably large contributing factors. In most cases, rapid circulation of air in a room will remove the stagnant element. In an experiment conducted by the New York State Commission on Ventilation, men were required to lift a five pound dumbbell through a distance of 2-1/2 feet. These men were all well motivated by a reward. They were tested under two temperatures, 68° and 75° Fahrenheit, and with the air either fresh or stagnant. The findings of this experiment are shown in Table III. From these figures we can see that production, measured in terms of the number of times these men performed the operation, was at its highest level when the temperature was 68° and the air was fresh. If this value is used as the base line, stagnant air caused production to fall off approximately 9% under each of the two temperatures. With the 75° temperature, production dropped nearly 15% both with fresh and with stagnant air. Under the worst condition, namely that of stagnant air at 75° Fahrenheit, production was nearly 24% below that of the most favorable condition.

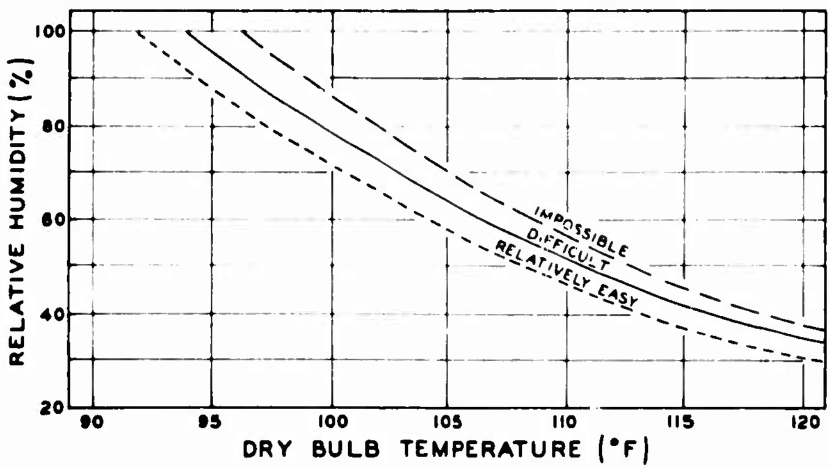

Fig. 7. Relationship between relative humidity and dry bulb temperature in determining the environments in which work was relatively easy, difficult, or impossible (acclimatized subjects). (From Eichna, 1944.)

Conclusion. The general trend of all the studies of this sort is clear: Atmospheric conditions, interfering with normal or constant body temperature, reduce physical efficiency. Ventilation systems which move and filter the air and which control temperature and humidity are usually a sound investment from the point of view of efficient work. The point of all this, for our investigations on psychophysical systems, is obvious. If the systems are to be used in environments which are hot and stuffy, we cannot expect the same kind of performance from the men operating the machines as we can when the environment is optimal.

Table III

Effects of Temperature and Air Movement on Physical Work

(Data of the New York State Commission on Ventilation; Adapted from Maier: Psychology in Industry, 1946)

Temperature	Air	Units of Work (100 Optimum)	Fall in Production Due to Stagnant Air	Fall in Production Due to Increase in Temperature
68°	fresh	100.0		
68°	stagnant	91.1	8.9	
75°	fresh	85.2		14.8
75°	stagnant	76.2	8.6	14.5

Physical versus Mental Work. In this connection it is interesting to note, however, that several studies seem to indicate that mental work, under such adverse conditions, does not deteriorate as rapidly as physical work. In the telegraph-operator study, for example, you remember that performance in receiving Morse messages did not begin to drop off until temperatures of about 87° were reached. Whereas, in the New York study, where the men were doing some fairly heavy physical work, performance dropped off at 75°. Men doing mental work show some tendency to take more frequent rest pauses under unfavorable conditions, but the surprising fact is that mental work is usually not affected until extreme conditions are used. The application of these findings to psychophysical systems aboard ships is certainly worth the consideration of design engineers.

Health. It is worth backtracking for a minute or two to consider an incidental finding in the Cambridge study to which we referred earlier. During the course of this experiment two of the subjects developed severe head colds. The results of these two

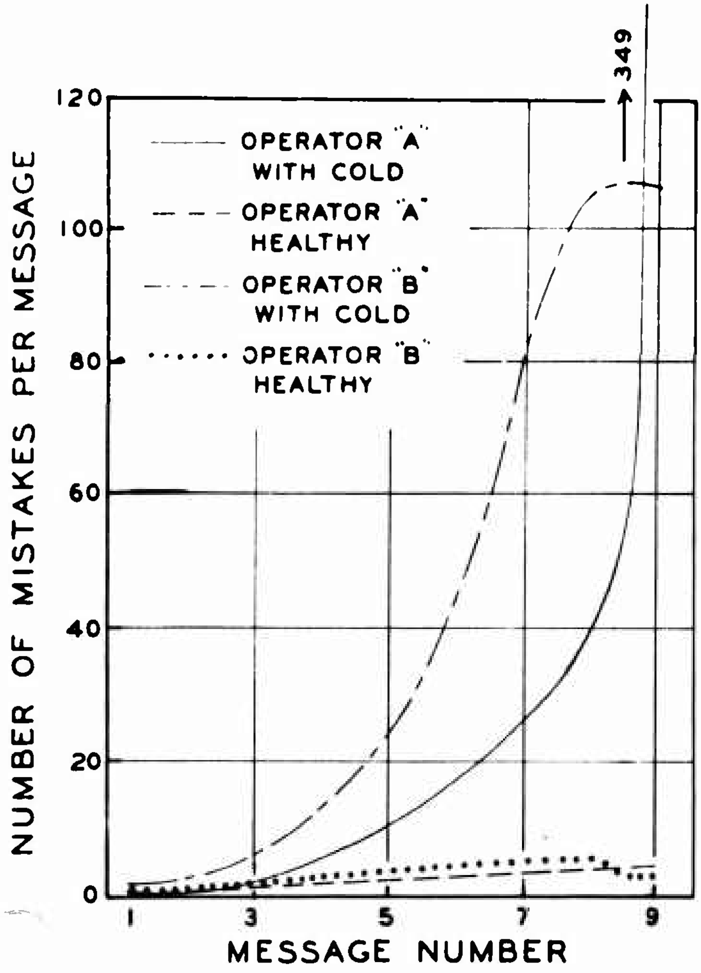

Fig. 8. Number of mistakes made by two operators in recording nine consecutive Morse messages when they had head colds and when they were healthy. (From Mackworth, 1946.)

subjects in hearing and recording nine consecutive code messages are shown in Fig. 8. Each message occupied about 16 minutes. The bottom curves in each instance represent the average performance of subjects when they were healthy, that is, not suffering from a head cold. It is interesting to note that when they had colds the two subjects started out with very few errors, but as the work period progressed into the second and third hours, the errors increased enormously. Although this finding is rather incidental to the general problem of the work environment, it gives us an indication that there are many bodily conditions of the man which may affect his performance greatly.

OXYGEN DEFICIENCY

Let us now turn to another aspect of the environment around us. All of us work and play, live and die at the bottom of an ocean of air. Ordinarily we pay very little attention to the chemical composition of this medium. Chemists tell us, however, that it consists of about one-fifth oxygen and four-fifths nitrogen with a very small percentage of other rare gases. The physicists tell us, too, that the pressure of this air around us at sea level amounts to about 15 pounds per square inch. The chemical composition and the pressure of this air are pretty much constant all over the face of the globe -- as long as we keep at least one foot on the ground -- and we ordinarily experience no difficulty in getting along in it.

Anoxia. In some of the complex psychophysical systems developed recently, however, man does not stay at the bottom of this ocean of air. Our aircraft now are capable of flying as high as 40,000 to 45,000 feet, and unless the supply of aviators is limitless, we had better know something about what happens to the organism at these altitudes before we send any up there. Physical experiments tell us that the pressure of air decreases markedly as we ascend to higher and higher altitudes. Although the composition of the air does not change, this means effectively that there is less pressure to force life-giving oxygen into the body at these altitudes. The condition which results when insufficient oxygen is fed into the body system is called, as you know, anoxia. A considerable amount of work has been done on this problem during the war, and it is of some interest to review briefly the main findings of this research.

Anoxia and Performance. As a result of experiments performed in the Andes Mountains, it is known now that the top limit at which men can work comfortably for prolonged periods of time is about 17,000 feet. Although there are individual records of men who have gone as high as 30,000 feet for short times and have lived to tell about it, the ordinary person can stay conscious for only two or three minutes at such an altitude. These are the top limits, however. We also know that at considerably lower altitudes the effects of anoxia may result in greatly impaired efficiency.

The sense of sight is an extremely sensitive indicator of the effects of anoxia, and Fig. 9 shows the relative amount of light required for vision at various altitudes. At an altitude of 14,000 feet, for example, a normal individual requires about twice as much light to see as he does at ground level. At an altitude of about 16,000 feet he requires nearly 2-1/2 times more light.

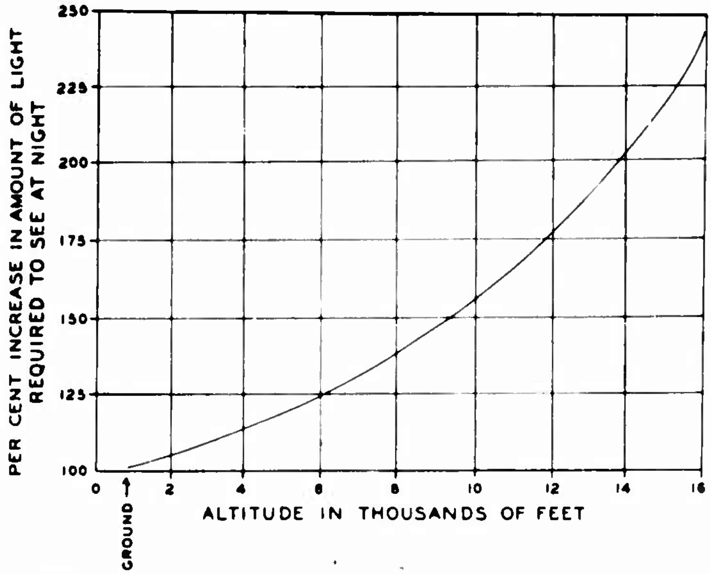

Fig. 9. Per cent increase in amount of light required to see at night as a function of altitude (ground level = 100%). (From Pinson, 1941.)

Other effects of anoxia have been also very carefully studied and documented. We know that at altitudes of 16,000 feet, the average person begins to suffer from a dimming of vision even in daylight. Tremors of the hands appear and it is difficult to move them with any precision. Exercise, even of the simplest type, becomes difficult, and a few deep knee bends may leave the individual panting and breathless. Worse than these effects, however, is the fact that thinking and memory become clouded and that serious errors of judgment are frequently made.

An especially dangerous aspect of anoxia is its insidiousness. It sneaks up on you. There are no warning signs that tell a person he is suffering from anoxia. There is no pain and, as a matter of fact, people under the influence of anoxia tend to feel happy and gay. They may even want to call up a dear old aunt in Los Angeles. Pilots have fallen over unconscious before they ever suspected that anything was wrong with them.

CARBON MONOXIDE

Obviously, our discussion of the effects of anoxia is primarily concerned with intricate systems such as aircraft which fly to those altitudes where anoxia can happen. Of somewhat broader and immediate concern to us is the problem of carbon monoxide. The effects of carbon monoxide poisoning are quite similar to those of anoxia. If we are to attempt to survey the important aspects of the work environment, we should certainly be amiss if we left out the noxious fumes and gases. It is now known that anoxia due to carbon monoxide poisoning affects visual acuity, brightness discrimination, and dark adaptation in the identical extent as do like degrees of anoxia. For example, it has been shown that a 5% saturation of carbon monoxide in the blood has an effect on the visual threshold equal to that of an altitude of about 8,000 to 10,000 feet. Smoking three cigarettes may cause a carbon monoxide saturation of 4% in the blood with an effect on visual sensitivity equal to that of an altitude of 8,000 feet.

Carbon monoxide is a serious problem in all environments where products of combustion, either of engines or machines or explosives, may contaminate the air. It is important because very small amounts of carbon monoxide in the atmosphere may affect efficiency enormously. Thus, we know that a concentration of one part of carbon monoxide in 10,000 will produce no symptoms for about two hours. With a concentration of only four parts in 10,000, however, the air is safe for only one hour. If the concentration rises to six or seven parts in 10,000, headache and unpleasant symptoms usually develop in less than an hour. It is conceivable that some of the unpleasant symptoms resulting from a prolonged exposure to a bar-room atmosphere come from gaseous rather than purely liquid causes. A carbon monoxide concentration of ten to twelve parts in 10,000 is downright dangerous if the exposure lasts one hour, and if the concentration is as high as 35 parts in 10,000, it is usually fatal in less than one hour. The effects of carbon monoxide poisoning are a little more noticeable than those of anoxia. Some of the common symptoms are a tightness across the forehead, headache, throbbing in the temples, weakness, dizziness, dimness of vision, nausea and vomiting, and finally collapse.

AIR PRESSURE

So far, in talking about the ocean of air around us we have been considering its temperature, its humidity, and the kind of gases in the air. For certain kinds of systems, however, it is important to consider another characteristic of the air, namely its pressure. Ordinarily we do not pay very much attention to the enormous weight of the column of air resting constantly on our shoulders and our bodies. However, we know from physical measurements that this pressure amounts to about 14 pounds per square inch, so that we carry a load of several tons of air on our shoulders at all times. So long as we stay at this same pressure, we experience no difficulty. However, the human body, if it is subjected to rapid changes in pressure, may suffer some serious effects.

Increasing vs. Decreasing Pressure. Ordinarily these effects are experienced when pressure is changed in one direction. If we go from a region of lesser atmospheric pressure to one of greater atmospheric pressure, we experience little or no ill effects. The reverse, unfortunately, is not true. In going from greater pressures to lesser pressures, we may experience symptoms which go under a variety of names -- aeroembolism, aeroemphysema, caisson disease, or bends. This kind of change is encountered in three types of occupations: caisson workers constructing bridges, docks and so on, below the water; deep sea divers; and flying personnel.

"Bends." If the change from a greater to a lesser atmosphere is too rapid, as, for example, a deep sea diver coming up too rapidly, or an aircraft ascending to high altitudes too rapidly, a variety of symptoms may develop. The worker may experience pain in and around the joints, which may be mild at the outset but very often becomes gnawing and boring in character, and may become so severe that it is intolerable. These severe pains can cause loss of muscular power of the body member involved and, if the pain is allowed to continue, may result in total collapse. Other symptoms go by the name of "chokes," which are a severe impairment of the breathing mechanism of the body. The individual suffers from a sensation of suffocation, and breathing becomes progressively more shallow and difficult, frequently resulting in collapse and unconsciousness. Skin symptoms also frequently develop and finally there is a variety of neurological symptoms, effects on vision, sensory disturbances, and loss of power of speech. A knowledge of these factors is obviously extremely important in the design of certain complicated types of military system.

ACCELERATION

If all of our psychophysical systems were built on nice solid foundations, and did not show phenomenal proclivities for traversing such vast amounts of geography, we would have a lot less to talk about in dealing with this general problem of the environment and its effect on the man who must work in it. Unfortunately, however, our modern man is not particularly happy to stay put anywhere. He moves -- and rapidly. This business of getting from one place to another in the shortest possible time raises very serious problems in connection with psychophysical systems.

Definitions. A good way to start our discussion of these movement problems is to define a couple of terms. Speed is defined as "the act or state of moving swiftly. Also it is the rate of motion or velocity." So if you are tooling the highway at 50 miles an hour, your speed is just that -- 50 miles an hour. But there is another kind of speed which is more important -- acceleration. The accepted definition of acceleration is "a change in velocity, or the rate of such a change, either as regards speed or direction or both."

There are several kinds of acceleration that a moving body may exhibit. There is either positive or negative acceleration, for example. If you are cruising at 50 miles an hour and step on your accelerator to pass another car, you undergo positive acceleration, if your valves are in fair shape, that is. If, on the other hand, you jam on your brakes to avoid hitting another car, you undergo negative acceleration. And then, finally, acceleration may be either linear or centrifugal. If you are traveling along in a straight line and either step on the gas or push on the brakes, your acceleration is linear in direction. If you suddenly turn a sharp corner, however, your acceleration is centrifugal or angular.

Speed. Quite a lot of work has been done on these problems of speed and acceleration, particularly as they concern aircraft. At the present time, many of our modern aircraft have cruising speeds up around 200 and 300 knots. We know that some special types of aircraft have attained speeds of about 500 knots. There is considerable uncertainty about the ultimate speeds which will be attained by aircraft in the future, but it is anticipated that when present difficulties with the compressibility factor are licked, rocket flights may become a reality and speeds of 25,000 miles per hour may eventually be reached. It is generally agreed that linear velocity per se has little or no effect on the body. But whether or not this general conclusion will be valid when we start scooting around the sky in rocket planes still is uncertain.

From the standpoint of psychophysical systems, the effect of speed, even though it does not appear to harm the body, raises some other problems. If an aircraft is flying at 600 knots, for example, that means that it is making 10 miles a minute or about 333 yards per second. We know from studies of automobile drivers that it takes some drivers about three-quarters of a second to react to a red light by pressing on the brake pedal, even under optimal conditions. If our pilot, therefore, suddenly decides to make a turn, he will have traveled several hundreds of yards before that nerve impulse can go from his brain down his leg, or his hand, to execute the decision. If, now, we add to this normal reaction time, delays arising from the fact that the pilot cannot see his instruments readily or that warning lights or signals are not detected immediately, it is very easy to imagine that a pilot will react a mile or more late.

Other problems of this sort arise too. We know from our experiences in this recent war that in high speed aircraft the pilot very frequently has only a second or two in which to line up his target in the gunsight. In short, as we increase the speed at which these various psychophysical systems go hurtling through space, we are going to come up more and more against the problem of the normal reaction time of the man who is operating this system.

Positive Acceleration. So much for the problems of speed as regards psychophysical systems. Much more dramatic effects are experienced when we consider the problem of angular acceleration, that is, changes in direction of movement. In talking about problems of centrifugal acceleration, the scientist uses a complicated equation derived from one of Newton's laws, which states that the force is equal to the mass times the velocity squared, divided by the radius of rotation. The force, in this case, is expressed in units of the force of gravity, called "G," or the force exerted by gravity on a unit mass.

In terms of their effects on the body, it is important to distinguish between positive and negative G-forces. Positive G normally acts in the direction of the long axis of the body and from head to foot. It produces effects which vary with the magnitude of the acceleration, and with the rate at which it is increased and decreased, and with the duration of its action. A force of +1 G is that normally experienced in the upright position. Gravity normally does 1 G to you. With a +2 G force, the principal sensation is an awareness that your body is exerting pressure on the bosom of your britches, and there is a heaviness of hands and feet. Plus 3 G or +4 G produces exaggeration of this sensation of heaviness, and movements are accomplished only with great effort. The skeletal musculature becomes tense, resisting the tendency for the body to be compressed in the vertical dimension. The trunk and head, unless well supported and maintained in a line parallel to the line of force, are held erect only with great difficulty.

At +5 G the body is beyond the control of the muscles except for slight movements of the arms and head, and for all practical purposes, one is physically helpless. At this point, there is a distinct dragging sensation in the thorax, from the heavy traction of the guts which normally float around loosely. The blood leaves the head and face and in some cases there is a distinct diminution or complete loss of vision commonly known as "blacking out." The lower parts of the legs feel congested and there may be cramping of the calf muscles. Breathing becomes difficult -- probably due to the lowering of the diaphragm from the pull of the liver from below and the pressure of the heart and lungs from above. As acceleration increases the G-forces from +5 to +9, there is no apparent exaggeration of these painful symptoms, possibly due to the anaesthetic effect on the brain by its loss of blood. Vision, however, is lost quite suddenly, and is sometimes accompanied by spots or light flashes before the eyes. Coma or unconsciousness usually appears between +5 and +8 G, depending upon individual tolerances.

Negative Acceleration. Negative G-forces, acting in the direction of feet to head, are not commonly experienced. They do occur, however, in certain kinds of acrobatic maneuvers in aircraft. At -1G, the sensation is equivalent to that of hanging head downward. If you experience -1G in an upright position, there is a moderate upward displacement of the organs in the body and a moderate congestion of blood in the face. As the negative G-forces increase, the feeling of congestion and distress about the head and face increases markedly. At between -2 and -3G, the face feels highly congested and there is a throbbing pain throughout the head. At -3 to -4 1/2G the congested feeling becomes intense, there is a sensation of greatly increased intracranial pressure, and the skull feels as if it is about to burst. The eyes feel as though they were being shoved from their sockets and there is a dry gritty feeling in the eyelids. In most cases, objects in the field of vision at this point appear red and give rise to the phenomenon of red vision, seeing red, or "redding out." Up to about -4 1/2 G, which is the highest sustained negative G force which has been studied in the human being, consciousness is retained but there is an increasing mental confusion. Following such an exposure this mental confusion persists for several hours and may be accompanied by a severe, hangover-like headache.

Well, there is no reason to hammer the point home any further. In certain kinds of psychophysical systems, speed or changes of speed of the work environment have to be considered by the designer and experimenter. The dimming and loss of vision, the loss of consciousness, and the greatly increased difficulty of making movements with the hands and feet all raise serious problems in the design of aircraft systems.

MOTION SICKNESS

Fortunately the movements of our vehicles are not always quite so extreme as those we have been discussing so far. But even if we are concerned with less rapid means of locomotion than aircraft, we very frequently encounter situations which affect men quite markedly. These are generally grouped under the general title of "Motion Sickness."

Kinds. Motion sickness includes a lot of different kinds of sickness, depending on the vehicle in which the person is riding. There is airsickness, seasickness, train sickness, car sickness, sickness on amusement park devices, sickness in parachute descents, and even sickness from riding animals -- especially camels. All of these types of sickness have pretty much the same general kind of symptoms. The victim experiences nausea, pallor, sweating and vomiting, and all of these experiences are produced by the same kind of stimulus -- motion.

Causes. Several recent investigations have been concerned with clarifying and understanding the dynamics of motion sickness. In one of these experiments, a vertical accelerator was used in which it was possible to control the wave form, acceleration, velocity, and amplitude of movement. As a result of experiments with this gadget, we know now that slow oscillations of large amplitude are more productive of sickness than faster waves of smaller amplitude. It is also known that there is more to motion sickness than just motion. A number of psychological and physiological factors also contribute. Fear, insecurity, inability to relax, and lack of confidence in the vehicle, for example, are some of the psychological factors which contribute enormously to motion sickness. Among the physiological factors are such things as temperature, ventilation, odors, fatigue, overindulgence in that well known beverage, or smoking and digestive disturbances.

Consequences. Fortunately most people after a suitable number of exposures to motion of this sort get used to it -- they acclimatize, as we would say in technical lingo. They do not get sick as often as they would when they are first exposed to the motion. Even so, as far as work is concerned, there can be no doubt that the efficiency of a man on a pitching, bucking, undulating and rolling ship is not as good as the efficiency of the same man in a good steady environment. This factor is certainly one which has to be taken into consideration in the design and study of systems.

VIBRATION

There is still another kind of motion that needs to be considered, and that is the kind of motion usually called vibration Vibration is a very high-frequency movement which may range anywhere from 20 to 140 cycles per second. It is also characterized by having a rather low amplitude.

Not very much experimental work has been done on the effect of vibration on human efficiency. There is, however, one fairly extensive analysis of this problem made by a German scientist working at the Institut für Luftfahrtmedizin in Berlin. He had a specially built oscillating platform which was capable of vibrating through a frequency range of 15 to 1,000 cycles per second. His experimental room was damped acoustically so that noise would not affect the subject. He gave all of his subjects a series of tests before, during, and after a two-hour exposure to vibrations of various known amplitudes and frequencies.

One of the most interesting findings of his research was that vibration greatly affected binocular acuity. The people could not see so well when they were being subjected to vibration. Two kinds of vibration were especially bad. One was at frequencies between 25 and 40 cycles per second, and the other between 60 and 90 cycles per second. Although it is not known exactly why vibration affects visual acuity in this way, some theories have been advanced to account for these findings. One of these is that the decreased visual acuity is due to the attempt on the part of the eyes to follow the movements of the vibrating instrument. Another possibility is that the eyeball may be set into resonance with the vibration as a result of the elasticity of the supporting muscles around the eyeball. Another interesting finding of this study on vibration was that certain reflex actions in the body were diminished and at certain frequencies and amplitudes were completely suppressed during vibration.

Although the effects of vibration on the body are still incompletely understood, these findings indicate that subjective complaints of tremor of the eyeball, changes in the muscle balance and depth perception, chronic headaches, and visual fatigue may all have their basis in fact. Those of you who have tried to read for any period of time on a jerky, bouncing train will be able to confirm from your own experience the effects of vibration.

NOISE

One characteristic of our working environment which deserves considerable attention is the problem of noise. One unfortunate aspect of our civilization is that the more complex it gets, the noisier it gets. The problem of noise has attracted the attention of specialists in many professional fields. Physicians, public health authorities, architects, psychologists, otologists, physicists, sound and electrical engineers have all contributed to the literature in this field. Safety engineers and insurance companies are also interested in the problem because of the growing recognition of occupational deafness. Many large cities have undertaken extensive noise reduction campaigns and in our general consideration of the work environment we certainly ought to know whether or not noise reduces human efficiency, because we find so much noise in many of the modern machines of war: the airplane, the tank, the gun battery, and the modern ship -- both in the engine room and, occasionally, in the ward room.

Facts? Because of all this interest in the general problem of noise, you would expect to find a very large body of respectable scientific evidence pointing to the effects of noise on human beings. Strange as it may seem, however, there is no large group of accredited scientific facts in this field. In part, this situation may be due to the confusion in the ordinary mind between the annoyance value of noise and the actual effects of noise as measured in terms of human efficiency. This distinction is very often overlooked. We know very little about what makes a noise irritating. We do know that the irritation produced by noise is not necessarily related to its loudness. The faint dripping of a kitchen faucet or the scraping of a fingernail along a blackboard may make a man's hair stand on end, and yet this same man may ride in a thundering airplane without the slightest inconvenience, even though the airplane may generate a hundred thousand times as much noise as the faucet or fingernail.

Annoyance. Only one thing can be said with definite assurance regarding the relative annoyance value of different kinds of noises, and that is that the high tones and extremely low tones are judged almost universally to be more irritating than those in the middle ranges. This general principle has been of considerable value in soundproofing aircraft, offices, and other work spaces. It has been found, for example, that the elimination of the very high frequencies in aircraft noise greatly reduces the annoyance value of the noise to the passengers in the aircraft even though the overall intensity of the noise may be only slightly reduced. Another thing we know is that interrupted noise or discontinuous tones are most generally found to be much more annoying than steady noises. There seems to be some fairly clearcut evidence, furthermore, that greater damage to the inner ear results in animals subjected to high intensities when the tones are interrupted.

There is also a large miscellaneous list of factors that probably influence the annoyance of noise. None of these, however, have been subjected to systematic investigation. Among these factors are the unexpectedness of the noise, the amount of reverberation, and the degree to which the noise is unnecessary or indicates malfunctioning of the equipment. It should be clear, therefore, that we need to know a lot more about this general subject. Another thing which needs to be systematically investigated is the general problem of the individual differences in noise tolerance; and we need to know, finally, what the limits of noise tolerance are for an average population.

Noise and Deafness. If we look at those studies which have investigated the influence of noise on human efficiency, we find again that there is very little known about this problem. A few things, however, can be said with certainty. One of these is that noise greatly increases the difficulty of verbal or oral communication. This general problem of voice communication by radio or telephone in noisy environments will be treated systematically in another lecture, so that we shall not dwell on it here. Another fact which has been very definitely established is that exposure to extremely noisy environments greatly reduces the sensitivity of the ear. Although the results of all of the studies on this problem agree in showing that the hearing loss is temporary, it may extend over several days and is certainly a factor to be reckoned with in systems which contain a lot of noise. The amount of the temporary deafness may also be extremely impressive. In one series of investigations at the Psycho-Acoustic Laboratory at Harvard University, it was discovered that the loss of hearing may amount to about 80 decibels with certain frequencies. Translated into terms of energy, this means that the victim needs a hundred million times the normal amount of energy to hear, following his exposure to the noise environment. It is also important to point out, however, that during five years of research at the Psycho-Acoustic Laboratory, all kinds of noise were used to produce an almost endless diversity of temporary impairment and not one case turned out to be permanently desensitized.

One final interesting fact is that the temporary deafness is almost invariably for tones higher in frequency than the tone to which the victim was exposed. There appears to be no question, therefore, that high noise levels can, and do, produce hearing defects, especially after long exposure. We still do not know, however, what levels can be tolerated, and for how long a given level of noise can be tolerated without incurring a hearing defect.

Noise and Efficiency. If we turn to the general group of scientific studies which have been concerned with the effect of noise on other aspects of human efficiency, we find a large mass of contradictory data. It is extremely difficult to interpret the results of those experiments which have been carried out in industrial concerns, because there are so many factors other than the noise which may affect performance. For one thing, it is difficult to control the factor of suggestion in these field studies. Workers may believe that since the work environment has now been made considerably quieter, they ought to be able to work faster and so do. This may or may not indicate any genuine effect on performance of a noisy environment.

Probably the most exhaustive study on the effects of noise was conducted by Stevens and his collaborators early in the war at the Psycho-Acoustic Laboratory. Subjects were exposed day after day for as long as eight hours at a time to extremely high intensities of airplane noise. They were given nearly 100 tests of intelligence and psychomotor efficiency. No significant effects could be detected in any of the test results despite the fact that people subjected to this barrage of noise claimed that they did not like it, felt fatigued by it, and were less tolerant of their friends at the end of the day. Other less exhaustive studies performed in military establishments have given essentially the same results.

The final answer on this, however, has not been given. There is still some important research to be done. We need new methods to study the relation between noise and people. The studies to date have revealed nothing of significance, yet most people are quite emphatic about their dislike of noise. It is probable that this dislike in realistic situations has an effect on human performance if we could measure it. One subject in Stevens' experiment, for example, reported that after hearing and feeling his daily dose of noise he felt much more inclined to beat his wife. This experiment, however, did not measure such tendencies.

Even though these studies have shown no overall quantitative effect of noise on human performance, there is considerable evidence to indicate that subjects require more energy to perform the same kind of work in a noisy environment than they do in a quiet one. A number of studies have shown quite consistently that the basal metabolism of subjects working in a noisy environment is higher than those working in a quiet one. Since the basal metabolism measures the overall work output of the body in terms of the amount of oxygen consumed, this seems to indicate that subjects in a noisy environment perform about equally well but require more energy to do the same amount of work. This may account for the numerous reports of fatigue from workers in noisy environments.

LIGHT AND COLOR

Another characteristic of the work environment which we need to touch on is that of the influence of light and color. The relationship between visual acuity and illumination, brightness contrast of objects, size of objects to be seen and the time of exposure, have all been so adequately explored there has sprung up a special engineering branch to handle these problems. This is the branch of engineering known as "Illuminating Engineering." The data in this field are so extensive that it is possible to go into reference handbooks and find the solution to most practical problems. The basic scientific relationships between these various factors in the visual environment will be discussed systematically in a later lecture. At this time we should like merely to indicate the importance of these factors in the work environment.

Lighting. Shown in Fig. 10 is a curve showing the relationship between illumination and visual acuity. This set of data was obtained nearly a hundred years ago and has been subjected to experimental tests many times since then. Since many indoor working environments, the Combat Information Center for example, have illuminations ranging from about 1/10 to 10 or 20 foot candles, we can see that the visual acuity we can expect from the normal observer is less than what we would get outside. It is precisely in this range of indoor illuminations that visual acuity decreases fastest as we reduce illumination. If we have only 1/10 of a foot candle in our CIC room, the dials and symbols which must be read have to be twice as large as those in another room with ten foot candles of illumination. Other factors such as brightness contrast, the degree of blackness or lightness of various kinds of visual symbols, and their color must also be considered in the design of visual displays in these types of systems.

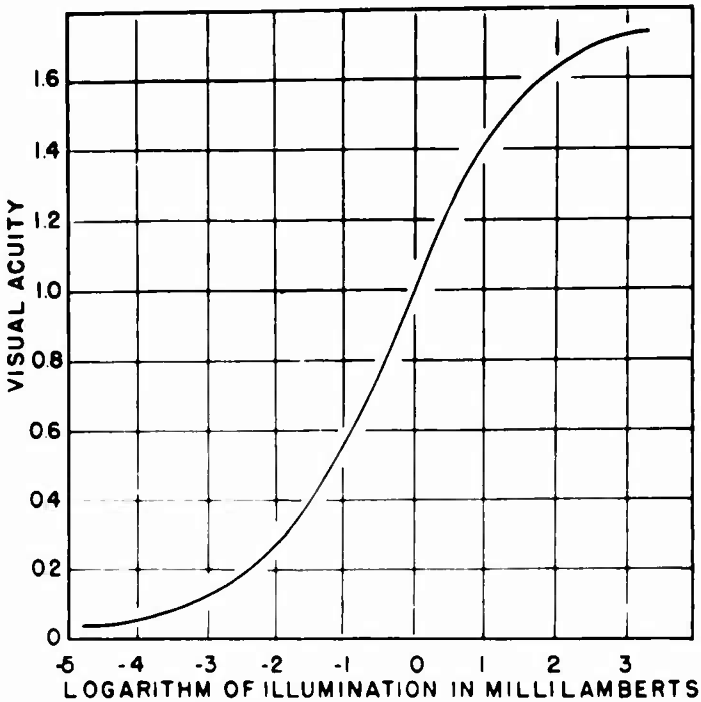

Fig. 10. Konig's data for the relation between visual acuity and illumination. (From Hecht, 1934.)

Color. For the time being, however, we shall leave this interesting group of problems and conclude this lecture with a discussion of one more factor in the environment which has recently gained a lot of attention. Coming to the fore is the question of the color dynamics of the work environment. Does the use of color schemes for walls and machinery have anything to do with the efficiency of work? The Pittsburgh Plate Glass Company, which manufactures paints as well as glass, says yes. They have put out a brochure making claims that workers' comfort, morale, and production have been increased by painting walls in various pastel shades. It is hard to tell whether there is any truth in the claim, because finding out whether this factor caused a jump in production is a ticklish problem. But there is now a great deal of interest in the problem and we may expect current and future research to give us some sort of an answer to it.

Contrast. One general consideration, related in a distant sort of way to this problem of color dynamics, is that of painting certain parts of machinery in lighter or darker colors so that they are more easily distinguished in the work environment. There seems to be no question but that this factor does increase the efficiency of people operating machinery. This general principle does not seem to have been made use of as much as it should be in complex systems such as the CIC and aircraft, for example. The basic idea is simple. If the general background of the aircraft cockpit is painted a fairly dull color, the pilot's job can be made considerably simpler if his important controls contrast with it markedly in color or in lightness. The same principle can be used in the design of CIC for example; if the background for the radar consoles is painted a dull color, then the important switches should be painted bright light colors to make them stand out so that they can be easily localized and reached by the radar operator.

Conclusion

So much then for a general consideration of the work environment. We have by no means exhausted this subject, but some selection of material obviously had to be made. To review briefly, in this lecture we have tried to advance the general thesis that machines do not fight alone. And they do not work except in environments. We must take into consideration the man who works in close harmony with the machine. In so doing, we are forced to recognize that a great number of environmental factors in the work space affect the performance and efficiency of the man in that work space. Our human requirements and our expectations of what a man can do in a system depend to a great extent on the kind of environment into which the system is thrown. If the temperature is excessively hot, if it is humid, if it vibrates excessively, if there is a lot of noise in it, and the illumination is down low, we cannot expect as much work or as efficient work from the man. Conversely, these various kinds of evidence give us some clues as to how we can increase the efficiency of men operating machinery. Too little attention has been given to this problem in the past, and it seems almost certain that a considerable amount of improvement can be made by altering many characteristics of the environment in which men work.

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IV: WORK AND THE WORK-PLACE

The first lecture of this series introduced you to the terminology, the problems, and the general subject matter of human engineering. The second lecture dealt with methods -- methods of approaching scientifically the various man-machine problems, methods of controlling and varying whatever it is desirable to control and vary, and methods of analyzing and measuring error. With the third lecture we began closing in on the more detailed facts and principles of men working machines. That lecture covered the effect of various environmental conditions on human performance. Now, in this lecture, we will close in still further and look at the man as he comes to actual and intimate grips with the machine. We will deal with man as a crank-turning, lever-raising, switch-throwing, tool-using and pedal-pushing piece of protoplasm.

The Problems

What is the nature and location of the most crankable crank, or the most pushable pedal? What is the best way for a man to go about cranking a given crank or handling a given handle? What posture, what sort of chair, what sort of sequence and rhythm of movement will help a man attain greatest efficiency in a given job? These questions are of the sort we want to worry about awhile today.

Engineering Analogies. A word or two may be necessary to explain how this lecture fits into the general outline of the series. You can look at human beings much as you do electrical or mechanical devices. They all have an input and an output. In the end, we are interested in output, but what comes out is a function of what goes in -- the input. Psychologists have other words for these two ends of the human machines. They speak of sensory or perceptual functions, by which they refer to the sounds and sights, the dials and signals -- in short, all the stimuli -- which are the input of human processes. Subsequent lectures will deal in some detail with these inputs and how best to get them put in. But today we want to talk about output -- about what the psychologists refer to as motor functions.

Loading the Output. Output, as you well know, is not only a function of input, but also of the load that is placed on the output. In acoustics or electronics, we speak of external impedance as the load that must be driven by a given output. In mechanics, the mass that must be moved or the resistance that must be overcome is the load determining the output of the mechanical device. So it is with human output. And just as we strive to reduce the impedance or resistance faced by the output of machines, so must we strive to find the optimal conditions for human work if we are to get the most from the human machine.

Questions and Answers. There are just as many questions as answers in this field, maybe more. The questions or problems are not only interesting but they constitute areas of research which have considerable promise for improving many aspects of military devices. But we shall save most of the questions till the latter part of the lecture series. At the appropriate time we shall give major attention to current research problems. Today we shall concentrate on answers -- not on detailed answers to specific problems, for they would probably make it hard to see the general picture -- but rather on the more general and more basic principles of increasing output.

"The Best Way to Work." These basic principles have come mostly from time-and-motion engineering, applied ever increasingly in the last 50 years to problems of industrial production. Just as there is an optimal impedance or load for a machine to drive -- engineers speak of matching impedances -- so there is usually an optimal way of doing work. Indeed, one might say that the slogan of industrial engineers has often been, "There is a one best way of doing any job," and the problem is to find it by careful study. In treating these "best ways of work," it may be a good plan to begin with gross physical factors and movements and proceed, step by step, to the more precise and more confined bodily motions.

PRINCIPLES OF WORK-EFFICIENCY

Perhaps the grossest work a man can do is to carry a load from somewhere to somewhere. But gross or not, quite a bit of such work goes on all the time and even for this weak-mind-strong-back sort of job there is a best way of work. This was established by a very exhaustive study of the physiological work done in carrying loads in many different positions -- in front with the hands, in front with shoulder straps, on the side with handles, on the head with the hands to steady the load, on one shoulder, on one hip, in packs strapped to the back, in packs suspended down the back from

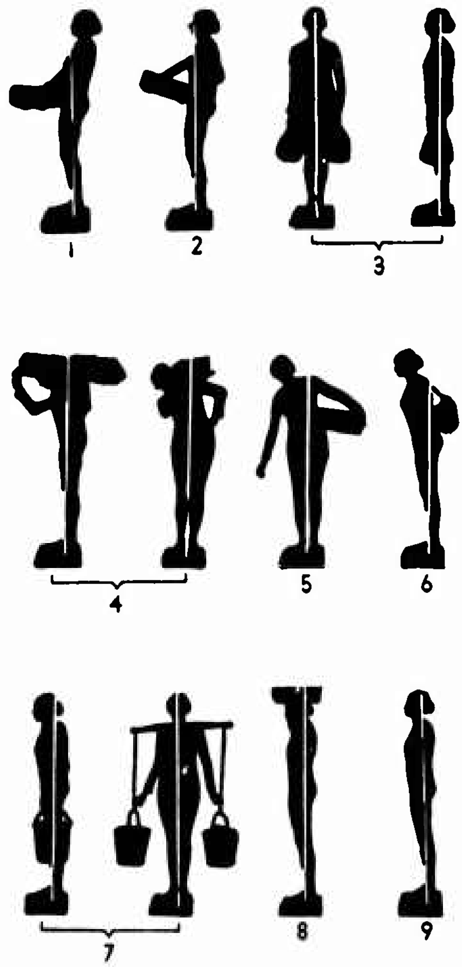

Fig. 11. Postures assumed in carrying loads. (From Bedale, 1924.)

a yoke worn on the shoulders. The primitive yoke method is by far the best. It costs much less in energy expenditure, and may be maintained for longer periods of time.

Principle of Erectness. It will help you to understand why the yoke method is the best method if you note that it is the only method which lets the man keep a perfectly erect posture while carrying the load. And it is also the method which distributes the load over a relatively large area. (The head-method permits erect posture but puts undue strain on the neck muscles.) This posture-principle is important, as we shall see, in all sorts of tasks performed by human beings, whether sitting or standing. That method is the best method, other things being equal, which permits a man to keep a perfectly erect posture from head to hips. There is some evidence also that in certain phases of recreation as well as in work, a man can perform with greatly increased effectiveness if he can manage to stay erect.

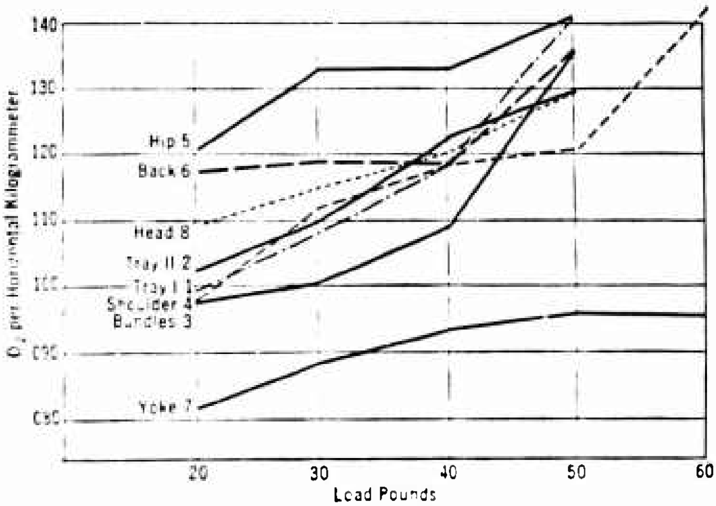

Fig. 12. Oxygen consumed in carrying loads. (From Poffenberger, 1942.)

Now let us pass on to consider posture in tasks which do not require lifting of loads or even walking, tasks which are done by individuals in one place, either sitting or standing. Most modern machines have been designed to reduce to a minimum all walking and carrying. The individual, in most cases, handles controls with or makes movements only of, his hands or feet. That is just as true of the Navy as of industrial production

Before we get involved in what the individual does, let us consider simply the question of posture. This is an elementary common-sense matter, yet one that is important. In the early days of motion-and-time engineering, very dramatic increases in production were brought about simply by making machine operators more comfortable. How does one do that?

Principle of Change of Posture. You can make a man more comfortable by allowing him to stand when he wants to stand and to sit when he wants to sit. Sitting becomes tiresome. If you need evidence, just remember, about 40 minutes from now, to consider introspectively the sensations emanating from your sitting equipment. Standing also gets tiresome. By allowing the operator to work the machine just as easily one way as the other, sitting or standing, at his option, you add materially to his comfort, allay fatigue, and increase his productivity. To accomplish this purpose, of course, it means that the machine must be designed at a greater height than is usually the case and a high chair must be provided. The worker's head, arms and body should be at the same height with respect to the machine whether he is sitting or standing.

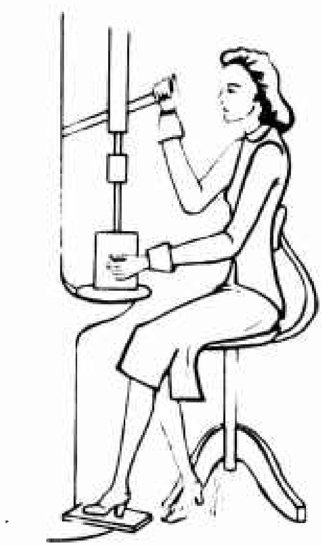

Fig. 13. A well-designed and properly adjusted back rest. (From Barnes, 1940.)

Principle of Comfort. The next and closely related principle is that a comfortable chair should be provided. To achieve the optimal in chair-comfort requires several things. First, if possible, the chair should be of adjustable height, because all operators are not built the same distance from the ground. And the chair seat and back should be properly designed. The seat should be of the saddle type, fitting well the peculiar contours of the human fundament. It should be wide enough to accommodate any body (16 or 17 inches), but it should be shallow enough to permit all who use it to bend forward easily at the hips while keeping the head and trunk erect. The back rest should support the lower part of the spine, but to do that it should not have a horizontal cross slat or bar lower than six inches above the seat.

Needless to say, not many chairs come up to these standards. Some cannot because of the nature of conditions prevailing. Many which do not could, if more attention were given to the matter. Perhaps you have seen some peculiar looking secretarial chairs, of steel frame with wide but shallow seats and with backs which are only a few inches high but which fit nicely into the lower hollow of the back. They are good not only for secretaries but also for the often more masculine backlines of all sorts of machine operators. The proper design of chairs, more often than not, will add many percent, sometimes 50 to 100 percent, to efficiency in a job.

Micromotion Methods

Now we come to the question of hands and feet and what they have to do in the man-machine situation. At this point, we must introduce some special terms and techniques. To find out the best way for hands and feet to work, we must know in some detail how they do work already. Time-and-motion engineers discovered long ago that you cannot find out much about hand and foot motions by observing them with the naked eye. They happen so fast that many essential motions can escape notice. To study such motions, time-and-motion engineers have developed micro motion techniques which analyze motions into their component parts.

Time-and-Motion Photography. The principal tool of this technique is the motion picture camera. Motions can be photographed and then played through at slow speed -- played through as many times as necessary to note every aspect of the movement patterns. The components of movement patterns are therbligs. This strange-sounding term is "Gilbreth" spelled backwards. The Gilbreths, you may remember, were the ones to use this technique extensively.

<u>Elements of the Work-Cycle</u>. The <u>therblig</u> is an element of the motion-cycle. It is not an absolute quantity, for human movements do not lend themselves to such scales. In some ways, the therblig is just a convenience. At any rate, it is the unit of movement which is significant for the operation being studied. There is an indefinite number of particular movements, depending on the operation, but for most practical purposes industrial engineers have found that eighteen basic therbligs will do.

Name of Therblig	Therblig Symbol		Explanation suggested by	Color	Color Symbol	Dixon Pencil Number	Eagle Pencil Number
Search	Sh.		Eye turned as if searching	Black		331	747
Find	F.		Eye straight as if fixed on object	Gray		399	747½
Select	St.	→	Reaching for object	Gray, light		398	734½
Grasp	G.	∩	Hand open for grasping object	Lake red		369	745
Transport loaded	T.L.		A hand with something in it	Green		375	738
Position	P.	9	Object being placed by hand	Blue		376	741
Assemble	A	#	Several things put together	Violet, heavy		377	742
Use	U	∪	Word "Use"	Purple		398	742½
Disassemble	D.A.	††	One part of an assembly removed	Violet, light		377	742
Inspect	I	0	Magnifying lens	Burnt ochre		398	745½
Pre-position	P.P.		A nine-pin which is set up in a bowling alley	Sky-blue		394	740½
Release load	R.L.		Dropping content out of hand	Carmine red		370	744
Transport empty	T.E.		Empty hand	Olive green		391	739½
Rest for overcoming fatigue	R		Man seated as if resting	Orange		372	737
Unavoidable delay	U.D.		Man bumping his nose, unintentionally	Yellow ochre		373	736
Avoidable delay	A.D.		Man lying down on job voluntarily	Lemon yellow		374	735
Plan	Pn.		Man with his fingers at his brow thinking	Brown		378	746
Hold	H		Magnet holding iron bar	Gold ochre		388	736½

Fig. 14. List of therbligs with standard colors and symbols. (From Barnes, 1940.)

The accompanying illustration lists them. As you see, they begin with the time that an operator is searching for a tool, control, or part, then, in sequence finding, selecting, grasping and transporting the object, etc. There is no need to repeat them all. More significant is the fact that their use has been standardized. They are now dealt with in terms of generally accepted initials and hieroglyphics. When they communicate with themselves, the time and motion engineers now use standard colors and color symbols and, to avoid any confusion with colors, they even specify the manufacturers' numbers of the commercial pencils they use.

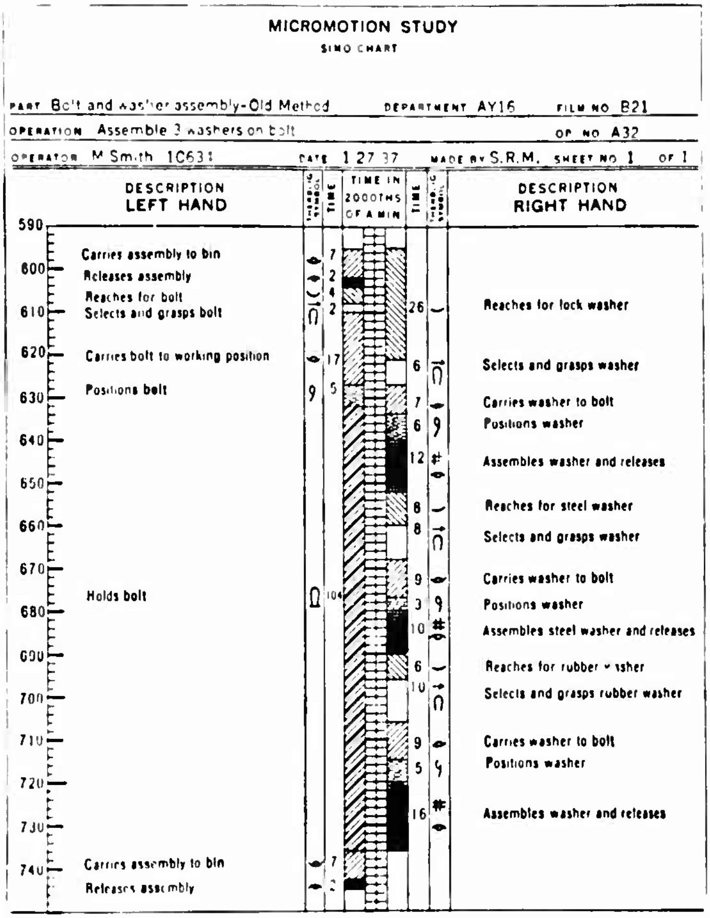

Fig. 15. A sample analysis sheet used in micromotion study. (From Barnes, 1940.)

The Analysis Sheet. With the eighteen therbligs and symbols for representing them, an experimenter may take a motion picture of a machine operation, play it back slowly, and then reduce the whole sequence on an analysis sheet. On this sheet, he can note the name of the therblig, the time that each one takes. From such a sheet, he can get ideas for eliminating useless motions or for redistributing work among the other hands and feet, if the worker has any left over. He may develop several alternative ways of carrying out the operation, set them up experimentally, reanalyze the changed operation, and determine which of the several possible ways is the one best way to do it.

Principle of Motion Economy

The most usual place to find such micromotion analysis is in industrial production -- on work benches and assembly lines. Gradually, however, the techniques are being applied to all sorts of situations, washing dishes and cooking meals, picking tomatoes, and repairing shoes. The details of these analyses are of no interest to us here. Out of all this work, however, have come some principles which are applicable almost anywhere. To get the best results out of the principles we have to apply them in detailed micromotion analyses of particular tasks, but here we can review what these principles are and get some notion of what makes, in general, for the best output of the human machine.

Distribution. The first main principle is the principle of distribution. One aspect of this principle is that the hands should be relieved of all work that can be performed better by the feet or other parts of the body. In general, we give the hands too much to do, thereby increasing the time for a sequence of operations and causing unnecessary fatigue. The feet, of course, cannot do all the detail work that the hands can, but there are many simple operations, such as switching and raising or lowering a fixture which could be done economically and well by the feet. The principle of not putting on the hands what the feet can do has not often been applied to speak of in Naval equipments. In many work situations the feet are merely things the man brings in, puts under his chair and forgets. Another aspect of the principle of distribution is the division of work between the two hands. This has become very important in industrial practice and accounts for many dramatic increases in production. The principle, in modified form, has also affected modern basketball. Players now are taught to use the left hand for those lay up shots where the use of the right hand would demand considerable awkwardness and contortion.

Simultaneous Motion. To be taken along with the principle of distribution is the principle of simultaneous motion, that the two hands should be used simultaneously, if possible, and at worst, they should never be idle at the same moment -- except during rest. One example of the use of the principle can be seen in the task of coating terminal blocks with solder to which wires would later be fastened. An analysis of the original method, practiced before application of this principle, is diagrammed in Fig. 16. There you can see that the right hand does practically all the work. All the left hand does is pick up the block from the supply pan and move it to a central position, whence the right hand moves the block to the flux pot, to the solder pot, to the knock-off plate and finally to the finished stock.

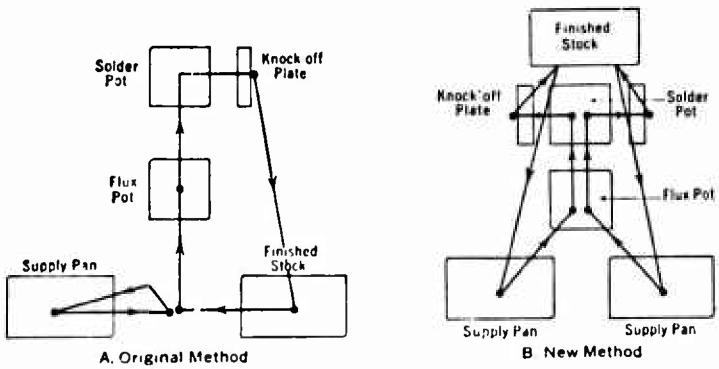

Fig. 16. A sample of improving and standardizing a movement pattern. (From Mogenson, 1932.)

A revised layout, however, designed to distribute the work equally between the hands is diagrammed on the right. There both hands carry out the same pattern simultaneously and do two units at once, rather than one at a time as before. Of course, the time per unit is not cut in half by this method because two hands cannot work as fast as one, but the total increase in production was about 85% -- a factor not to be sneezed at either in production or in military situations, where seconds are becoming more and more important.

The Simo Chart. So important is the distribution of work between the hands and keeping them in simultaneous use that time-and-motion-engineers have a special name -- the simo chart -- for the simultaneous analysis of motions of the two hands. By studying it, one can see at a glance how much time is being wasted by unequal balance of work between the two hands.

MICROMOTION STUDY
ANALYSIS SHEET

PART Bolt and washer assembly—Old Method DEPARTMENT AY16 FILM NO 821
OPERATION Assemble 3 washers on bolt OP NO A32
OPERATOR M. Smith 1C634 DATE 1 26-37 ANALYSED BY M.E.R. SHEET NO 1 OF 1

CLOCK READING	SUBTRACTED TIME	THERBLIG SYMBOL	DESCRIPTION LEFT HAND	CLOCK READING	SUBTRACTED TIME	THERBLIG SYMBOL	DESCRIPTION RIGHT HAND
595	7		Carries assembly to bin	595	26		Reaches for lock washer
602	2		Releases assembly	621	6		Selects and grasps washer
604	4		Reaches for bolt	627	7		Carries washer to bolt
608	2		Selects and grasps bolt	634	6		Positions washer
610	17		Carries bolt to working position	640	12		Assembles washer onto bolt and releases
627	5		Positions bolt	652	8		Reaches for steel washer
632	104		Holds bolt	660	8		Selects and grasps washer
736	7		Carries assembly to n	668	9		Carries washer to bolt
743	2		Releases assembly	677	3		Positions washer
745				680	10		Assembles steel washer and releases
				690	6		Reaches for rubber washer
				696	10		Selects and grasps rubber washer
				706	9		Carries washer to bolt
				715	5		Positions washer
				720	16		Assembles washe and releases
				736			

Fig. 17. Sample simo chart for micromotion study of simultaneous motions of the hands. (From Barnes, 1940.)

Let us give you one example of the application of simo micromotion study of one military task. The problem was to devise the most effective way of getting course and speed of a raid on the standard horizontal airplot table -- most of you are familiar with it. Micromotion moving pictures were taken of the standard way of doing it. Then simo charts were constructed. From these it could be seen that determining course and speed were two distinct operations requiring, on the average, a total of 12 seconds. Moreover, the right hand was doing all the work, and the left hand remained idle throughout. The problem was how to get the left hand to help the right hand, thereby distributing the work and cutting down the time. The construction of a special ruler -- a course and speed indicator -- was the answer. As one can see in the simo chart of the new method using this indicator, the left hand brings up the indicator to the track of the raid, while the right hand uses the plotting pencil as before. The result is to reduce the time for determining course and speed to 7.1 seconds, on the average, a saving of about 40%.

Symmetry. There is another principle, illustrated by the diagram of soldering, which you saw above. The motions of the two arms should be in opposite and symmetrical directions, instead of in the same direction, and should be made simultaneously. This principle is upheld, not only by many time-and-motion studies, but

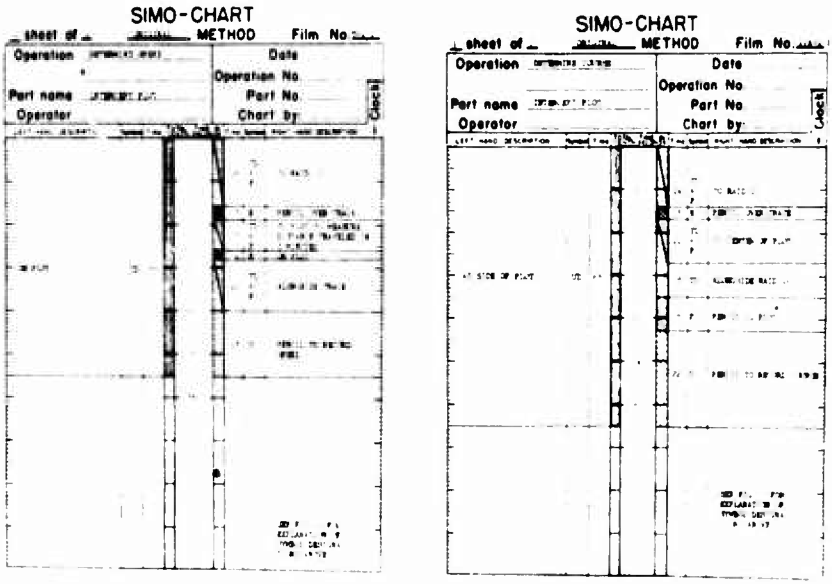

Fig. 18 and 19. Simo charts of original method of determining speed and course on the Navy standard air-plot table. (From Research Report No. 11.)

in the basic physiological design of the human organism. Areas of the cerebral cortex, pathways in the central nervous system, the pattern of nerves to the muscles, and the structure of the muscles themselves are all laid out in duplicate and in mirror images of each other. Activity in one side of the body tends to be mirrored on the other side. As a consequence, it is very difficult to do two different things at the same time with the two hands, but it is very easy and efficient to do the same thing in symmetrical patterns at the same time. A good demonstration of this is to try rubbing the stomach -- your own -- circularly with one hand while patting the head with the other. It is much easier to rub both or to pat both. Application of this principle to the design of tasks and machines often can increase output by 50 to 100%.

Least Effort. To explain the next principle -- the principle of least effort -- we must first note that hand motions can involve five different parts of the arm: the shoulder, the upper arm, the forearm, the wrist, and the fingers. Hand motions can be divided into five general classes according to the number of parts involved. The lowest class simply requires the fingers, the next class, the fingers and wrists, until the fifth class involves all parts of the arm including the shoulder. The general principle here is that movements should be restricted to the lowest possible class, to the fingers alone if possible, or if not, then to the fingers and wrists. Gross movements requiring bending of the shoulders should be avoided as much as possible. Such movements cause distortion of posture, much more energy expenditure, and take much more time.

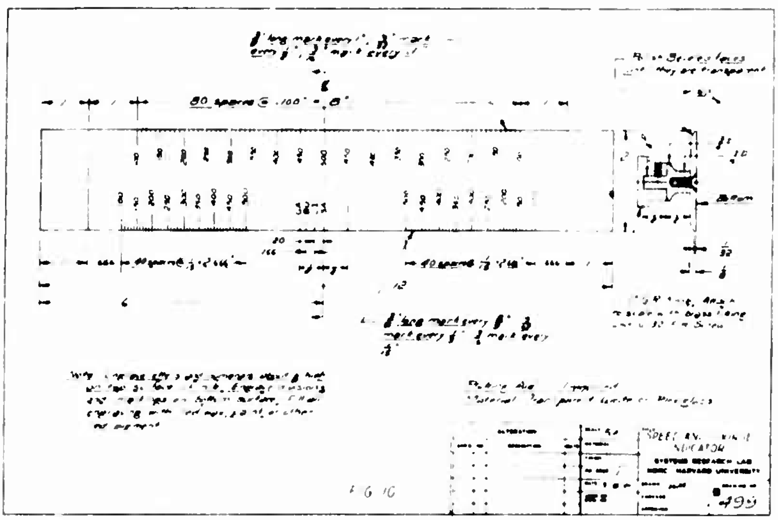

Fig. 20. Sketch of experimental course-and-speed indicator. (From Research Report No. 11.)

An exception to this principle, however, must be noted. Though finger motions are faster and should be used where occasional and non-continuous speed is the important thing, they are nevertheless more fatiguing than wrist and forearm motions. You may remember that in your early instructions in writing you were taught that the free movements of the forearm and wrist are easier and less fatiguing than "finger-methods" of writing. A similar point holds

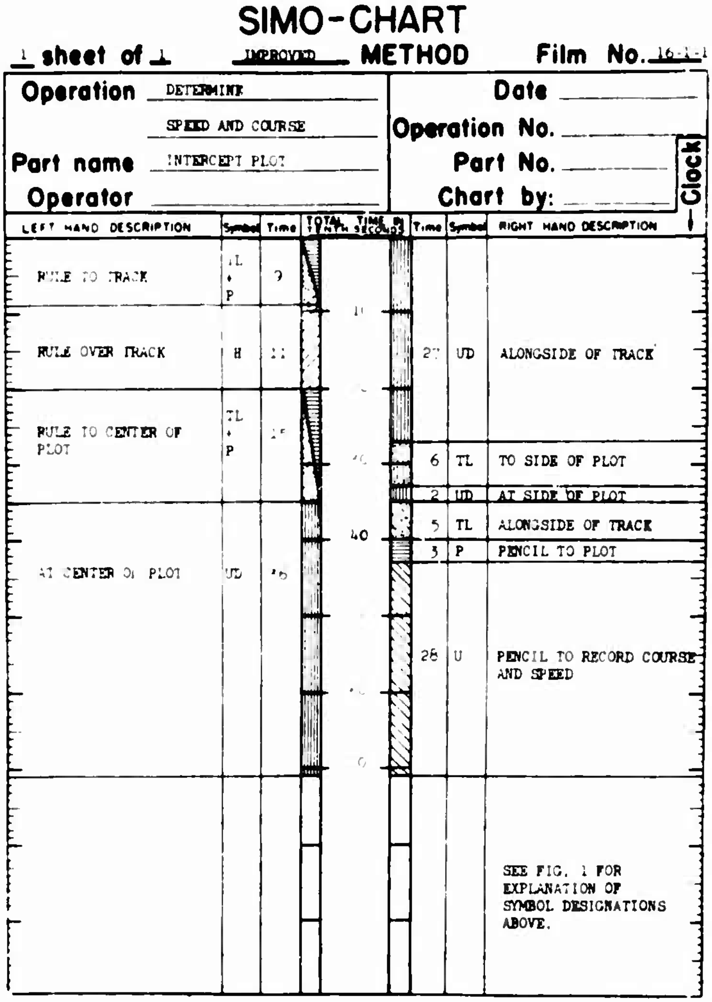

Fig. 21. Simo chart of improved method of determining course and speed from the standard air-plot table. (From Research Report No. 11.)

for telegraphy, and the use of the lateral, rather than the vertical, key in recent years is based on a study that the loose movement of the wrist is more prominent with the lateral key and helps avoid telegrapher's cramp. This and much other evidence shows that for movements requiring steady repetition for periods of time, it is better to use the wrist and forearm. For such movements, the fingers alone are not recommended. Nor is the involvement of the upper arm and shoulder.

Smoothness. One could go on for a long time with principles and subprinciples of motion economy. Perhaps just one more is worth noting here -- the principle of smooth motion -- that rhythmic, smooth, and circular movements are better than straight, jerky and controlled movements. If, for example, a straight motion between two mechanical stops is made, the time required to start, change direction and stop is almost constant regardless of the length moved. Fifteen to 24 percent of the time is used in changing direction alone. This is all waste motion, and can be saved by setting up the task so that movement is circular and continuous.

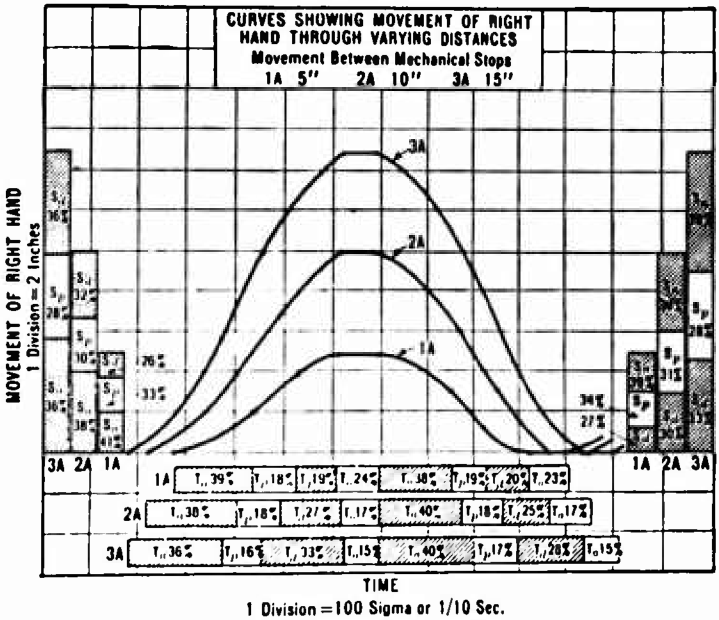

Fig. 22. Curves showing movement of right hand through varying distances between mechanical stops. (From Barnes, 1940.)

ARRANGEMENT OF CONTROLS AND WORK-PLACE

It is easy to see that if we are going to apply the principles we have just enumerated, we will have to do something about the arrangement of the work-place To redistribute work among the hands and feet means redesigning the machine so that switches or tools are found in different places. To make a man comfortable requires a specially designed chair, and to make movements simultaneous and symmetrical for the two hands means adding tools and controls, as well as rearranging those already there. So our next topic to consider is the design of machines and the arrangement of the work-place. New principles will come out in the discussion of this topic.

Definitions. First of all we must make a basic distinction about the work-place. In industrial production, we must consider tools, their number, shape, size and placement, and likewise the materials which are used in manufacturing or assembling a product. Aside from tools and materials, however, all the items in a work-place can be divided into two main classes, displays and controls. Displays are all those devices that tell us what the machine is doing: cathode-ray tubes, dials, indicators, gauges, and so on. Controls are the knobs, cranks, switches and handles that control the operation of the machine. Controls are the input of the machine; displays show its output. Looked at from the point of view of the operator, manipulating controls is his output, though at the same time, the input of the machine; and the displays, though the output of the machine, constitute the input to the operator.

Here we are concerned with the output of the operator -- controls and controlling. In later lectures we shall take up the input of the operator and shall deal with the problem of designing displays.

Industrial Principles. If this were a motion-and-time lecture in industry, we would now take up a list of principles dealing with manufacturing problems. These would stress the proper design and arrangement of tools and materials rather than of controls. The list of principles would read something like this: (1) All tools and materials should be placed at permanent and fixed stations. (2) Tools and materials should be arranged in front of and as close as possible to the worker. (3) Gravity-feed bins should be used wherever possible to deliver material as close to the worker and point of assembly as possible. (4) Tools and materials should be arranged so as to permit the best sequence of therblig movements. (5) The work-place should be well illuminated to permit good vision. These principles, however, are better suited to mass production than to naval operation, and we shall not take them up in detail here.

Other principles are more applicable to military problems -- problems in instrument operation where we have only displays and controls, not tools and materials. Let us consider these more relevant principles.

Working Areas

The first principle for the arrangement of the work space is that controls should be located within the normal working area of the hands. Most instruments which you see are laid out on a plane surface, in straight lines, and often at some distance from the operator. Boarding house experience or no boarding house experience, a man can reach only so far. This is a simple point, but one, nevertheless, that is consistently neglected. Some men, of course, can reach farther than others. Anthropologists, in a study of individual differences in reach, have made exhaustive and useful measurements of aviators' length of arm. Using these systematic measurements it is possible to take a few individuals, set them down in mock-ups and at various distances from control panels, and measure how far they can reach in various directions. Then, by reference to the anthropometric data we can state the normal working areas for the majority of cases.

Maximum Working Areas. In studying the business of reach one of the first things we note is that the maximum working area of one hand and arm is a semicircular, not a straight, flat area. We noted earlier in the lecture that, for efficient operation, movements should not involve the shoulders or distortion of posture. Thus, all control instruments should be located within the semicircular area describing the maximum reach of the arm, without such distortion of posture.

Next we note that the maximum working area for one arm is not identical with that of the other. The two semicircles overlap in front of the operator. This means that any controls which must be used simultaneously by the two hands, or which must be used first by one hand and then by the other, should lie within the restricted area in which the working areas for the two arms overlap.

Normal Working Areas. The maximum working area, however, is not the normal working area. Earlier we pointed out that movements of the upper arm and shoulder required the greatest energy expenditure and, in general, are least efficient. The normal working area in which we can work most easily and conveniently is an arc described by the movement of the hand and forearm without movement of the upper arm. Just as was true for the maximum working area, the normal working area for the two arms overlaps in a restricted area directly in front of the body. It is in this zone that controls which must be used most often by either or both hands should be located.

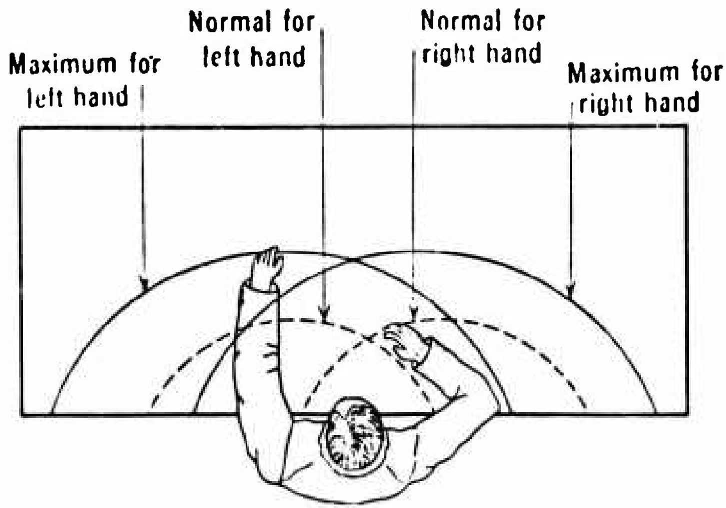

Fig. 23. Normal and maximum working areas. (From Barnes, 1940.)

With a moment's thought, you can see several implications of this analysis. First, controls should be arranged in a semicircle or arc, not in a straight line. No controls should be located outside the maximum working areas. Those that are used less frequently should lie in the outer zone of maximum reach, outside the normal working area.

Plane of Working Surface

What we have said so far simply concerns the distance of controls from the body. The next question is: In what plane should controls be located? Should controls be located horizontally on tables, on vertical panels, or on some inclined plane? There is no iron-clad rule to apply to these questions. And further research is necessary to tell us what planes are best for what situations.

Vertical Surfaces. As far as studies have gone, we can say that vertical surfaces are not the best. For one thing, vertical surfaces usually require more reaching. For another, it is usually impossible, for engineering reasons, to build vertical surfaces in an arc conforming to the principle of normal working spaces. For a third thing, vertical surfaces always waste a good deal of working space -- though they may conserve physical space -- in front of the operator. And finally, vertical surfaces almost invariably require the use of the upper arm, which is fatiguing and inefficient. For almost any purpose you can think of, a vertical surface is not as good as a horizontal surface.

Horizontal Surfaces. Horizontal surfaces also have their disadvantages. They make the operator bend his head to look down, which is not desirable. They make it easy for one control to get in the way of the other, impeding movement of the hands, and making it easier to grab the wrong control at the wrong time. But for many industrial uses, especially where loose tools and materials must lie on the working surface, horizontal surfaces are definitely superior to vertical surfaces.

Inclined Surfaces. If all controls, levers, etc., are in a fixed position, the best surface is usually some kind of an inclined plane. It usually has to be determined by tests or research what angle of inclination is the best. But you can easily see that some reasonable angle makes the fullest possible use of the normal and maximum working areas. It places most points on the surface at an equal distance from the center of swing of the elbow or upper arm. It allows for reasonably erect posture. It allows controls to be arranged in arcs without creating special problems in engineering design. Admittedly, there are often good reasons why control panels cannot be laid out on either a horizontal or inclined surface, especially where the panel contains displays which must be observed by several people at a distance. But there are many, many situations you know of where greater efficiency can be almost immediately achieved by applying these relatively simple principles of arrangement.

Arrangement of Controls

That, in brief, covers the problem of the general layout of equipment. Now we come to questions of how to design and arrange individual controls. This breaks down into two separate questions:

(1) Where does one put each control? and (2) What kinds of controls are best: that is, what are the best designs for controls? We shall take these questions in turn.

First, what is the best arrangement of controls? Obviously there is no general answer to this question. Where you put each control depends on what it controls and how often it gets used. Better than any general rules for arranging controls which cannot be formulated anyway, are techniques for finding out how to arrange them. These procedures have been worked out reasonably well, although there is still considerable research to be done.

Frequency and Importance. There are several steps we have to take in finding out the best arrangement of controls for any particular equipment. First we have to compile a complete list of all controls and their functions. This is easy, once you know the basic characteristics of a machine and what an operator must be able to control. Next -- and this is the important step -- we have to find out how important is the control. Does anybody's life depend on it? Will the whole machine blow up or fold up or fall apart if the control is misused or not used in time? In general, what priority should the control have? The third step we must take is to find out how often the control is used. Is it the operator's most-often-used or least-often-used? Is it used once every 20 seconds or once every 20 minutes or once every 20 months?

The design engineer can be trusted to carry us over the first step. He generally knows what controls are there and what they control. But generally we had better be skeptical of his opinions about the importance and about the frequency of use. He tends to look at the machine in terms of what may go wrong with it, how it must be babied, or what adjustments must be made to calibrate it. The safest way to get the answers to these two questions of frequency and importance is to make a careful survey of operators who know their stuff about earlier models of the machine or about a similar machine. For this purpose, one should have available not less than about a dozen representative operators and preferably as many as thirty.

Methods of Measurement. With this pool of operators, there are various ways of going about the survey. (a) The crudest one is to let operators give a subjective judgment in two or three categories of the relative importance and use of controls. For example, very important, important, and unimportant, or very frequently used, frequently used, or occasionally used. (b) Such crude methods, however, are not desirable, for each operator is likely to have a different notion of what is important and what is frequent. A better method is to have operators rank order all controls according to frequency and importance. Rank orders force the same kind of judgments from all operators and they also allow us to find out just how much operators agree with one another in their judgments. (c) An even better method, to be used in conjunction with the rating method, is to make systematic observations of the frequency with which operators use various controls in fair samples of their activity for reasonable periods of time. This is often impossible because personnel are lacking or realistic conditions of observation are lacking. But it is a good method if it is feasible. Ordinarily it should be used in addition to, not instead of, the rating method.

Needless to say, very few pieces of equipment have been designed on the basis of such systematic research into arrangement. The results would sometimes be quite striking if they were. But so much for the placement of knobs and controls.

The Design of Controls

Now let us turn to the question of the design of controls. Here much research remains to be done. We can state several general principles, but before the principles can be applied precisely to concrete situations somebody has got to do a good deal of basic research and specific testing.

Distinguishability. The first principle of design is that controls should be built so that the operator can tell one from another immediately. Hardly any means should be neglected for making obvious the difference between controls. The operator, even when fatigued, worried, hasty, or being shot at, should be able to reach quickly for the proper control and get it -- now. This is especially important where the control is a critical control. You no doubt are familiar with the woeful air-station phrase, "I reached for my flaps and got my wheels." In some planes, at least, the two controls are located near together and are not readily distinguishable. Of course, many such errors are just carelessness and we cannot completely eliminate all human fallibility. But it is possible to compensate for this inevitable fallibility by proper design and placement of controls.

'Coding.' Controls can be distinguished by size, shape, color, and position. One study already done shows that the hand, even when wearing ordinary flying gloves, can discriminate among at least ten different shapes. These ten shapes can be used to code controls. Another study is now in progress on the number of sizes of controls that can be used in practical situations for coding controls. Another is in progress on the accuracy with which men can reach in different locations and in different directions with and without looking where they are reaching. There is already considerable information arising principally from time-and-motion studies in industry about the use of different colors to make controls easily distinguishable. We will not have to look far to find devices with controls apparently designed according to somebody's notion of beauty or economy or manufacturing simplicity. While the story on control design is by no means complete, information now available would enable us to do a lot better than rely on some designer's hunch or esthetic sense.

Speed, Precision, and Timing. In addition to having distinguishability, controls should be designed around the basic requirements of speed, precision, and timing. There are obvious defects in many equipments with respect to this principle, but like the principle of coding, this one also needs considerable fundamental and applied research before it can be applied effectively to existing and new equipments. What, for example, is the best cranking ratio, for control cranks that drive counters or indicators? What sort of ratio gives the highest speed and the greatest accuracy? In the VF indicator, for example, the very high ratio, based on a theoretical accuracy of the device, was obviously too high. It has been reduced, but we need some general rules to go by here. What, again as an example, is the best radius for a crank? That question goes hand in hand with: What inertia or resistance should a crank have? There is an optimum combination of these two variables, a study now in progress shows.

Though the study is incomplete we can show a sample of the data obtained. Here you can see that with radii of cranks larger than 5 centimeters, it does not matter much what the crank-resistance is, but the maximum cranking speed falls far short of that to be desired. With less than 5 centimeter radii, it is desirable to have as little resistance as possible. Since, however, no system is frictionless, we see that there is an optimum radius of about 3 centimeters that is best regardless of the friction.

All sorts of factors may be involved in the smoothness, speed, and precision of control movements. Not only cranking ratio, crank radius, and inertia, but also spring centering, damping, and type and extent of movement. Several studies are now in progress on the factors influencing "ability to track smoothly with a gun sight, ability to reproduce desired pressures on a control stick, and ability to move conventional flight controls to compensate for erratic movements of an indicator" (Fitts).

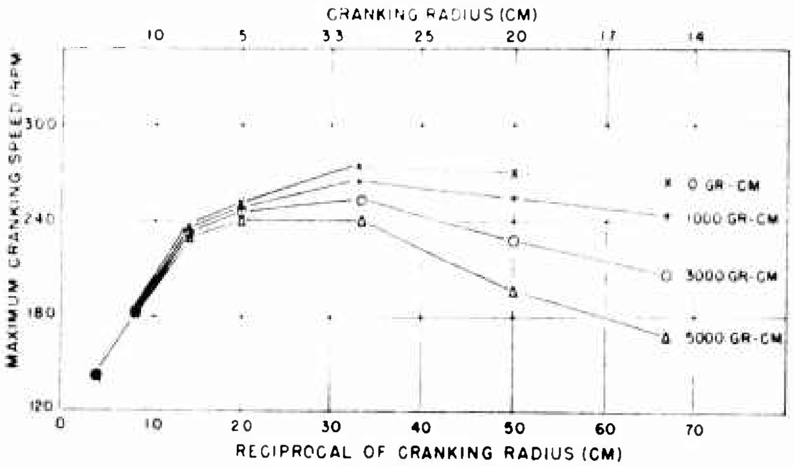

Fig. 24. Relation between maximum cranking speed, drag, and cranking radius. (From unpublished experiments by J. D. Reed, Psychological Laboratory, The Johns Hopkins University.)

Grouping of Controls. Another principle is the grouping of controls according to their function and the overall simplicity and efficiency of operation. Many difficulties in the operation of controls come not only from their bad position, confusion as to individual functions, and so on, but also from errors in the sequence of control operations. Very frequently controls may be so arranged on a panel that an operator may follow a simple sequence, like reading from left to right, or tracing out a box with his arm movements. Such arrangements speed up the work, and greatly reduce the possibility of errors, and they place much less strain on the thought processes of the operator.

Designing for Most Operators. Another more general principle, but one which is frequently forgotten is that controls should be designed not for the most intelligent, but for the vast majority of operators. The design engineer tends to assume that an operator is just like himself, just as bright, just as proficient in mechanical aptitude, and just as acquainted with the details of the equipment as he is. Equipment designed on this assumption can be operated by very few people, and the consequence is to require that an extensive selection and training program be set up for the procurement of operators. That is a very expensive way to go about it. Personnel, no matter how well trained, have their limits, and selection of personnel is extremely expensive. But a little care to design a machine so that even a child can operate it, will usually cost very little in the design and manufacture of the machine and save thousands of dollars in selection and training.

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V: OPERATION, APPRAISAL, SELECTION AND ARRANGEMENT OF EQUIPMENT

In last week's lecture we talked in general about the input and the output of the man at his machine. We put off the question of input -- of displays, of sensory stimuli -- to a future lecture. But we came to fairly intimate grips with (a) motion economy and (b) design of controls as determiners of the operator's output. Today we will again put off the business of displays and will get ourselves involved with an aspect of systems research that cuts across the input sort of analysis. Both the input and the output of the operator, and indeed, of the whole system, depend on what equipment is there, how it works, how it is arranged. These are the sort of problems we will think about in this lecture.

Problems of the Lecture. If we assume a gadget is well designed, and that the operator wastes little motion while he is working it, we can still ask many questions about it -- pointed questions. Do we really want to use the thing at all? Does it fit into the system? Does it really work when an average human being is turned loose on it in a typical situation, or is its operational usefulness merely the pipe-dream of an eager engineer? If we want it, how will we use it? How can we get the most out of it in a realistic situation? If it is a good gadget, do we want just one of them, or will we need 67? And finally, how can we arrange it -- or them -- so as not to clutter up everything?

Outline of the Lecture. We need good and trustworthy answers to these and similar questions if we are to get our systems up to their best snuff. Today we want to look at some answers in this area and to examine the procedures whereby more answers can be achieved. In the first section of the lecture we will contend with the problems of how to operate equipment. The next section will cover the appraisal of equipment. The third section will deal with the logical and practical result of appraisal -- selection of equipment. In the final and largest section we will have a fairly careful look at the business of arranging equipment in the work area.

OPERATION OF EQUIPMENT

When you initially encounter a finished piece of equipment, specified to do a certain job, a first and at least mildly logical sort of question is: "How does a man go about getting the thing to work?" If some preliminary fiddling does not answer the question, you turn to the instruction book. Here, if you puzzle over it long enough. you can read about what the machine will do and how to get it to do it.

The Best Way of Operating? But it sometimes -- and perhaps often -- turns out that instruction books are not to be trusted implicitly. They will tell you one way to get the gadget to work but there is seldom any real assurance that the one prescribed way is the best way. Instruction books tend to get themselves written before anybody has gone to the trouble of finding out the one best way to use the equipment the instructions instruct about. Too often the instruction books are based on what somebody thinks the machine should do, or on what it does do when operated by highly selected people in a sequestered situation, or on what the designer hopes it will do. Sometimes the books are written on the basis of purely engineering considerations, with the rather necessary human element ignored. Unless the instruction manual was written after, and on the basis of, some controlled and thorough experiments, it had better not be treated with obsequious reverence.

All this talk about instruction books is simply a build-up to the fact that there is no easy method of finding the best way to work a machine. Hunches, intuitions, wishes, and opinions come thicker, quicker, and slicker than do decent experiments. But they should always be taken with several grains of skeptic's salt. Experimentation -- rigorous, controlled, hardheaded, thoroughgoing experiments -- is about the only really trustworthy way to get answers about almost anything -- including the best way of operating a given machine.

Experimental Tests. Unfortunately there are no specific rules to tell us how to determine, experimentally, the best way of operating machines. Every gadget is different. And every experiment concerning gadgets will be different. The only rules we can safely follow are the general rules the scientist tries to adhere to -- the hardheaded, cantankerous, often disagreeable, but generally fruitful sort of rules that make up the scientific method. Be reasonably suspicious, ask intelligent questions, probe into the intended purpose of the machine, be curious about the alleged function of each control or indicator, try the various ways of operating the thing, don't take anybody's data-less dictum about it, and subject every reasonable possibility to experimental test. And when testing, use the most incisive, inclusive, economical experimental design you can create.

Let us try to give you a picture-by-example of the sort of problem and sort of answer that happen in this area. Look first at the VG projection-type remote radar indicator. Because it combined a large plotting surface and a radar pip in one instrument, there was high hope, when it reached the fleet, that it would cut down time and error in the indication and plotting of radar information. The hopes were soon dashed. The elaborate and expensive instrument soon became just another plotting table, failing entirely to measure up to the optimistic expectations. What was the trouble?

Part of it was maintenance. The indicator with its new and delicate projection system, was complicated. It was difficult for anyone to get into its entrails to see what was what, and to fix it. But a great deal of trouble was purely psychological. The instruction book said to set the CRT bias so that the intensity of the sweep line on the scope would be kept low. (The VG, unlike most radar equipment, is a dark-trace indicator.) The tubes last longer that way. Also some physical measures of brightness-contrast on the scope had indicated that the detectability of the instrument would be better at such (high) CRT biases. But these physical measurements turned out not to mean a thing to the human eye -- which does not work like a light-meter. The eye has its own laws for operating, as you will see in more detail in a later lecture. Suspecting that somebody had inferred from physical measurements to human functions, psychologists did experiments to compare detectability of targets on the VG for different levels of operating scope-brightness and for the presence or absence of radar noise -- "grass." The results were quite clear (see Fig. 25). There was an optimum scope-brightness for detecting targets, and that optimum was much nearer to being the maximum intensity (low CRT bias) than the minimum intensity (high CRT bias) of sweep line recommended on the basis of engineering data. By applying this fact and a couple of others, the VG indicator turns out to be about as good as any other indicator. (The findings concerning scope-brightness, incidentally, have recently been extended to several other radar indicators.)

Another Example, the Cursor. Consider another example from the field of radar. Almost since the beginning of remote radar indicators, they have been supplied with a bearing cursor. The operator, by using the cursor, was supposed to increase his accuracy in reading the bearing of radar targets. But the mere installation of a device for increasing accuracy does not automatically insure greater accuracy, especially where such a bothersome thing as a human being is involved in the process. Our laboratory has made experimental measurements of the value of cursors on several different remote indicators -- specifically the VF, VD, and SG-1 (mod 50). In none of them, is there any marked increase in accuracy due to using the cursor. In some cases there is no increase

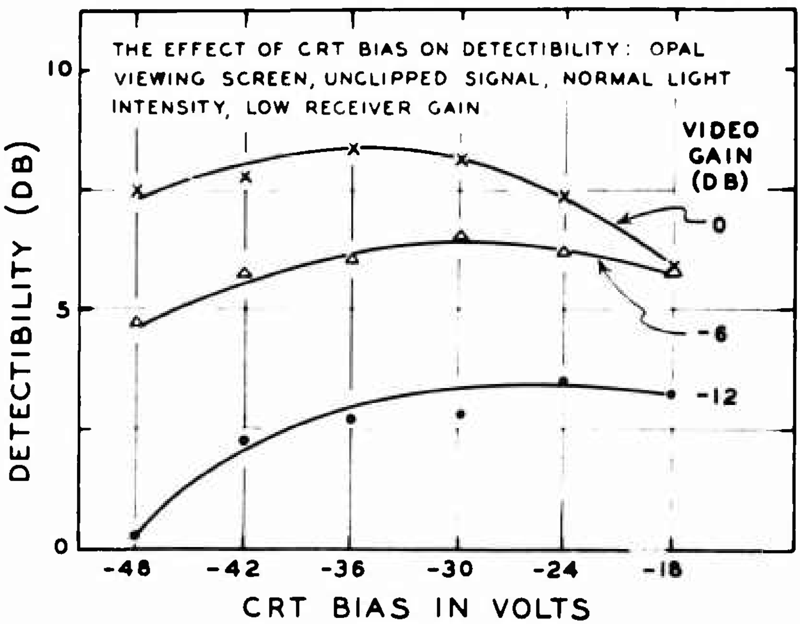

Fig. 25. Curves showing best CRT bias for visibility on the VG remote radar indicator. (From Garner, 1947.)

at all. But where there is a small increase, it is bought at a price. It takes time to use special contrivances. Using the cursor may increase accuracy a little, but it also increases the time required to make a target indication. When this is taken into consideration, the use of the bearing cursor adds nothing to the accuracy of reading slow air-target pips, and for high-speed targets, the cost in time more than offsets the increase in accuracy and actually decreases over-all effectiveness. For air targets, then, operating radar indicators with a bearing cursor does not do any good, and may even be a detriment.

Another Example, the Range Trace. Recent models of radar indicators have been provided with an electronic range trace, a device designed to increase accuracy. Careful experiments show that on the SG-1 (mod 50), the use of the range trace does increase accuracy -- but not for the reasons one might think. When there are not many targets and the general pace of operation is slow, accuracy is no better with the trace than without it. When the traffic gets thick, the use of the cursor simply keeps the accuracy from getting worse. To use the trace, one must have it fairly near the pip and must read the pip as it appears on the antenna sweep.

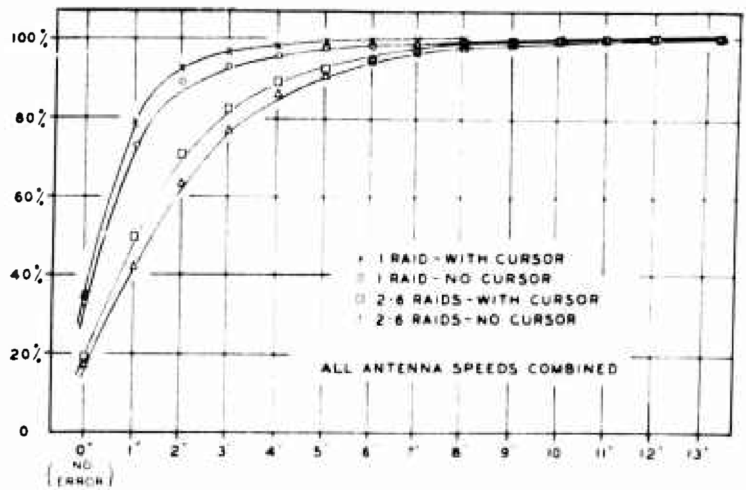

Fig. 26. Error of bearing reports with and without the use of the cursor: PPI of the SG-1b (mod 50) radar. (From unpublished work by N. R. Bartlett, Psychological Laboratory, The Johns Hopkins University.)

The trace makes the operator keep up with the targets, reading them as they come, rather than letting them get old and stale before he attends to them. The saving in time by this pacing effect contributes more to the increased accuracy than any inherent value of the trace. So, for operation, the answer is that there is no need to use the trace when one is not rushed, but it does a lot of good when the traffic is thick. At times of great activity, it keeps the operator reporting fresh pips rather than old ones. That is a handy piece of fact for anyone operating remote indicators, and it could not have been predicted from the physical performance of the equipment.

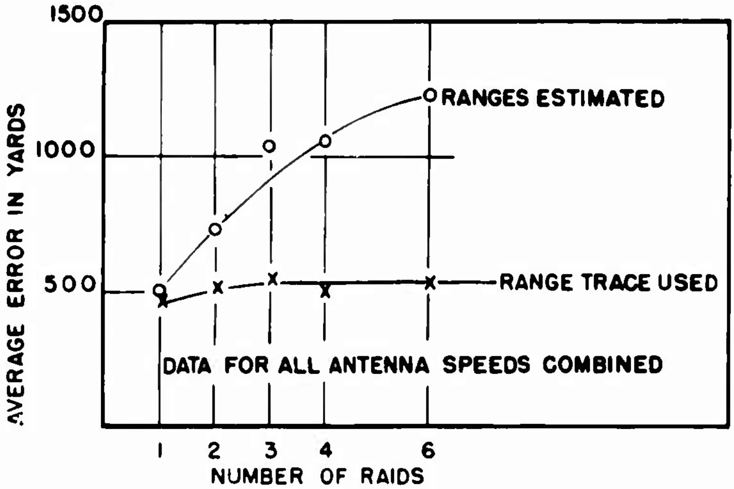

Fig. 27. Function of range trace in maintaining accuracy with increasing traffic load. (From unpublished work by N. R. Bartlett.)

There are many, many examples of devices that have some optimal combination of conditions for operation. The particular questions which one asks and answers by experimental tests are different for each device. But it is generally worthwhile to ask questions about devices-at-work, and the running of experimental tests is rarely a bad investment.

APPRAISAL OF EQUIPMENTS

Closely linked with the problem of optimal operation of equipment is the appraisal of its performance -- that is, its performance when operated by human beings under typical conditions. Again one must name the instrument to state the kinds of tests that must be run to appraise it. In general, however, we can always look for three basic kinds of performance: accuracy, traffic-load, and time-requirements.

Accuracy. In almost every man-machine combination, there is the question of accuracy of performance. With what precision can a man read the bearings and ranges of pips on radar indicators? With what accuracy can he plot an horizontal or on a vertical plot? With what accuracy can target information be telephoned over a sound-powered system? What is the accuracy of a radar operator or a gunner in tracking a target? With what accuracy can a pilot bring his ship into the desired attitude for a dive? And so on. You are familiar with all of these problems and more too.

The answers always require specific tests under controlled conditions. The answer often depends on the conditions of operation, the number of targets or the number of things that have to be done at once, or upon the fatigue of the operator. So all of these factors must be considered in the tests. Then, when one is dealing with a system of operators and equipments he must take into consideration the cumulation of error in the system. This is necessary not only to evaluate the total accuracy, but also to get at the accuracy of the specific performance in terms of the accuracy of the instrument or the information given the operator.

Traffic-load. By traffic-load, we mean the number of operations that an operator can perform in a given time. What number of targets can an operator read on a radar indicator? How many can a plotter plot on a plotting board? How many telephone messages in antiaircraft designation can be communicated per minute over a telephone line? These are simple questions -- very simple. But they are all too frequently neglected.

Many systems have been designed without much regard, apparently, to the simple matter of how much traffic they can bear. Operators are often assigned according to the number of handles there are to operate, or the number of spaces that are available to them, or to some other consideration, with no thought or the least thought, being given to how much work can be expected of them and their machines. In the design of any system, it is necessary to have some measures of the traffic-handling capacity of the man-machine combinations. If we do not have such a measure, we do not know what to expect of the system, how many equipments to have, how many men to assign to each, or what tasks to assign to each man-machine combination.

Let me give you just one example. We now have fairly good measures of each link in the chain of air target designation. First is the radar operator. Measurements show that he can do eight to twelve target-readings per minute -- no more -- depending on how many targets there are, whether he used cursors or range traces, and how good he is. A safer figure for normal operation is six to eight readings. That figure, six to eight, is also about the limit for plotting on an air table. The number of targets that can be designated over telephone systems is slightly larger. Put the whole picture together and it says very clearly that the chain from radar to gun directors is limited in each link to about two or at most three targets at a time (assuming two or three readings per target). It is no wonder that, even though most ships had fire power enough to deal with six to twelve targets simultaneously, it was a rare occasion -- in any exercises which we observed -- when more than three or four air targets were simultaneously acquired by radar designation to the batteries. The traffic-load limits in the systems would permit no more than that. You cannot run a big-inch load through a little-inch pipe line.

Many inadequacies in a man-machine system of this sort may be helped by the development of automatic devices. To trust entirely in such remedies is, however, a delusion. For every new "automatic" machine takes operators to run it. These operators usually provide the data for the input of the machine. When you involve a human being in the system, the man-machine unit inevitably has its limits in traffic load. The cure is to measure and know these limits in each case and, where they are inadequate, to redesign the system to offset them. In air designation, for example, the partial cure would have been to make three or four parallel systems, each dividing the work so that the combined traffic limits would have been multiplied by three or four.

Time. Finally, as a measure of the appraisal of an instrument, there is the measure of time required for each operation. On first thought, you may suppose that this is no different from traffic-load or frequency of operations, that if one can handle six targets per minute, it requires ten seconds per target. That is not entirely so, for there are two factors to consider: (a) the time per se the man requires to do the operation, and (b) the delay which may accumulate while he is doing one operation before he gets to the next. The total time, beginning with the time the operation should have been started till it is completed, is time-delay. This is an important measure in the appraisal of a man-machine unit.

In radar indications, for example, the time required to make a reading may be eight to ten seconds when the operator is not rushed, it may decrease to four seconds when the traffic gets heavy or when the antenna-rotation speed is moderately fast, but when the traffic really gets heavy, the operator may, for one reason or another, fall behind by several seconds and his time delays may get as high as 12 or 15 seconds. This added together with other times in the system may give total delays of 30 or 40 seconds. These delays are much more important sources of error and confusion than any aspects of the machine. In air designation, for example, the traffic capacity of the chain might be, of itself quite adequate -- even if the capacity is six readings per minute. But the delays are so great that the information, upon arrival at the business end of the chain is functionally hoary with age. Several readings have to be made before the target is acquired. This, of course, clutters up everything. If the first reading can reach the directors in five or six seconds, there is usually accuracy enough for immediate target acquisition. With such speed the chain could support five or six directors rather than only two. Time, as much as sheer traffic-capacity, is the limiting factor. Other examples could be given of time-measure of man-machine performance, but this will illustrate the need for knowing, by actual measurement, the time required for operations under various conditions.

THE SELECTION OF EQUIPMENT

The foregoing material on operation and appraisal build up to our third consideration: the selection of equipment. Obviously all that we have said about the operation and appraisal of equipment is pertinent to its selection. We must know what a man-machine combination will do, and how it will do it before we know whether we want it or not.

But there is another aspect of this matter of selecting equipment; that is, what is it a man needs to do his job? This question is not always important, but in some cases it is extremely crucial. Like many of the other matters we have discussed, this one all too often has not been settled by scientific decision but rather by guess, hunch, opinion, and sometimes just high hopes. Often it has been settled by the man just saying what he needs. Again, decision by experiment is the only safe and sure decision.

Visual Aids on the Bridge. There is time to give you just one example of the kind of selection problem sometimes encountered. During the last part of the recent war, we took rather complete recordings of conversations between CIC and the bridge during refresher exercises on air and surface gunnery problems. The Captain and Gunnery Officer had remote PPI's available to them, but they had no summary plot to view the history of target movements or to evaluate information coming from CIC. It happened over and over again in the recordings that there was confusion on the bridge because a target could not be identified by Command. In some cases, target bearings were obviously misunderstood by Command. We, knowing the officers involved, did not believe the difficulties were due in any way to incompetence. We asked several Command officers whether they thought a summary polar plot would do them any good. Some thought so. Some said no -- definitely no.

It seemed about time to put the matter to experimental test. We could not take any real Captains out of the war long enough to experiment on them, so we selected one of our civilians who had seen a lot of Navy operation, who had gone to CIC school, who had spent more than four months, off and on vessels in refresher training. To top it off, this fellow was a summa cum laude at Harvard -- which is a guarantee of one of the best memories in the world -- and had been a rather distinguished scholar and experimentalist. We felt it no insult to the Navy to say that this man's ability to remember was perhaps as good as that of the average Command officer.

We then set up a simulated bridge and CIC for surface problems, using exercises following rigidly the pattern of those we had used in studies aboard ship. Six complete, two-hour battle operations were used to make CIC and the bridge operate in a normal and realistic manner. The tests were carefully balanced, according to the best principles of experimental design, to compare the performance of the Captain with and without visual aids on his bridge. Data were taken by popping questions at him or forcing tactical decisions on him which required up-to-date knowledge of the action. In addition, after intervals of about 20 minutes in each problem, everything was stopped long enough to give him a rather complete examination on his memory of the problem. The examinations and the spot questions during the action concerned the bearing and range positions of targets, their courses and speeds, the composition of raids, and similar items.

Perhaps the questions were not always possessed of mid-Pacific realism, but the results were clear-cut enough to leave little question. The only item on which memory was just as good without the board as with it was knowledge of the presence or absence of targets and, if present, their raid designations. The ranges

Table IV

Design of Plotting-Board Experiment
(From Research Report No. 12)

Problem No.	Battle No.	Plotting Board on Bridge
1	1	Used
2	2	Not Used
3	3	Used
4	1 (revised by 180°)	Not Used
5	2 (revised by 180°)	Used
6	3 (revised by 180°)	Not Used

and bearings of air targets were known and used much better with the board than without. Courses and speeds of targets were remembered about three times as often with the board as without it. The composition of raids was known correctly about twice as often with the board as without. And, finally, among the most significant results was the fact that it took the Captain, on the average, about 20 seconds to get an answer from a smoothly running CIC, whereas on the average it required about three seconds to obtain desired information from the polar plot. In all, there could be little question about the value of a polar plot at Command Stations.

You may say that this is a simple-minded experiment and you could have told us so all the time. That is the way it is with experiments. After you do them, it is hard to see how they could have come out any other way. We were surprised, however, at the size of the difference.

This experiment is important because it establishes the fact that a polar plot is a handy thing for the Captain to have around. But just as important is the illustration of the sort of thing that can be done to settle differences of opinion about what is and is not needed to get a job done. Of course, there are not always differences of opinion about such questions. People may be in very agreeable agreement about it. But it is not impossible to obtain unanimity about a mistaken idea. It is always safest to turn on the light of experimentation.

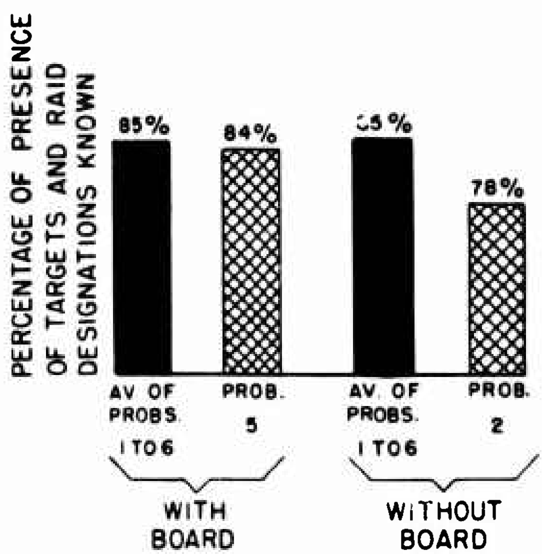

Fig. 28. Graph showing no value of polar plotting board in knowing targets present and their raid designations. (From Research Report No. 12.)

So much for selection of equipment. We have seen that the experimental method can tell us the best way of operating equipment, can appraise the accuracy, traffic-load and speed of equipment-at-work, and can settle questions about the selection of equipment. Now we turn to problems about arranging equipment in the work area.

Techniques of Arrangement

As more and more machines and more and more men to operate them are incorporated in our systems, the problem of arrangement becomes more and more important. How can we place our men and our machines -- with respect to each other and with respect to the work space -- so as to get the best performance? This is a question we will wrestle with for the remaining part of this lecture.

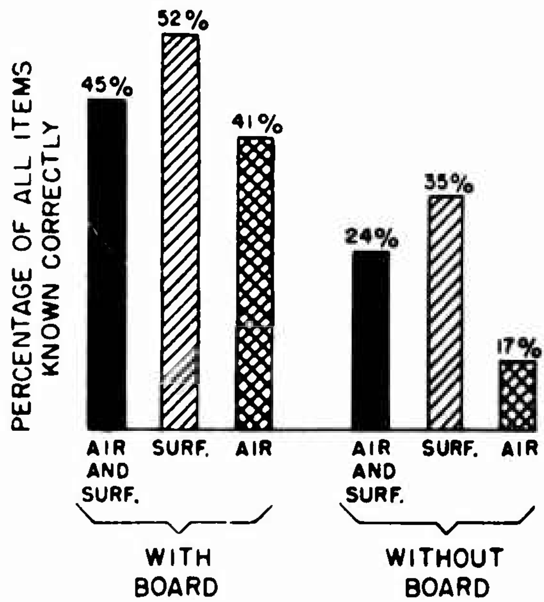

Fig. 29. Graph showing that polar plot significantly increases total amount of information known. (From Research Report No. 12.)

To talk most sensibly about arrangement, we will need to use some new concepts. The first of these is the term link. It means pretty much what it sounds like it means -- a connection of some sort between two somethings. In the scientific design of a psychophysical system we need to talk about links between a man and another man, between a man and a machine and between two machines. The term link will become more meaningful as we go on.

Kinds of Links. Several kinds of links happen in systems. The three we will encounter often are visual links, auditory links, and control links. Visual links are those in which one individual must see the displays on a device or must see what another individual is doing. Auditory links are those in which an individual must hear what a machine is doing or must hear what another individual is saying. Auditory links also include the cases in which the speech or sounds made by one individual must be heard by another. And finally, by control links we mean those cases in which an individual must control the operation of a machine or must control another individual by touching him, pushing him, kicking him, or taking over his control activity. All types of linkage in human engineering systems may be considered in terms of these basic distinctions -- visual, auditory and control.

Link-value. The next notion to consider is link-value. Simple cases of arrangement may be made with or without bothering with how important any given link is. All we need to know is that it exists. If, however, the situation is so complex that some links have to be sacrificed or discriminated against, it is essential that we know the value of man-to-man, man-to-machine, and machine-to-machine links in the system.

Getting the Link Values

How do we determine link-value? That is probably the most important question in systems arrangement. To answer it, we must first realize that link-value, whatever it is, depends upon the activity in a system at a particular time. This activity is varying from moment to moment and so we cannot get any precise answer. We can, however, take the activity of a system performing a certain type of function and average activity in links over some period of time. In the Combat Information Center, for example, we can divide its functions into several categories: air target designation, surface target designation, fighter direction, shore bombardment, and so on. We can then ask how each link is performing in some representative problem covering each of these functions, such as air target designation.

All right. Let us take one function at a time. How do we determine link-value? There are two aspects of link-value. One is the frequency with which a link is used, the other is the importance of the link when it is used. These are the quantitative and qualitative aspects of the link. So we can break the question down into determining two values, link-use value and link-importance value. How do we determine them?

Link-Use Value. This is a quantitative value and can be gotten quantitatively. There are two ways to do it. One is by actual measurement. We can look at a system as it handles a representative problem -- for example, a Combat Information Center, handling several air target designation problems -- and we can measure the amount of time or the number of times each link in the system is in use. But sometimes one cannot actually study the link-use values in a system, because the system is not around to submit itself to study. This is especially true where one wants to lay out a system which includes new equipments which have never been used before. Without the system to experiment on, a second more crude way of evaluating link-use is to use questionnaires. That is to say, one can get ratings by competent personnel -- those who have a lot of experience operating the equipment in the system and who have been in similar systems.

Questionnaires. Questionnaire methods have their dangers. You would be amazed at the poor memories people have for the details of jobs at which they have worked for years. You must also exercise care to make such questionnaires secret, so that the old hands or the braid-wearers do not influence the answers you get from your men. If you ask people to put items in three or four categories as they see fit, you will get widely different proportions for the same thing from different people, depending on their temperament. Some people will always say that almost anything they use is used 100 percent of the time. Others are more conservative and more accurate in their estimates.

Rank-Order Methods. It is safest, to avoid difficulties of this sort, to use rank-order methods. Give an officer, for example, seven pieces of equipment and ask him to rank them in the order of the frequency with which he uses them. Each rater, therefore, must give you a different rank, from one to seven, for each equipment. His judgments cannot be inflated or deflated. By comparing the ratings of several competent observers, one can determine the reliability of the judgments and end up with relative orders of use of different links. That is all you need for most arrangement purposes. In summary, then, one determines link-use value either by actual measurement or by rank-order questionnaire methods.

Link-Importance Value. This value, you will realize after a moment's thought, is something which is extremely hard to quantify. How important a link is depends upon what will happen if that link fails. If the ship can be counted on to sink suddenly when a certain indicator reads a certain way, we can say with some certainty that the visual link involved is fairly important. It is important to hear a particular communication if a plane is likely to crash as a consequence of its failure. Importance, therefore, in military situations is usually determined by tactical consequences or danger to the safety of the ship or plane. This is a pretty hard thing to measure, and in general, the systems man should not try to make that judgment. The link-importance value is sometimes obvious to anybody who knows anything about the system. The best way of establishing link-importance values, if they are not well known to the systems man, is to use the questionnaire technique described above to poll competent personnel to find out what they think is important. In the end, that is going to determine the design of the system anyway. Those who use a system and whose health and longevity depend on the system will have fairly definite notions about link-importance. These notions, good or bad, cannot be contradicted too flagrantly in the final design.

Systems Design

With link values established we are ready to consider the next important phase of systems arrangement. How shall we lay out the system? There are many details to this problem, but first we want to describe the general method of attack. This method can then be used in various ways for different detailed problems. Before one can begin with systems arrangement, he must get an over-all link-value. That means the combination of link-use values and link-importance values. There is no scientific formula, nor can there be, for putting these two together. The combination must be arbitrary depending on how one balances off use and importance against each other. For most purposes, however, one can use equal weights and one can go about it this way.

Over-All Link-Value. First one converts link-use and link-importance values into standard scales. The numbers one has for link-use may be times, frequencies of use, or seven-point ratings. The numbers one has for link-importance may also be in some arbitrary units, such as number of votes, or ratings. These should all be gotten into a simple term. A three-point scale will serve for most purposes. All links can be rated, 3, 2, or 1 according to relative use or importance. The most used and most important links would be rated 3 on each scale. Those used moderately often and of moderate importance would get 2. Those used infrequently and of slight importance get 1. Then, to combine them, one multiplies the link-use value by the link-importance. Actually it makes no difference whether one multiplies them or adds them. The consequence is to give use and importance equal importance in the final link-value. Multiplication, however, is a slight psychological advantage in magnifying the differences, say, between links that are both frequently used and important compared with those that may be important but little used. Let us, at any rate, assume here that the link-value is the product of link-use value and link-importance value, and that they are given equal weight in a system.

The Mathematical Problem. Knowing every link of any kind in the system -- man-to-man, man-to-machine, and machine-to-machine, and knowing the value of the link, we are ready to consider how to arrange optimally the men and machines. This is both a simple and a complex affair. It is something about which people are seldom scientific or systematic, yet it is one of the most complicated mathematical problems one encounters. The proper placement for each man and machine in the system is dependent on the placement of every other man and machine. The problem is comparable to the solution of a myriad of simultaneous equations in each of which there are as many constants as there are men and machines in the system and in which the values of the constants are not simple linear values but rather vectors. No one, except the chronic mathematician, likes to get ensnarled in such problems, for he may never get out again.

The Graphical Solution. Fortunately there is a rough graphical solution to the problem that is about as good for most purposes as any precise mathematical solution. The steps in the graphical solution are simple.

First, select for analysis only the important and major items. Do not include jacks, telephone boxes, small independent indicators that can go almost anywhere after the main design is completed. Next, select only the men and machines which have some link-value. A chart, for example, may be a major item, but if it is not used in the main function of the system, in relation to some other man or machine in the system, leave it out of the problem. Now tabulate all link values. As a matter of convenience, one should use a code for each man and machine, letters for machines -- A, B, C, and so on -- and numerals for men -- 1, 2, 3, etc. The job is easiest if one makes a column for each item and tabulates the links and link values. Next total each column and get the link-value, weighted or unweighted, for each man and machine in the system.

MAN-LINKS

Link	Link Value	Link	Link Value	Link	Link Value	Link	Link Value	Link	Link Value
1:2	9	2:1	9	3:1	9	4:B	9	5:C	2
3	9	B	6	A	6	A	4		
C	6	C	4	C	4	1	2		
A	2	A	1	B	2				
4	2								
B	1								
Total Link Value	29		20		21		15		2

MACHINE-LINKS

Link	Link Value	Link	Link Value	Link	Link Value
A:3	6	B:2	6	C:1	6
4	4	4	4	3	4
1	2	3	2	2	4
2	1	1	1	5	2
Total Link Value	13		13		16

Fig. 30. An example of how items having link-value may be arranged in columns with link-value as the first step in the solution of an equipment-arrangement problem.

Now we come to the graphical stage. Start with the man or machine with the highest link-value. For convenience in distinguishing them use rectangles for machines, and circles for men. Plot and code the highest item, now plot the item linked with the first one which has the highest link-value. Then plot and connect the third item with the highest link-value which is also connected with the second item. And so on. When you come to the end of your rope, go back to the first item, selecting another item connected with it which is the highest remaining item, and so on. Continue until all items are on your graph. Then draw in all remaining links between all items on your chart. The result will usually be a little confusing, but you can generally straighten out the chart by a little obvious rearrangement (See Fig. 31). This is the solution. It is the best pattern for your layout. It has all of the items in the correct relationship.

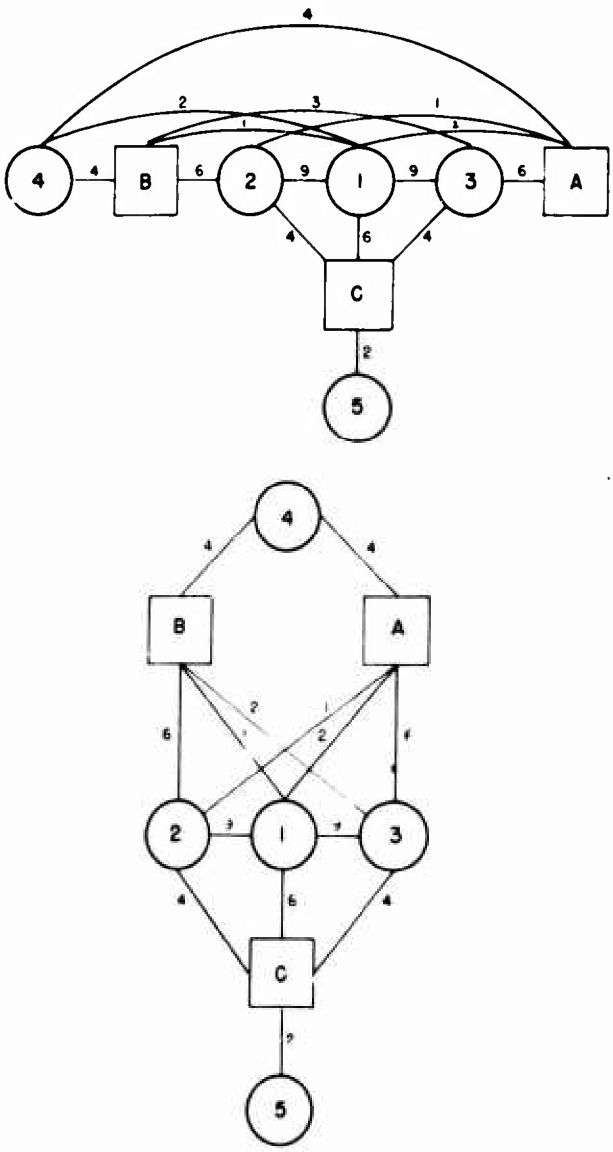

Fig. 31. A graphical representation of the data in Fig. 30, before and after rearrangement, to give simplest general form of solution.

Applying the Solution. The thing to remember, however, about the model is that it is made of rubber. You can twist and bend it, make it rectangular or circular, swing items around their axis into mirror image positions without destroying the essential relationship of items in your model. These elastic properties of the model, in fact, must be used to fit the solution to any particular space that is available.

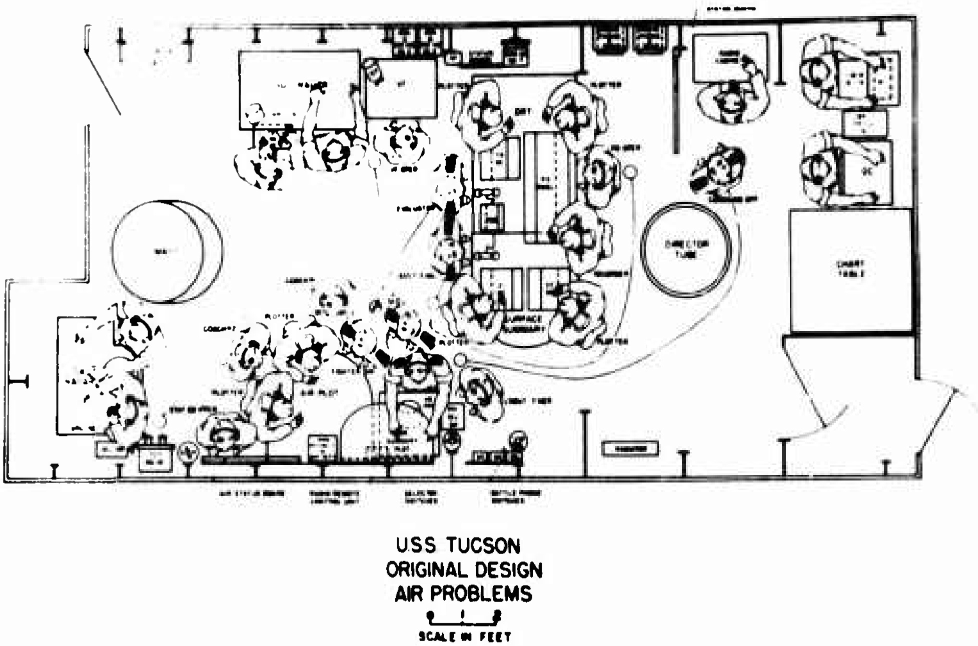

Fig. 32. A sketch drawn to scale of the layout of the Combat Information Center, U.S.S. Tucson, as it existed in February, 1945. (From Research Report No. 4.)

As one example of the method let us see how it has been used in the Combat Information Center -- in fact, the CIC of the USS Tuscon. When we boarded her about two years ago, the layout was as you see it in Fig. 32. Since she was an antiaircraft cruiser, the important functions to select were air target designation and fighter direction. The functions could be easily combined for the analysis. Data were not available for getting weighted link-values in terms of use and importance, but it was easy to establish the existence or absence of man-machine links. The problem, though apparently complicated, was simple enough so that no weighted values were necessary anyway. Aside from operators who were glued to their machines and thus need not be considered, there were four personnel and seven equipments which had some linkage value. The personnel were the Evaluator, Assistant Evaluator, Communications Officer and Gunnery Liaison Officer. The equipments were The VF and VD remote PPI's, the Air Plot Table, the Surface Summary Plot, the DRT, the PD Panel, and the Radio Desk. All other equipments that had linkage value, such as bearing indicators, telephones, interphones, etc., could be placed conveniently after the main items and equipments were laid out.

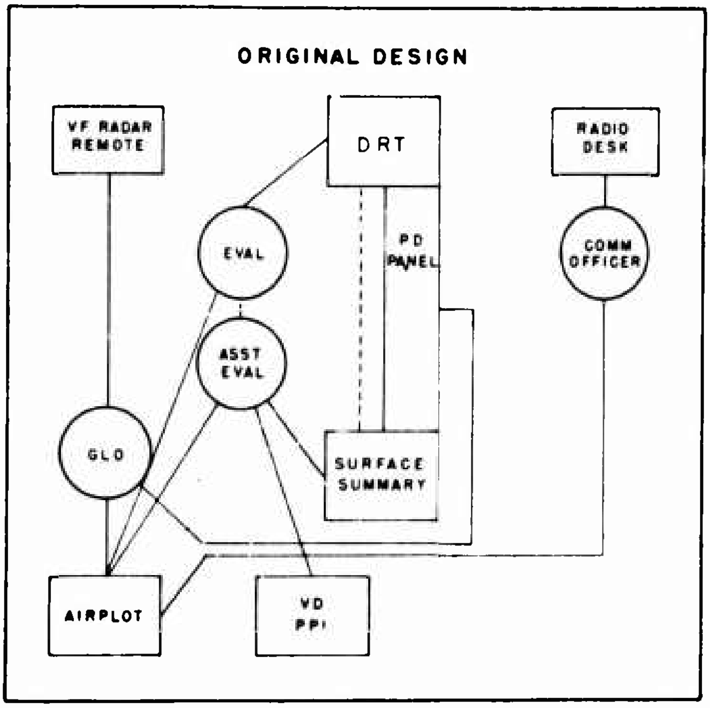

Fig. 33. A rough representation of original design of the U.S.S. Tucson in terms of links between men and equipment.

The schematic diagram of the existing layout is shown in the accompanying figure. The lines drawn indicate links, visual links, communication links, or control links. It is easy to see that this is not the best arrangement, for the links, in general, are too long and cross each other too much. That means waste motion, lost time, and too much confusion and cross talk. By using the method described a moment ago it is easy to get the correct solution. The best pattern before decoding or twisting to fit the shape of available space you can see in the illustration. The diagram also shows the same pattern after it is adjusted to the space and decoded. It only takes a moment to see that this is a better arrangement by

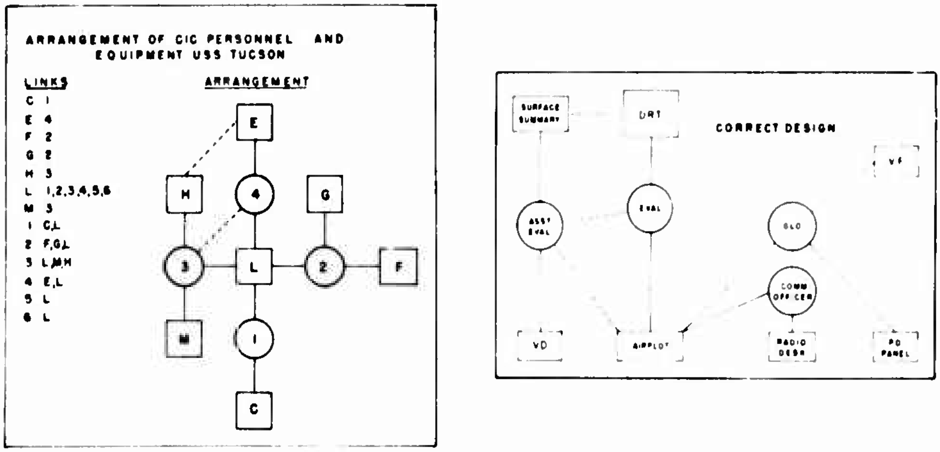

Fig. 34. The method of solving for the correct solution of CIC layout. On the left: links and pattern of solution; on the right: schematic of major items and personnel.

far than the original arrangement, especially when it is translated back into an actual layout (see Fig. 34). Many more examples of this approach to layout problems could be given, but time will not permit here.

<u>Solution Without Weighting of Link-Values</u>. That, briefly, is the general method we can use to arrive at the correct pattern for arranging a system of men and machines. Before we leave the example, however, there are two features of it which are worth pointing out because they introduce us to the next topic. First, note that no weighting of link-values was used in the analysis. A more accurate discriminating method would have determined values both of link-use and link-importance. But in this case the answer would have been the same, for the problem, though it looked complicated at first glance, was really quite simple. The solution involved no conflicts or compromises. It was possible to give every link, important or unimportant, its fair share in the arrangement. This is

not unusual. Many, many problems can be successfully solved without the accurate information required for weighting the different links in the system. In general, it is a good idea to see whether one can get a good solution without weighting, and only as a last resort go to the trouble of weighting the various links to see which ones must be sacrificed in the final solution.

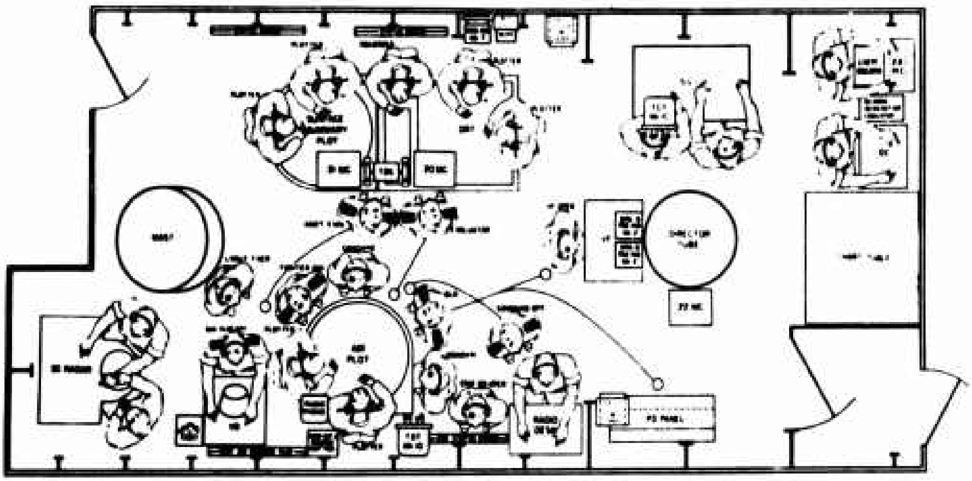

Fig. 35. The rearrangement of CIC, U.S.S. Tucson, conforming to solution by link-analysis. (From Research Report No. 4.)

Solution Without Distinguishing Kinds of Links. Secondly, note that there was no particular discrimination of the kinds of links. We just spoke of links in general, meaning that the men and the machines were in some way connected. The man had to see the machine, talk to another man, or give orders to the operator of the machine. This, too, is all that is necessary in a great majority of cases. Only where there are too many important items linked to too many other items is it necessary to break down the problem and make an analysis in terms of the kinds of links. The general solution gotten in the example above actually will serve regardless of the links. The fact that the links do not cross means that communications will be improved, for men will not attempt to talk across each other's path of talking. The fact that the links are shortened means that the visibility will be improved -- men can see what they are supposed to see, and with less difficulty. And finally, the shortening of the links means that there will be less walking about and consequently fewer people bumping into people.

Evaluation of Layouts

With those two points noted, we can go on to consider two or three matters remaining concerning the arrangement of systems. These are indices of arrangement. After one has the general solution in terms of the best pattern for the system and after one has adapted the pattern to the space that is available, there are still a few details that determine the layout. It is at this stage that certain indices of good arrangement come in handy. These indices also serve as a rough check on the adequacy of the layout. They help give us an evaluation of the layout. Here are the principal indices that may be used:

Index of Visibility. If one were concerned only with visual factors in the arrangement of a system, he could proceed with the analysis of visual links in the same way that we did a moment ago with links in general. One could set down each link between man-to-man and man-to-machine and then solve for the best pattern for such linkages. Then, if -- and this is a big if -- there were standards for the design of various indicators and displays, as well as for their illumination, it would be a simple matter so to place equipment that it would be of maximum visibility. One could do that on paper just by knowing that such and such an equipment was legible at so many feet. Such, unfortunately, is usually not the case. Consequently the construction of an index is a highly practical matter. One must determine how visible each thing is that is to be seen. Having these data, the index can be constructed by rating visibility -- say, 0 for excellent, 1 for good, 2 for fair, and 3 for poor for various links, dividing by the number of links and getting an over-all index. One can then make such minor rearrangements in men and equipment as to improve this index. Such indices of visibility have not been used very often in the arrangement of military systems, but they should be more and more in the future.

Index of Talking. When two men must talk to each other, there are two general factors that determine how easy their talk will be and how much confusion there is. One is the distance between them.

The other is the interference from other noises in general, and from other talking in particular. In a later lecture, we shall discuss the problem of talking in relation to communications equipment. Here let us consider it briefly as an oral matter in a man-machine system. The first step in improving an index of talking is the general solution for the pattern of men and equipment. When talking-links cross each other, that makes for cross-talking -- and often, cross talkers. When the distance is great from one talker to another, as when a man has to walk some distance before he can talk to his listener, the index of talking is poor. The general solution cuts out the cross lines and lessens the distance and thus improves the index of talking. After that, further improvements are a matter of detail and consist mainly of spacing those individuals who must talk to each other as evenly as possible in the spaces available.

Index of Walking. The numerical principles for arriving at this index of the walking-links are the same as for the other indices. The details are a little different. One first gets the linear distance of each walking link for the particular layout. Then, if it is possible, it is desirable to weight the length of each link according to how often it is used under representative operation of the system and according to the importance of the link. The total of the length of the paths times the weighted link-value, divided by the number of paths gives the walking index. Without the information with which to weight the walking-links, one must do with an unweighted index, that is, the total linear length of the walking-links divided by their number. Just as with links, in general, such an unweighted index gives an adequate measure of one systems arrangement, as compared with another, for most practical, not-too-complicated problems.

Index of Crowding. One factor impairing human performance, but usually neglected in the design of complex man-and-machine systems, is the space allotted for each person to do his work. Crowding can be just as great a source of confusion and inefficiency as any other single factor. Unfortunately, there is not a standard formula for determining how much space a man needs at a machine. This depends upon whether he is sitting or standing, whether he must make wide sweeping movements of his arms or simple manipulations in front of him, whether he must see the whole working area in front of him, or just a part of it. Knowing the functions, however, it is relatively easy to construct a crowding index from having a scale plan of the systems arrangement and placing manikins of the proper type in each position. One can easily rate the crowding on a scale, by assigning numbers such as 3 for completely insufficient space, 2 for restriction of the body, 1 for partial restriction, and 0 for adequate space. All personnel can be rated from the scale layout and manikins and an index computed. Minor arrangements in the pattern of the arrangement can be made, the index recomputed, and the layout accepted which, other things being equal, gives the best index of crowding.

Index of Accessibility. A factor of importance in many military systems, particularly on naval vessels where space is at a premium, is the index of accessibility. We refer not merely to the doors or accesses, but rather whether there is enough room for a man to move from one station to another along his walking-link. This is an important detail to consider in the final stages of a layout. Placement of the equipment can determine how quickly men can enter the room to man their stations. It can determine how much interference there is with activities in the system from personnel passing through. And it affects to a considerable extent waste motion, waste time, and confusion in men moving along the walking links within the system. We will not bore you again with the method of constructing the index. It is easy to see how an index might be constructed. The important point is that the systems design man consider accessibility in a systematic manner and evaluate any proposed system according to this index as well as according to indices of visibility, talking, walking, and crowding.

That takes care of arrangement -- and of this lecture. Next week we will talk about ears and how they get involved in systems.

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VI: SPEECH, COMMUNICATION AND HEARING

In the first five lectures of this series we have dealt with a general definition of our field of interest, with some of the methods by which we come to grips with the problems we encounter, and with several specific ways in which we can get better output from our man-machine combinations.

Now we turn to the general question of displays.

You will not want to argue with the statement that the efficiency of any functioning psychophysical system is often drastically, sometimes even fatally, affected by the quality and accuracy of the signals that go into it, bounce around within it, or come out of it to be acted upon by some other individual or system. The displays, the signals that can so facilitate or so clutter up the workings of a system -- and the winning of a war -- can be either visual or auditory. Visual displays we will talk about later. Auditory displays, principally those comprised of human speech, will be our concern in this lecture.

Speech as Communication

The Importance of Speech. Our civilization is a wordy civilization and our wars are wordy wars. Some few human activities seem to happen successfully without verbal communication, but speech seems to get itself intimately involved in a phenomenal variety of situations. A good deal of information is picked up by the eyes and occasionally there is transmission through the sense of touch or kinesthesis But the ears are crucially important instruments of communication -- particularly in the dark, around corners, and over great distances.

When we approach the area of speech and communication, our chronic interest in efficiency will, of course, rear its inevitable head. Few of you will need to be convinced that much alleged communication is highly inadequate, inaccurate and often downright dangerous. When one man speaks into one end of a communications system, whether the system is simply air or an elaborate electronic device, several things may happen. The man on the receiving end may hear it correctly and behave in an adaptive fashion. He may hear nothing and do nothing. He may hear and interpret incorrectly and behave in a manner that would astound the speaker. Or he may not hear clearly and keep asking for repetitions until the speaker gets laryngitis, until the message is too old to be important, or until one or the other of the participants in the procedure suffers a nervous breakdown. Errors, inadequacies, inefficiencies do happen. They happen because of discoverable and often remediable causes. These causes and remedies will concern us here.

Systems of Transmitting Speech. There are many means available for transmitting speech so that one person in one place can say something to somebody somewhere else. Obviously the simplest medium for transmitting speech is the air. One man talks, another listens. One voice and one ear can get the job done. But when a man needs to talk with somebody five or 500 miles away, he will have to call in some electrical or electronic assistance.

There are various types of devices for overcoming the impotence of the naked voice in situations where the listener is beyond air-borne earshot. The least complicated device we can use is the sound-powered telephone. As you know, this phone translates the acoustic energy of the voice into electrical energy, which, even though not amplified, can be transmitted over appreciable distances.

A slightly more complicated device and one with a greater distance span is the intercom system. Here the energy put out by the voice is transformed into electrical energy, amplified, and passed along. But when the distance becomes still greater and the use of wires is awkward, radio links are included in the chain.

Generally at least two human beings are involved when one of these devices is doing its appointed job. But today we will not concern ourselves much about the human element per se. Some people could certainly speak more intelligibly -- and perhaps more intelligently -- but today we want to look primarily at the physical systems and how they contribute to the overall performance of the communications chain. We will have to remember, however, that the operator is always there and, being human, he has limitations which we must, at every turn, take into account.

Methods of Testing. You can judge a communications device either from an esthetic or a utilitarian point of view. If you are buying a phonograph so you can listen to Fats Waller or Lily Pons, you choose on the basis of quality of tone or something of the sort; you do not like it if Lily Pons comes out sounding like Fats Waller, or vice versa. But if you are selecting an intercom system for military purposes, you ask the utilitarian question, "How well does it work?" You do not care about the prettiness of sounds; you are interested solely in their intelligibility. Do messages get across? This is the criterion for a good communications system -- and the sort of thing we are interested in here.

Intelligibility can be directly measured. It is not always a simple process, but fairly precise techniques have been devised for assaying it under various conditions. Some of the techniques were worked out by the Bell Telephone Laboratories before the war and many have been elaborated upon, revised and sharpened during the war by the Psycho-Acoustic Laboratory at Harvard University. Much of the material we will look at here comes from the Psycho-Acoustic people.

The simplest paradigm of the basic method is this: you put a message into a system and measure precisely what percent of it comes out at the other end. What comes out you call an articulation score. If 10% of the message gets understood, the articulation score is low. If 99.44% of it is understood, the system has a high articulation score.

The running of actual intelligibility experiments, of course, is not quite so simple-minded. There are various sorts of material, for example, that you might put into the system. Each sort of material would give you a different score. The methods have been so well worked out, however, that we know the relations between the various types of material and we can hence use the type of material demanded by the expediencies of the particular situation.

We can use nonsense syllables like guk, mip, og, oit, aug -- monosyllabic noises that have no English meaning. With such material it is possible to construct a test containing all sounds and combinations of sounds in the English or any other language. In such a test we can find out which sounds are most often and least often understood.

Or we can use monosyllabic words. These are like nonsense syllables except they have meaning. They recommend themselves as test material because they make possible the relatively speedy attainment of articulation scores.

A third type of material used for certain purposes in articulation testing is the spondaic word. Spondees, as they are called, are words of two syllables with no primary accent on either syllable. Words like beehive, blackout, hotdog, and whizzbang are spondees. If we want, of course, we can use whole sentences in our articulation tests. For example, "Ring twice and batter down the door," or "If a man answers, hang up." In scoring these sentences you score only those words found, by other tests, to be key words. In the first sentence we gave you, we would score ring, twice, batter, down and door. If the listener gets these he gets the meaning of the sentence.

These methods enable us to compare the articulation scores of any two systems or to evaluate the results of any experimental alteration we want to make in any system. We can say that the articulation score for system A is 80% and for system B is 50%. Or we can say that under condition X, system A scores 90% while under condition Y it scores 75%.

FACTORS INFLUENCING SPEECH INTELLIGIBILITY

The number of factors which can affect speech intelligibility is rather amazing. In 1944, for example, somebody listed a total of 30 factors affecting intelligibility in one radio communication system. These factors vary all the way from the announcer, his speech, the microphone, and on through to the earphone-mounting and the listener. For example, there are five aspects of microphone design which can affect intelligibility of speech. These are its frequency response characteristic, its non-linear distortion, its efficiency and its impedance, its behavior at different altitudes, and its directionality. Likewise, there are six amplifier conditions which can affect intelligibility. Again its frequency response characteristic, its non-linear distortion, its input and output impedances, its gain, its peak power limitation, and its shielding. Since that list was made in 1944, many other factors have been shown to be important.

General Principles. In the discussion of some of these factors, we will very rarely make reference to a specific type of communication equipment. Seldom will we refer to a specific earphone, a specific microphone, or a specific radio transmitter. We now have so much information about communication systems that it is no longer necessary to discuss specific cases. We can talk about the general case. We can make valid general statements with complete assurance that they will apply to any given specific case.

This sort of achievement in any branch of science is quite impressive -- at least to the scientist. Without valid general laws about basic variables, we must run a new and laborious experiment every time we are confronted with a practical problem. If we are clever enough or lucky enough or persistent enough to arrive at good general principles, we can get quicker, better, more insightful answers to a wider variety of practical problems. In the field of intelligibility of communications we can talk -- and talk significantly -- in terms of general factors. We can cover the field without dealing with specific tests of specific gadgets. We can deal instead with the general factors of intensity, frequency responses, amplitude distortion, etc., and cover the field far more adequately and usefully.

Intensity

Obviously, one of the prime determiners of speech intelligibility is the intensity of the speech. If we cannot hear the speech, we cannot understand it. The exact relation between intensity and speech, however, is not quite as simple as one would expect.

In Quiet. In Fig. 36 we see how the word articulation score varies as a function of the intensity of speech. The abscissa values in this illustration are stated in terms of sensation level, which simply means that intensity is relative to the intensity which can just be heard. The curve on the left shows how intelligibility, or articulation, increases with intensity when there is no noise in the environment. From this curve we see that intelligibility increases very rapidly -- reaching almost its maximum within a range of 30 decibels, but does not reach its real maximum until approximately 60 decibels above threshold. One very interesting thing about this curve, however, and about all such curves, is the fact that as speech intensity is increased to very high levels, speech intelligibility decreases, rather than increases. What this means is that there is an optimal intensity for intelligibility. If the intensity is decreased below that optimal level, or increased above that optimal level, speech intelligibility will be impaired.

In Noise. The curve on the right shows how speech intelligibility increases with intensity when there is a very loud masking noise in the environment. You can see that this curve is roughly the same as the curve for the quiet condition, although the rise is much steeper, and intelligibility never reaches 100%. In most situations intelligibility never does reach 100% as measured by an articulation score. This is of no serious concern, however, since if 80% to 90% of the words are understood, the meaning of a total paragraph can be reasonably well comprehended. It should be clear from the curve on the right hand side of the illustration, that intensity alone is not the prime determiner of speech intelligibility.

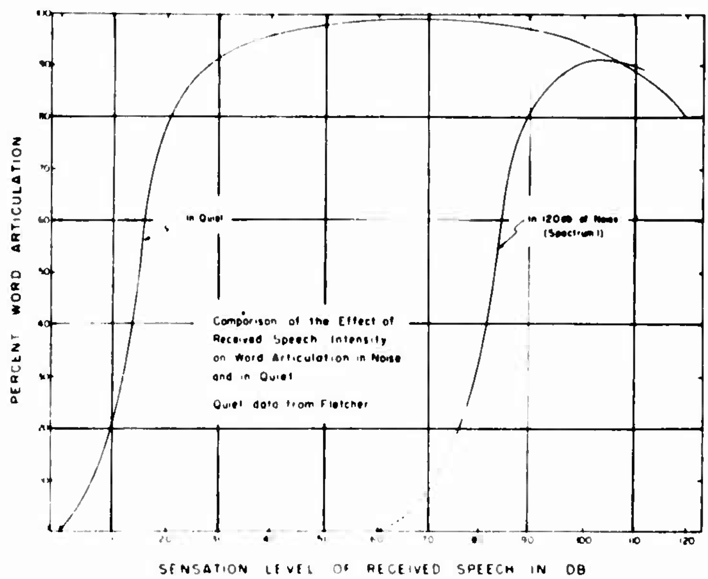

Fig. 36. The effect of speech intensity on percent word articulation in quiet and in loud ambient noise. With this much noise, the range of levels of received speech available for intelligible communication has been reduced 60 db. (From Egan, 1944.)

Rather it is the ratio of speech energy to noise energy. By this we mean that intelligibility of any speech is determined primarily by how much more speech energy than noise energy there is in the listener's environment.

This problem of the masking effect of noise in the environment is a very serious one. Furthermore, it becomes more serious the more electronic links there are in the communication system. For example, when using straight voice-to-ear talking, the only noise which can interfere with the speech is the noise in the air. When, however, intercom systems are used, we not only have to contend with the noise surrounding the speaker and the noise surrounding the listener, but also all noise which is introduced in the amplification process. Vacuum tubes themselves generate a certain kind and amount of noise. The more noise they generate, the more difficult it is going to be to secure intelligible speech. In a radio system of communication, noise may also be introduced in the RF amplifiers and in the air. Electrical static is probably well known to all of you. It not only is very annoying, but it also is hard to hear speech in static. All this we can see from the curves in the figure.

Speech-to-Noise Ratio. Intensity per se is not nearly so crucial a determiner of speech intelligibility as we would first suspect. It is rather the ratio of the speech energy to the noise energy -- what we commonly call the speech-to-noise ratio, or just S/N ratio. This ratio is easily expressed in decibels. If the signal-to-noise ratio is held constant, articulation is reasonably constant, regardless of the level of speech.

Fig. 37 shows us percent articulation as a function of overall intensity, with various values of signal-to-noise ratio. In this figure, we see that several different values of signal-to-noise ratio are applied, and we can read percent articulation as a function of the sound level of the speech. You can easily see that the signal-to-noise ratio has more effect on word articulation than does the overall level of the speech, particularly at the lower levels. As these overall levels become greater, however, articulation becomes poorer, even with the same signal-to-noise ratio. There is an optimal overall intensity, even though the signal-to-noise ratio is predetermined.

Optimal Signal-to-Noise Ratio. These general relations contain direct and helpful hints about operating a radio receiver. As we can see from these relations, there is an optimal overall level for a given signal-to-noise ratio. If the entire noise that is masking speech in a particular circumstance is coming from the radio receiver, then changing the gain level on the receiver does nothing at all to the signal-to-noise ratio. It simply changes the overall level -- giving you a stronger speech signal but at the same time feeding you a bigger dose of noise. When this is the case, you can easily see from these graphs that for every S/N ratio there is an optimal gain for the receiver. If the signal-to-noise ratio is on the order of 5 db, then we can see from these curves that we will get the best intelligibility around 70 db.

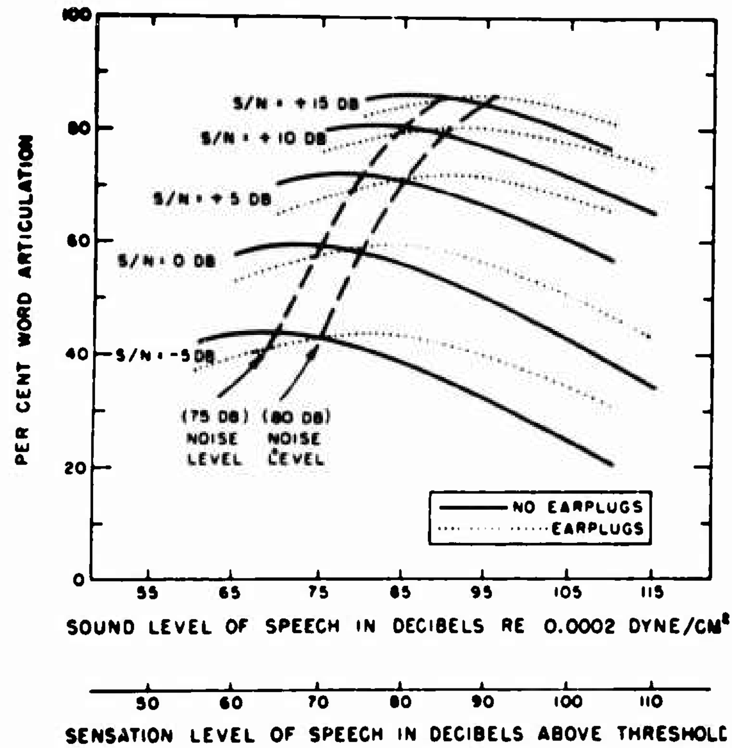

Fig. 37. The relation between percent word articulation and speech intensity for various signal-in-noise ratios. The use of earplugs (Dotted lines) tends to shift all curves to the right. (From Kryter, 1946.)

<u>The Importance of Gain</u>. If, on the other hand, the main source of noise is external to the receiver, then the situation becomes entirely different. For example, if the receiver itself is relatively quiet but there is considerable noise in the air -- such as in an aircraft -- then the optimal position to operate the equipment would be at the maximum possible gain, since we would want to get as

much speech energy as possible relative to the noise energy. When you turn up the gain you turn up the speech without turning up the noise. That is good. It gives you a better signal-to-noise ratio and better intelligibility.

The Advantage of Ear Plugs. We have not mentioned anything about the dotted lines on these curves, but they too present a rather interesting problem. If we have a fixed signal-to-noise ratio, there is still a possible means for increasing speech intelligibility. Let us take the case we just mentioned -- the case in which all the noise is produced by an aircraft. In this case we would want to push up the speech energy as far as possible above the noise energy. By this means, we would get the best possible signal-to-noise ratio. But we can see that any given signal-to-noise ratio, if the intensity is too high, can produce better word articulation if the overall level beating against the ear drum is decreased to a certain extent.

Now when the noise is primarily in the air, we cannot decrease the overall level of both signal and noise by changing the gain of our receiver. We can, however, effectively change the overall level as it occurs at our eardrums by inserting some kind of a stop in the eardrum. We can use some sort of earplug, or even a wad of cotton. Either will do essentially the same thing, except that the earplug will do it better. We essentially decrease the overall level, and thus increase speech intelligibility. What has happened in these dotted curves is that the insertion of an earplug has shifted the whole curve over so that its optimal occurs at a higher signal level. Remember that this signal-to-noise ratio was already determined by the amount of noise in the environment; therefore, that is fixed. But if we can change the overall level by changing the amount of noise and signal hitting the eardrums, then we can improve speech articulation, or intelligibility. In such noisy places as aircraft, submarines, factories and cocktail lounges, where the environment comes with a built-in noisiness, the use of earplugs, paradoxical though it may sound, will increase a person's ability to get himself communicated with.

In summary then, the intensity of speech is a prime determiner of the intelligibility of speech. The signal-to-noise ratio, however, is more important than the overall intensity of the noise. But even with a constant signal-to-noise ratio, speech intelligibility can be improved if the overall system is operated at a proper gain level

Under conditions where the noise and speech are coming from the same source, this overall level can be determined by means of a simple gain control. However, when the noise and the speech are coming from different sources, then the overall level can be changed only by attenuating some of the sound at or near the eardrum. Earplugs do this.

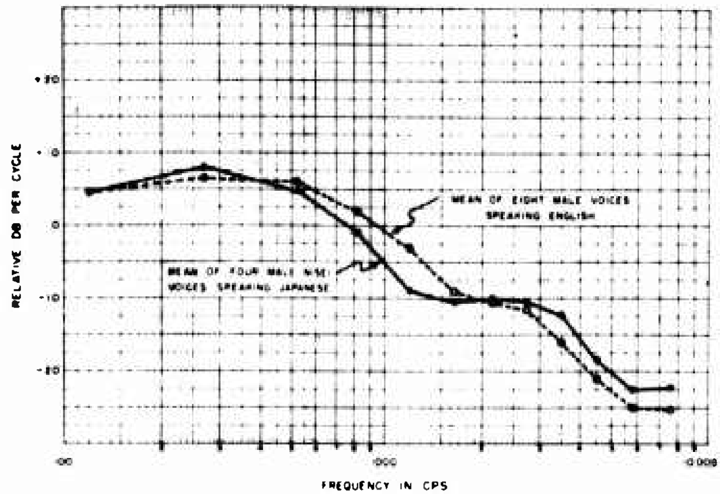

Fig. 38. The average frequency spectra of English and Japanese voices. (From Mills and Mitchell, 1945.)

Frequency-Response Characteristics

Intensity is not the only thing that determines speech intelligibility. The spectrum of the speech -- the patterned distribution of energies among the various frequencies in speech sounds -- also has a lot to do with the intelligibility of speech. Here we immediately encounter the problem of frequency distortion -- the problem of infidelity on the part of communications devices. But before we get involved with the problem of unfaithful reproduction, let us have a look at the normal speech spectrum.

The Speech Spectrum. Fig. 38 shows the distribution of energy in normal speech. These spectra were obtained from male voices speaking (a) English and (b) Japanese. We can see here that the main energy of speech falls in the region below 1000 cycles per second, and that the energy begins to fall off from about 600 cycles on up. These spectra mean that if our communications system did us out of the frequencies below 2000 cps., we would have a tough time making sense out of speech. But we could probably get along fairly well without the frequencies above 2000 cycles.

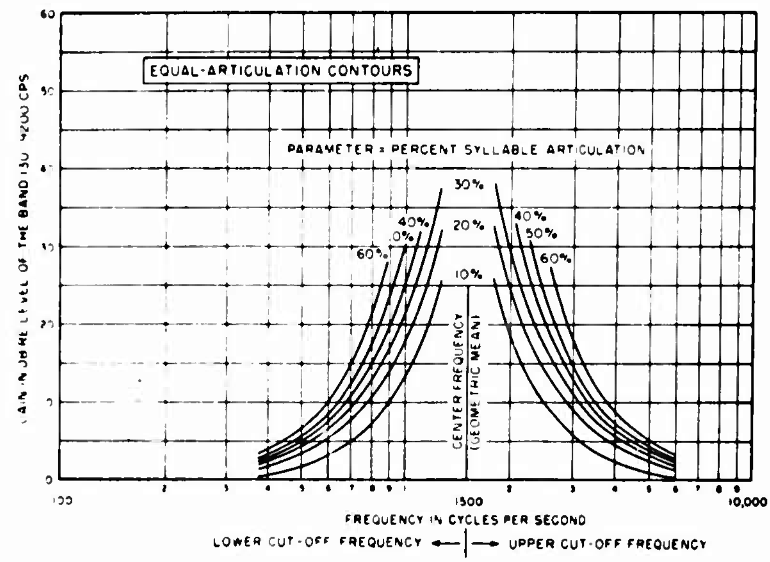

Fig. 39. Equal-articulation contours for various band-pass systems having a center frequency of 1500 cps. (From Egan and Wiener, 1946.)

Frequency Distortion. Almost every known electronic device produces some frequency distortion. That is, some frequencies are reproduced faithfully while others are discriminated against. If distortion must occur, and apparently it must, then we at least should be diligent in our efforts to make it happen where it does not matter much. As we can see from Fig. 38, less harm will be done if the higher frequencies are discriminated against. In general, we can say that the wider the band of frequencies which are transmitted, the greater will be the intelligibility of the transmitted speech. Likewise, if certain frequences are rejected in the system, the loss of intelligibility which this rejection of frequencies causes can be compensated for to a certain extent by increasing the overall gain. In fact, a whole family of relations can be plotted showing how speech intelligibility interacts with intensity and frequency response. Fig. 39 shows a family of such relations. These curves are essentially equal articulation contours. They show the conditions of gain in intensity and frequency response which will give equal articulation.

Equal Articulation Contours. The curves may seem a little confusing, so we will take a moment to explain how they can be read. Let us take that lower set of curves, the ones marked 10% articulation. These curves tell us that if we have transmitted a band of frequencies from about 1000 to something over 2000 cycles they will give 10% articulation if the gain of that system is increased approximately 15 decibels above the reference. If, however, the band-width of frequencies is narrowed down to approximately half of that amount, then the overall gain must be increased to 25 decibels in order for speech intelligibility to remain at the 10% level. The gain scale on the ordinate is with reference to what is essentially a flat spectrum.

Let us take as another example the curves labelled 60% articulation. We see from these curves, one on either side, that if we pass a band of frequencies from 700 cycles to 3300 cycles we will have 60% articulation if we increase the gain of that system 15 decibels with respect to the reference system. If, however, we increase the gain to 25 db we can now decrease the band pass for frequencies to a band between 850 and 2700 cycles. As the band of frequencies transmitted is narrowed, we have to increase the gain in order to maintain the same intelligibility.

The Design of Earphones. You can probably see immediately the practical importance of these relationships. These curves represent basic, general knowledge. Such knowledge can replace the haphazard hunches so often involved in the design of instruments. For example, let us see what these basic facts have to do with the design of earphones. As you know, few earphones could be accused of being high-fidelity instruments. Most of them distort -- plenty. Most pass only a limited band of frequencies, and most of them pass a very narrow band of frequencies much better than they do surrounding frequencies.

This sort of behavior on the part of an earphone is called resonance. We have seen that such distortion hampers intelligibility. If you take a highly resonant phone and compare it with a relatively non-resonant phone, both operating at the same level of overall intensity, the resonant phone would come off a poor second in intelligibility. We know, however, that an increase in intensity can compensate for frequency distortion. Now if it happens that the resonant phones, by virtue of being resonant, can put out greater intensity, this increased intensity will up the intelligibility. And the resonant phone, operating at its maximum energy output, may turn out to be more intelligible than the non-resonant phone operating at its maximum. In designing earphones we can compensate for poor fidelity by increasing intensity and we can compensate for low intensity by increasing fidelity. From the basic curves we can decide precisely on the best sort of compromise to make in our actual design.

It should be pointed out that the curve shown in this figure can be shifted along the abscissa scale within limits, so that the center frequency occurs at any point. Since this is a log scale, it does not change the relative shapes of these curves.

The Frequency-Design of Systems. We mentioned the case of design of earphones, simply because that is one very clear-cut case. The problem of frequency response, however, occurs at almost every point in a total system. We have the problem of frequency response in the microphone, in the amplifiers, both audio frequency and RF amplifiers. We have the same problem in the receiver, and the amplifier associated with that receiver. And we also have the same problems in the earphones, or the speaker, which is used to transform the electrical energy back into acoustic energy. At any one of these points the design can be worked out exactly. on the basis of relations such as we have in this figure. There is no longer any need to guess about what is the most efficient way to build an earphone or an amplifier. By using information such as we have here we can determine exactly where we lose and where we gain.

The Masking of Speech

A moment ago, we pointed out that in most situations intelligibility of speech is determined not only by its intensity, but also by the level of the masking background. We have talked as though the masking background, being a noise, were the same under every condition. Actually that is not so. Furthermore, there are many cases where we want to mask speech -- somebody else's speech. When masking noises just happen, as adventitious by-products of a mechanized civilization, we speak of interference. When masking noises -- ingenious, infernal, insanity-producing noises -- are deliberately made for purposes of cluttering up somebody's communication, we speak of jamming.

Where there is a will to mess up somebody's communication, there is a way. And there is a way to do it cheaply. The most effective ways to stop speech communication, we must report, are, perhaps unfortunately, considerably beyond the limits of politeness and hence cannot, with propriety, be used at the breakfast table or at cocktail parties or -- even in lectures. But in less refined situations, if you want to stop communication, the techniques are available.

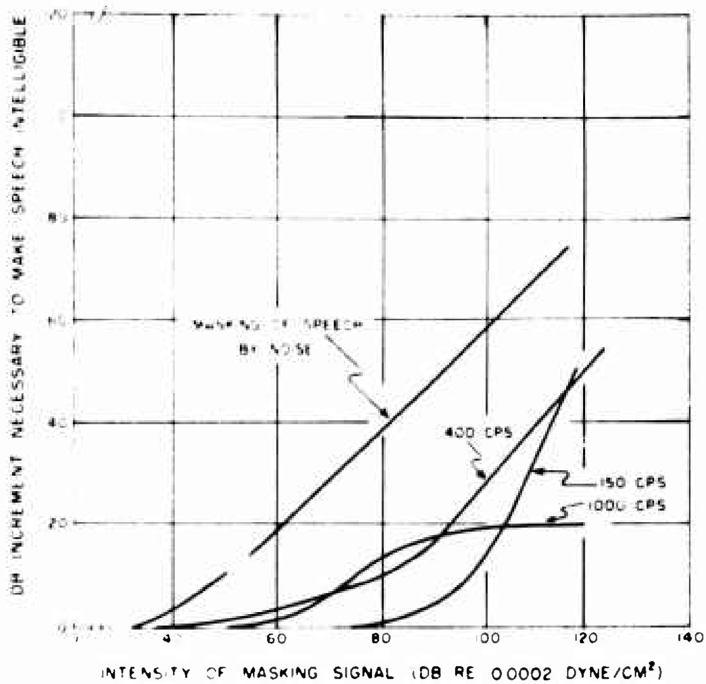

Fig. 40. The effect of noise and various tones on the masking of speech. (From Miller and Mitchell, 1945.)

Noise vs. Tones. Pure tones were the first devices tried out in the attempt to mess up speech. Fig. 40 shows us how effectively a pure tone compared with noise can mask speech. We see from this figure that the low tones, particularly at higher intensities, are more effective maskers of speech than the high tones. None of the tones, however, is as effective as the noise. This is because a pure tone tends to mask only those frequencies in speech that are close to the frequency of the tone. Frequencies mask frequencies near them better than they mask frequencies far away. We have previously seen that speech energy is spread over a fairly wide range of frequencies. Thus when we introduce a 1000 cycle tone, we mask a lot of the frequencies, to be sure, but we have no effect at all on most of the frequencies. The lower frequencies mask more efficiently than the higher frequencies because masking effects spread more easily from low frequencies to high frequencies than from high frequencies to low frequencies. But the fact still remains that no pure tones work as well as a noise spectrum. In other words, the best way to mask something which has a lot of frequency components is to use as your masking device something which has a lot of frequency components.

Other Maskers. During the war all sorts of masking signals were tried. We used pure tones, and we used stepped pure tones -- that is, pure tones whose frequency continually changed in discrete steps, and whose changes were random. We used frequency modulated tones and amplitude modulated tones. We also used what has been called "night club." Night club is a type of signal which combines the noises -- sometimes called music -- produced by various jazz orchestras. Sonovox was also used. Sonovox uses the principle of voice modulation of some other sound. It is the same principle as that used in the production of the well known BO signal.

Speech as a Masker. Another type of signal used to mask speech was, strangely enough, speech. Come to think of it, it is not at all surprising that the best way of masking speech is by the use of other speech. The reason for this should be perfectly obvious. The most efficient way to mask any frequency is to use another tone of the same frequency. By far the most efficient way to mask any particular frequency spectrum is to use an identical masking spectrum. The one best way of getting a masking spectrum identical to the speech spectrum is to use voices in producing the masking spectrum. In Fig. 41 we see how masking efficiency is affected by the intensity of the masking voice, as well as the number of masking voices. The coordinates are reversed a little bit in this graph, since we are now plotting masking efficiency instead of percent articulation. The one is simply the reverse of the other, and if this confuses you, simply stand on your head and look at the graph upside down.

We can see from these figures that one voice is not a very good masker. Two voices are somewhat better, but by the time you get up to six and eight voices masking is pretty good. When only one voice is used, there are sufficient gaps in the temporal continuity for words to be picked up in between these gaps. When a good many voices are combined, however, the gaps from one person's speaking are filled in by another person's speaking, so that we tend to have a continuous noise. This type of jamming has been called "babble," and the term is exceedingly appropriate.

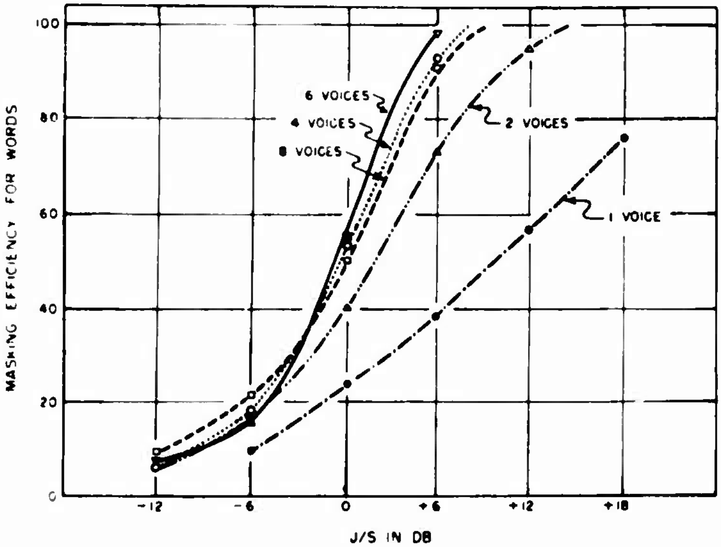

Fig. 41. The relative masking efficiency of various numbers of voices. (From Miller and Mitchell, 1945.)

Altitude

One problem which is becoming more and more important today is that of communication at high altitude. As the altitude gets greater and greater, as you all know, the thickness of the air gets less and less. Air just does not weigh as much, and it becomes much more difficult to create air pressures. This change in air pressure makes it more difficult, for example, to move the diaphragm of a microphone, or of an earphone. This difficulty is in part due to the fact that the voice of the talker is not nearly so strong, but is also due to the fact that microphone and earphone diaphragms do not behave the same at high altitudes as they do at lower altitudes.

Equipment can, however, be designed to operate at high altitudes; and when properly designed will give as efficient operatior

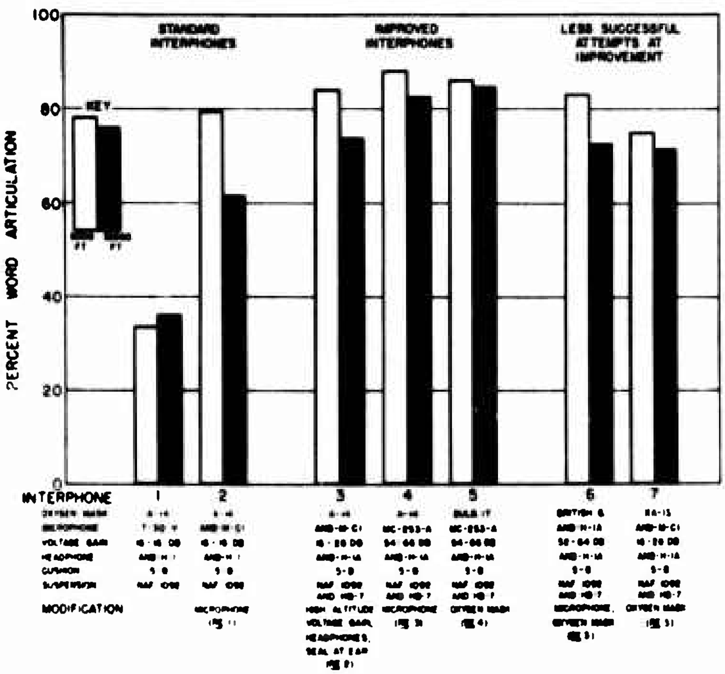

Fig. 42. Percent word articulation for various interphones at low and high altitudes. (From Licklider and Kryter, 1941.)

at high altitudes as other equipment will at low altitudes. Obviously the best equipment is that which will operate well at both low and high altitudes. In Fig. 42 we see some comparisons in terms of percent word articulation between various interphone systems used on standard aircraft. It can be seen that there is considerable variability between the various interphone systems. Furthermore, in every case except one, articulation efficiency is better at the low altitude than it is at the high altitude, although the improved interphones are not quite so disparate as the unimproved interphones. We do not yet possess much general and basic knowledge about communication at high altitudes, and this problem is, to a large extent, still on the very practical and applied level. This is partly due to the fact that most of the problems are purely physical in nature, and have very little to do with the ability of a human to work at those altitudes.

We shall not spend any more time on this particular problem, because it is a fairly specific one -- one which does not have much general application to the problem of speech and communication.

Amplitude Distortion

We have spoken about the effect of overall intensity on speech intelligibility, and also of the problems involved in frequency distortion of speech. We have not mentioned previously the problem of amplitude distortion. That is, however, a very serious problem and one about which we know a great deal. Amplitude distortion occurs whenever there is some non-linear amplification in the system -- when the intensity of what comes out of a system is not linearly related to what went in. The distortion may occur in the amplifiers, it may occur in the earphones or the microphones, or it may occur in the modulation stages of a radio transmitter.

Types of Amplitude Distortion. There are many types of amplitude distortion, and different effects occur with different kinds of distortion. When we speak of non-linear amplification, that non-linearity can occur at any point along the amplification curve. We may, for example, speak of center clipping. By center clipping we mean that the area in the center of the total wave form, that is, the area around the time axis, is rejected from the system. When we speak of peak clipping, we refer to the fact that the top and the bottom of the wave are flattened off and not amplified at all. These are actually two extreme cases of amplitude distortion. We may have all the intermediate cases. For example, simple linear rectification, either half wave or full wave are forms of distortion. Also we may have symmetrical peak clipping or asymmetrical peak clipping, or the clipping may not be sharp. In other words, we may have linear amplification up to a particular point, beyond which the amplification, while still linear, may have a different slope. In Fig. 43 you see two forms of clipping -- two extreme forms. These two forms of amplitude distortion -- we call peak clipping and center clipping.

Differences in Peak and Center Clipping. Peak clipping and center clipping produce different results. The difference between the forms of clipping is due primarily to the nature of speech. All speech, every word, is made up of both consonants and vowels. Vowels usually have considerably more energy than the consonants

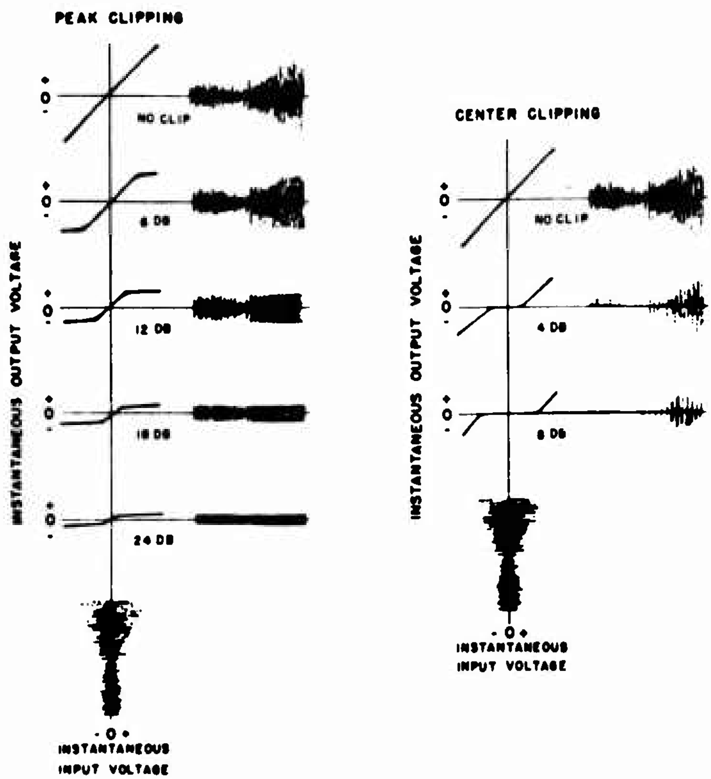

Fig. 43. Oscillograms showing effects of peak clipping and center clipping upon speech waves. Twenty-four db clipping is intelligible. Four db clipping is unrecognizable. (From Licklider, 1944.)

do. Peak energy of vowels may be five and ten times as great as energy involved in the consonants. Thus when we peak clip, we tend to discriminate against the vowels in favor of the consonants. On the other hand, when we center clip, we tend to discriminate against the consonants in favor of the vowels.

Actually, we can get along much better without vowels than we can without consonants. In rapid speech, vowels are pretty much alike. We really do not discriminate between vowels very well. If, however, we are not careful in our consonants, words are very poorly understood. For example, in the following sentence, try pronouncing all the vowels as they should be pronounced, but pronounce all consonants alike. "Iv iv vivvivuvv vo veav vviv vevvevve." As you can see this sentence is hardly intelligible. What you have done is simply to make every consonant sound alike, although you have pronounced all the vowels as they should be pronounced.

Now in contrast let us give you a sentence in which all the vowels are pronounced alike, but in which all the consonants are correctly pronounced. "But thus suntunc luks und sunds sumwhut undurstundubl." This sentence, unlike the previous one, is readily understandable, because all the consonants are correctly pronounced. In the cases of center and peak clipping shown here, peak clipping of 24 decibels is readily understandable, while center clipping of 4 decibels is not comprehensible at all. Center clipping is definitely disadvantageous. Peak clipping, on the other hand, may have certain advantages.

Advantages of Peak Clipping. While it is true that peak clipping makes speech sound unreal -- makes it sound distorted -- still this peak clipping may produce certain advantages in a communications system. This is due to the fact that in any system where one is limited by peak power, one can get more average power relative to the peak power by peak clipping the signal. The most obvious case in which this holds is in modulated carrier systems. In an amplitude modulation system, for example, the limiting factor is the peak amplitude, rather than the average amplitude. Greater average power can be obtained with any given peak power if the speech is squashed down, so to speak, and neatly packaged into a small bundle. We do that when we peak clip.

With ordinary speech transmission, for example, the peak amplitude may be as much as five and ten times as great as the average amplitude. This means that the peak energy in the RF system will also be five to ten times as great as the average energy. When, however, the speech is severely clipped, the peak energy may be no more than 50% greater than the average energy. This is certainly efficient in terms of a power system.

Peak Clipping in Transmission. The question still remains, however, whether this increase in power actually leads to an increase in intelligibility or whether the distortion introduced has made the speech unrecognizable to the extent that it is actually less efficient. We have plenty of information on that matter. Fig. 44 shows us the relative intelligibility of undistorted and peak clipped speech, when the speech is equated in terms of peak instantaneous power. In other words, in a radio transmission system, the carrier power would be the same, and the percent modulation would be the

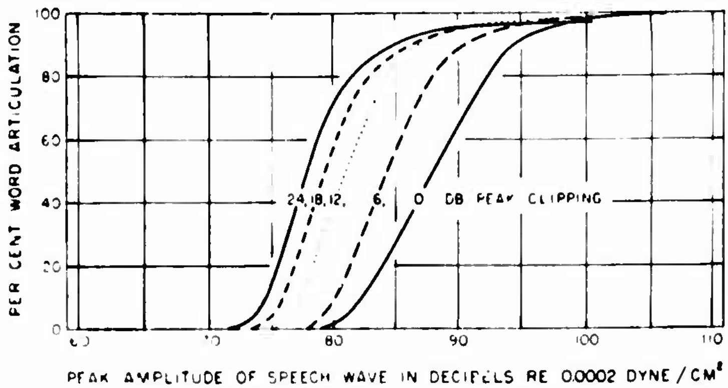

Fig. 44. The effect of peak clipping in a transmitter on percent word articulation when the waves are equated in terms of peak instantaneous amplitude. (From Licklider, 1946.)

same. In this figure we can readily see that an advantage in per-cent word articulation is obtained even when the clipping is as great as 24 decibels. Twenty-four db clipping means that the speech has been clipped off to 1/16 its former amplitude, and then amplified so that its peak to peak amplitude is the same as it was when it started. This is an amazing amount of distortion, and it is even more amazing when we realize that articulation can actually be improved by introducing such distortion.

We have been talking about peak clipping in terms of clipping a speech wave for use in such circumstances as amplitude modulation of a carrier. You can easily see how clipping can have a good effect in such a circumstance. You have neatly packaged the speech, and you have increased the average power relative to the peak power. This increased power has more than offset the disadvantage of distorting the speech. It is true that distortion in speech ordinarily is not desirable, but as we saw in the case of frequency distortion, distortion can be overcome by means of an increased gain.

Peak Clipping in Receiving. There is another case where peak clipping is advantageous, although for quite different reasons. Instead of clipping before modulation, we can do our clipping in the receiver. In Fig. 45 we see the effect of clipping at the receiving end of the system. The two curves shown are for clipping and no clipping. With the limiter -- the clipper -- in the receiver, it

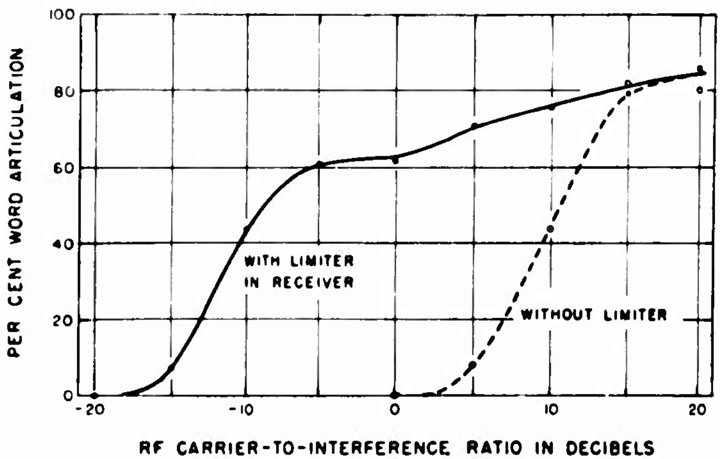

Fig. 45. Effect of peak clipping in the receiver on percent word articulation. The noise-limiter is in the audio section of the receiver. (From Licklider, 1946.)

is very apparent that word articulation is considerably increased. What has actually happened in this case is that the noise, which ordinarily masked the speech, has been discriminated against in the clipping. A good portion of the noise which comes through most radio receivers is of the static type. Static noise is very sharp and spikey in appearance, and its peaks may be considerably greater than the peaks of the speech. By clipping this whole signal, both the speech and the noise, the noise is clipped off more than the speech, so that we realize an advantage in terms of the overall signal-to-noise ratio.

With pre-modulation clipping, clipping is performed before any noise has been introduced into the system. What we do, essentially, by this sort of clipping, is to increase the overall power of the speech with respect to the noise. With receiver clipping, we likewise can increase the speech energy with respect to the noise energy due to the differences in wave form of the two types of energy. We know that we can clip speech a great deal and still have good intelligibility of speech. We also know that if in that clipping process we can get rid of a good bit of the noise we have gained a twofold advantage. Not only have we increased the average power of the speech but we have also increased the power of the speech with respect to the energy in the noise.

In closing, we should like to point out that we have discussed only a few of the many problems related to speech and communication. We have selected particular relations to use as examples in our discussion. We have tried to present the most general type of illustration, the type of illustration which is applicable to the greatest number of cases. As we warned you in the beginning, we did not mention much in the way of specific equipment or specific situations. We know far too much about the general problem of speech to have to talk about specific situations. It should be clear to you, however, that these generalized relations are useful only when they are applied to specific situations. Such applications can be made, and have been made. We hope these applications will continue to be made.

And finally, we should like to re-emphasize the point that in communications, as in other fields, we are interested in finding and eliminating errors and sources of errors. None of you will doubt that errors do occur and that the failure to get messages quickly, accurately, from one place to another has had many dire consequences. Each of you will be able to recall, without straining your memory, at least one incident where the fate of a ship or a plane or a mission or a man depended on the speed and accuracy of voice communication. And some of you can recall incidents where the failure of communication decided that fate in a manner not conducive to victory. The aviator is perhaps most dramatically dependent upon communications. He often finds, if he stops to think about his situation, that his success, his safety, his life hangs by one thin thread of voice communication. If that thread breaks, scratch one aviator, one plane, one mission.

We could hardly be accused of weaving a rope entirely of sand if we argued that communication is an important thing to worry about. We can accurately say that research in this field has paid rich dividends. But errors still happen; improvements can still be made. Research in communications can continue to pay off.

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VII: SPECIAL AUDITORY INFORMATIONAL SYSTEMS

In the last lecture, we began our attack on the problem of displays -- on the problem of getting information into the man who operates the machine, or, more realistically, into the man who tells the officer who orders the mate who signals the sailor who turns the crank that aims the gun that shoots a shell that blows up the house that some Jack has built. We examined speech as a means of getting information to and through the man or men who get themselves involved in functioning systems.

Here we will have a second fling at displays. We have seen how the peculiar characteristics of speech and of the systems for its transmission do affect communication and should affect the design of those devices used in getting verbal messages across. Now we want to look at some non-spoken (but still auditory) procedures for keeping men and machines in touch with one another and working on the same side in any given battle.

The specific devices we will consider are (1) sonar, (2) the radio range, and (3) a system recently come to be known as Flybar. In talking about the functioning and design of these systems we will have to think, at a basic level, about the functioning of the human ear and about the ways various sorts of sound interact with these functions.

UNDERWATER SOUND

Let us begin with sonar. As you know, sonar is a sort of ball-point radar -- radar that works under water. During the recent international conflagration, sonar came into wide use and presented a series of auditory problems -- problems somewhat different from those connected with earlier underwater sound devices. As you know, sonar sends out a high frequency pulse, which, if it hits a target, is reflected. Directional microphones and receivers pick up this reflected sound and shoot it to the listener, loaded with useful information. If the sound comes back at all, the listener knows a target is there. If he can judge the time it takes the pulse to get there and back, he knows something about the range of the target. And the directional receivers tell him about the bearing of the target.

Intensity Discrimination. There is considerable information in these returning pulses of sound. The problem is to get it out -- efficiently and accurately. This is not always easy. We talked in the last lecture about the deleterious effect of masking noise when speech is happening. The sonar signal is also subject to masking. The ear of the sonar operator often has to work amid a barrage of masking noise. Much of this noise may be made by his noisy ship and its noisy inhabitants as they carry out a noisy business. Sometimes, however, the worst type of masking noise is comprised of echoes. The pulse is continually reflected from the surface of the water or from small objects in the water -- fish, or a ball-point pen at work. Since these small objects do not shoot back we are interested in them only in a negative way. They clutter up the information about targets that do shoot back. The echo from an enemy ship must be picked out from a confusing sea of echoes. The operator has to tune his ear and his attention to the longer, louder signals. In other words he must make intensity discriminations.

Pitch Discrimination. Then, once the operator has overcome masking noise and has his ear on the important echo, he has to make some pretty delicate pitch discriminations. The returning echo from an approaching target will have a higher frequency than that of the original pulse. And the retreating target will send back an echo of lower frequency. This is the familiar phenomenon known as the Doppler effect. When the returned echoes are heterodyned to audible frequencies and squirted into the listener's ears, it is very helpful if he can make good judgments about the relative pitches of the outgoing and returning pulses. If the discrimination is keen, he can tell something about the speed of the target.

You can see that the ear of the sonar listener is confronted with fairly intricate chores. It must make judgments (1) about the presence or absence of echoes, (2) it must make subtle intensity discriminations, (3) it must make pretty delicate pitch discriminations. Let us look at the behavior of the ear and of the man who owns it, in the presence of these chores.

Duration

Probably more than any other single factor, the duration of the pulse impinging on the ear determines the effectiveness of the sort of discrimination the operator must make. If you change the duration of a pulse you automatically change a lot of other aspects of the perceived tone.

Pitch vs. Click. One of the first things that turns up in this duration business is the fact that very short tones (or pulses) do not sound like tones at all. They sound like clicks. Very short pulses are made up of a wide variety of frequencies and become, in effect, split-second noises rather than tones. If we are to make judgments about the pitch of pulses, therefore, the pulse has to be long enough for the ear to catch its pitch. Fig. 46 shows how long the pulses must last for the ear to recognize pitch-character. We can see from these curves that very low tones must last longer

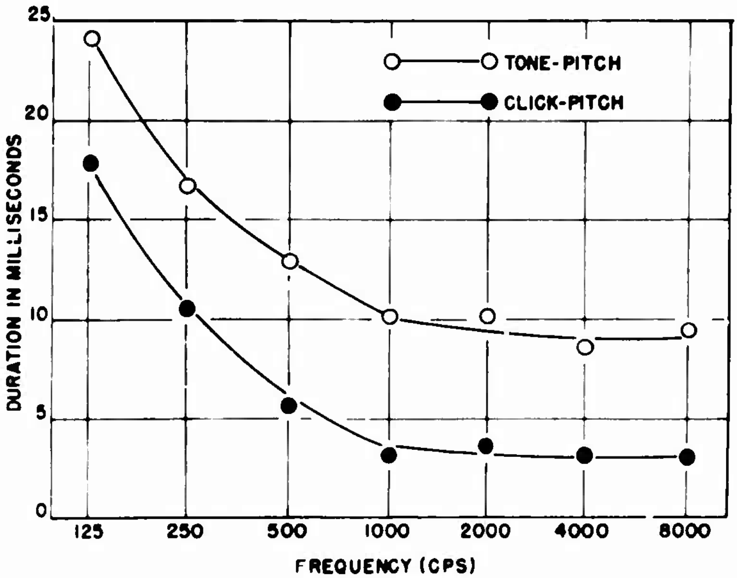

Fig. 46. The durations necessary to hear two kinds of pitch as a function of frequency. (From Doughty and Garner, in press.)

than high tones if the listener is to get the pitch. The two curves are for two different kinds of pitch -- "click pitch" and "tonal pitch." We need not bother here about the differences between them. The important things are that (1) the success of tone-pitch discrimination varies with duration of tone, (2) that the tone can be of shorter duration if its frequency is higher, and (3) if you use a tone of too short a duration, there can be no pitch discrimination. These curves show that a tone must last about 20 milliseconds if it is to have any definite pitch character.

Pitch Changes. The next illustration (Fig. 47) shows another effect of change in the duration of the tone. Here we see again that the tone must have a certain minimal duration to be perceived as a tone. But there is also something else. The apparent pitch of the tone varies as the duration increases -- particularly if we are working with very short durations. For example, if the duration is six milliseconds, the perceived pitch may be three or four per cent off, as compared with slightly longer durations. You can see here that the misperceived pitches are mainly below 25 milliseconds in duration. Above that, pitch changes very little with duration. We have more evidence, then, that a pulse should last at least 20 milliseconds if it is going to be useful in a sonar setup.

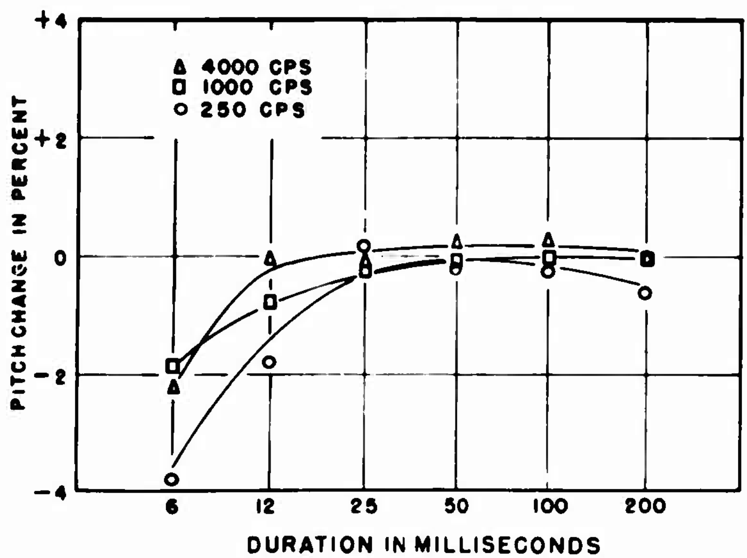

Fig. 47. Percent pitch change as a function of duration for different frequencies. (From Doughty and Garner, in preparation.)

Pitch Discrimination. Fig. 48 brings up another aspect of the pitch-duration problem. You might readily suspect that if you cannot hear pitch in very short pulses, you cannot judge the difference between the pitches of two very short pulses. This illustration confirms that suspicion. The ordinate scale here is a relative difference scale. That is, it is the difference limen plotted in cycles change as a per cent of the number of cycles in the center frequency.

The curve shows, to get back to English, that you cannot tell the difference between the pitch of tones when those tones are very short. Pitch discrimination is poor if the duration is less than 100 milliseconds. It is very poor by the time we get the duration down to 20 milliseconds. This means that if we want very accurate discrimination of pitches -- as in the case of an opening or closing sonar target -- the tones should be longer than the 20 millisecond limit we mentioned.

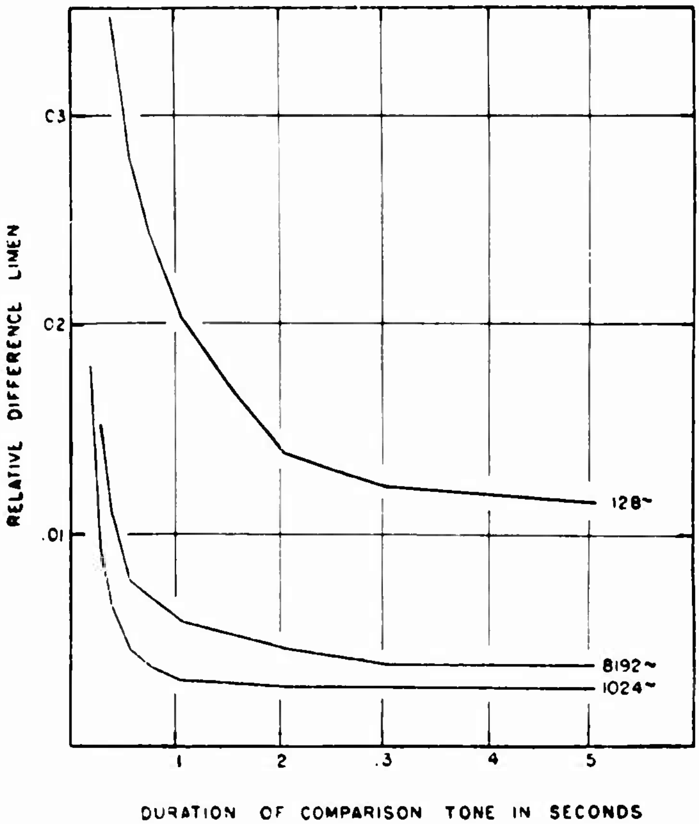

Fig. 48. The relative difference limen for frequency as a function of duration for different frequencies. (From Turnbull, 1944.)

Range. But there is a limit on the duration that can be used. If the tone is made long, pitch discriminations will be good. But if it is too long we cannot use it to get estimates of range. The longer the pulse lasts, the harder it will be to judge precisely the time of its echoed return So in this, as in other situations, problems of design must be solved on the basis of compromise -- a compromise that avoids both undesirable extremes. We have seen that these and similar basic curves guide the making of adaptive compromises.

Detection. There are other collections of precise data bearing on the relation between the duration of the tone and the man's ability to make judgments about it. But perhaps we had better simply indicate the nature of the functions and pass on. There are detailed curves showing how the detectability of a tone varies with its duration. Roughly speaking, the longer the duration of a tone, the easier it is to detect in a life-like situation. There are similar data on the duration of tone needed to get optimal intensity discrimination. If you want to stay after school we can refer you the curves for these functions. Each of these curves can give us information to use in the design of sonar equipment.

Frequency of Sonar Pulses. The duration of the sonar pulse has a great deal to do with the effectiveness of sound detection. But there are other aspects of the sonar business. One of these is the frequency of the tone. If you hold duration constant and vary the frequency, you discover a couple of functions that come with built-in practical significance.

Frequency Discrimination. The next illustration (Fig. 49) shows the relation between the frequency of the heterodyned signal and the observer's ability to discriminate between various frequencies. This means that if you want your sonar man to be able to judge which of two very similar tones is higher in pitch, as in the Doppler situation we have talked about, you do well to choose carefully what frequency you pitch at him.

The solid line in this illustration is a theoretical curve and we will not insist that you worry about it. The open circles show actual measurements. You will notice here that the frequency discrimination is plotted in terms of actual frequencies discriminated -- not in terms of per cent discrimination. The curve is done this way for a purpose. If a Doppler effect is happening in an actual sonar situation, the effect, in physical terms, is the same whatever the frequency of the pulse you are using. If the echo comes back two cycles above a tone of 100 cps it will also come back two cycles above a tone of 1000 cps. The two cycle change is the Doppler and our problem is to get at the psychological curve -- or a psychophysical curve. It says, in brief, that if you want your sonar man to do something smart about a Doppler effect of two cycles, you will heterodyne his ear with a basic pulse of between 400 and 800 cycles per second.

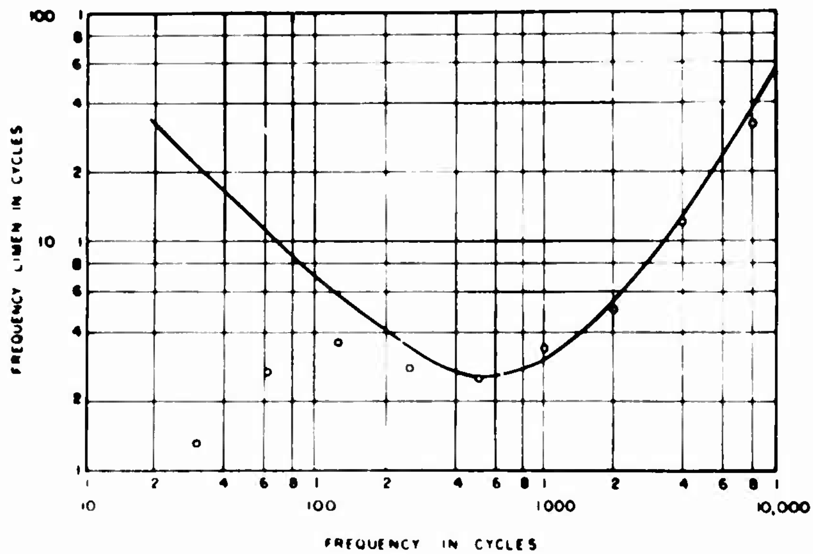

Fig. 49. Frequency limen for different frequencies at a sensation level of 40 db. (From Spector, in press.)

Detectability and Frequency. We also have pretty complete data on the relation between detectability of a signal-in-noise and the frequency of that signal. We will buy you a drink sometime if you will agree to let us tell you about that. At the moment, so much for frequency. There is a matter of intensity now to consider.

Intensity of Sonar Pulses

Signal-in-Noise Ratio. We made the point in the last lecture that intensity has a good deal to do with the intelligibility of speech. But we said that absolute intensity does not matter. It is the ratio between what you want to hear and what you do not. If you are talking in a boiler factory, the intensity you generate does not amount to a thing unless you can generate significantly more than the boiler factory can. The same relation holds for non-vocal signals. The signal-in-noise ratio again enters. The sonar signal must be more intense than either the surrounding noise or those background noises the sonar itself shoots into the listener's ears. In the latter case the operator must make an intensity discrimination between the significant sound and the insignificant sounds it comes wrapped in.

Intensity Discrimination. The next illustration (Fig. 50) shows how this sort of intensity discrimination is dependent on frequency. It also shows how intensity discrimination is dependent on intensity. The upper curves here are for very weak tones. The lower curves are for very loud tones. You can see that the stronger the tone, the easier it is to discriminate between intensities of tones.

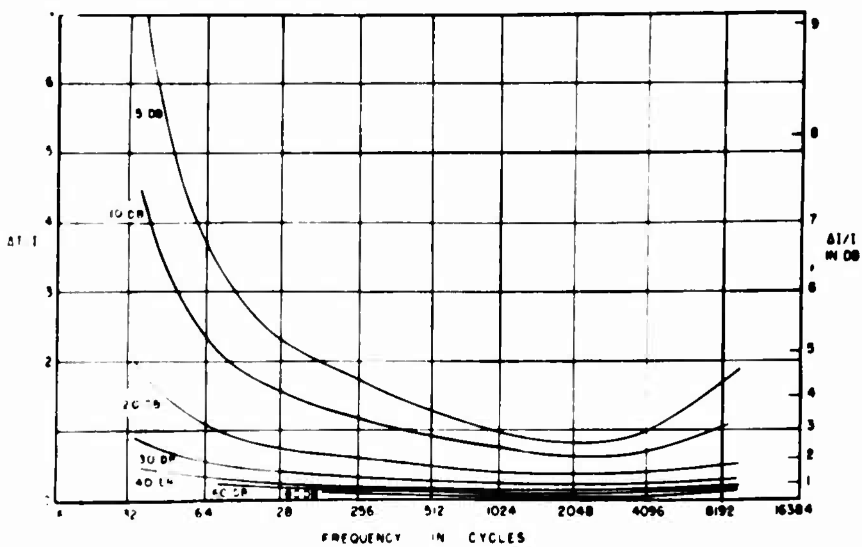

Fig. 50. Relative intensity limen at different frequencies and sensation levels. (From Spector, in press.)

Frequency Discrimination. Frequency discrimination is best in the middle range of frequencies, particularly when the tone is weak. For weak tones, you can do the best frequency judgments at around 2000 cycles. For more intense tones, however, one frequency seems to work about as well as another. At least there are no clear-cut optima. So in choosing the frequency for our signal, we are free to choose on the basis of the curve we saw a moment ago -- the one which says a Doppler effect will get itself registered best at frequencies between 400 and 800 cps.

Frequency Response Characteristics of Sonar Systems

A final problem concerning underwater sound devices is the frequency-response characteristic of the system involved. We saw in the last lecture how speech intelligibility is affected by various sorts of distortion. Sometimes the effect is positive, sometimes negative. This distortion question is with us also when we deal with sonar. Is distortion universally bad when we are transmitting tones? Or, as in the case of speech transmission, can we turn distortion to a useful end?

Band-pass Filters. Since we are interested in hearing a tone and in not hearing noise, you might well expect that we could do ourselves a lot of auditory good by picking a filter that would pass the tonal frequency and exclude all of those random frequencies that make up noise.

You will remember, however, that very short pulses of tone are far from being made of pure frequencies. There is an oscillation-frequency there, but in the sudden turning on and off of a very brief oscillation, much gets in beside the oscillation frequency. Thus the short tone is actually a whole band of frequencies -- much like the noise we would like to filter out.

Well, let us see what happens when we use band-pass filters in a sonar-like situation. Fig. 51 has the answers. We see here, at the top, that a filter passing a very narrow band helps when the tone lasts a reasonable time. For relatively long pulses, a filter passing a band only 1-2/3 cycles wide is better than no filter at all.

Figures at the top right show what actually happens to a pulse when it is put through a very narrow band-pass filter. The narrower the filter, the more gradually the pulse rises and falls. For wide filters, the pulse rises and falls almost instantaneously. We can see why, for longer pulses, the use of a narrow filter is helpful.

Duration and Band-pass. When we reduce the duration of the pulse, however, the optimal width of the passed band becomes greater. At .2 seconds the optimum filter is 15 cycles wide. A five-cycle band-pass does not help at all. The short pulse involves a lot of frequencies. We need them all to hear the tone. If we discriminate against unwanted noise we discriminate also against the wanted tone. The filter cuts out the wash but a big chunk of baby goes out with it. This gets us nowhere. It is possible, of course, to pick a filter that will pass just what we need in order to do the

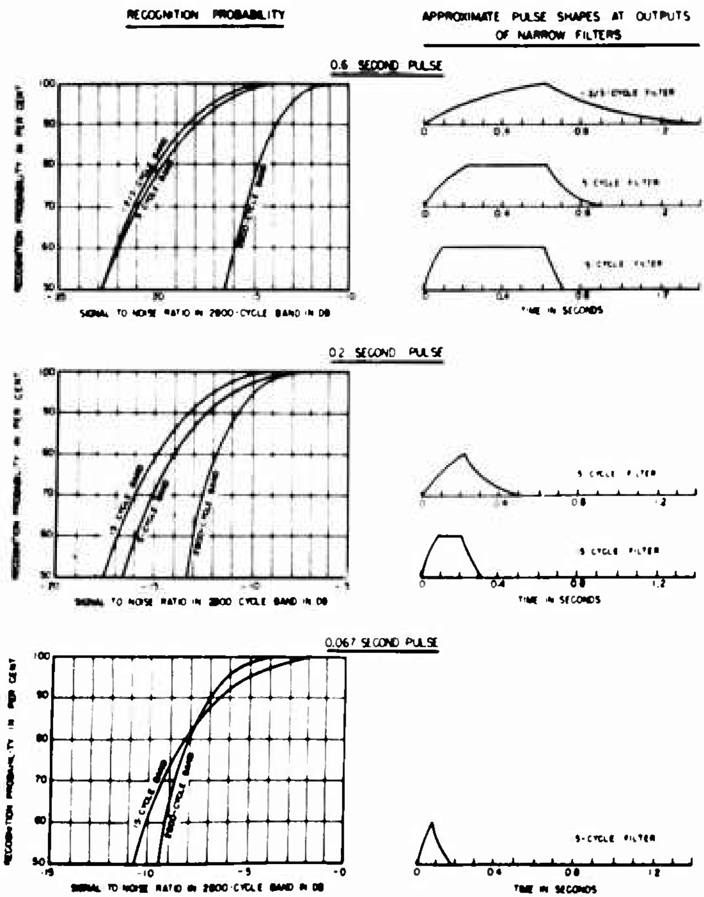

Fig. 51. Effects of pulse length and bandwidth on the detectability of pulses masked by noise. (From Spector, in press.)

best job of hearing. You can see at the bottom of the figure, for example, that for a pulse lasting around 67 milliseconds a fifteen-cycle band filter gives an advantage for relatively weak signals. But as the signal becomes stronger, a wider band is better.

Summary. Now let us pause a moment and summarize. Sonar has a lot of auditory angles. Its efficiency depends upon (1) the duration of the tone, (2) the heterodyned frequency of the tone, (3) the intensity relations of the tone, and (4) the frequency relations of the tone. The ultimate sonar systems must be designed around these factors. We already possess good basic knowledge immediately applicable to design. The data we have seen here demonstrate clearly that the proper control of, allowance for, and capitalization upon the four basic psychophysical factors can not only pave the way to really good sonar design but can bring about impressive improvement in sonar systems now in use.

RADIO RANGE SIGNALS

Now let us consider for awhile another type of auditory signal -- the radio range. For eighteen or more years the low frequency radio range has been the most important single factor in making possible the navigation of aircraft under instrument flight conditions. Even today, in spite of our talk about ground controlled approaches and other elaborate systems for handling air traffic, this relatively simple system plays a very important role on our airways.

Radio range signals are commonly produced by using two directional radio beams with their axes crossed. The indicated range is the line along which the field strength of the two beams is equal. The pilot flying along the range must have some means of determining the relative strength of the two beams in order that he may know his position. The necessary indication has usually been auditory. That is where we come in.

The Auditory Discrimination. The pilot's ability to fly along a radio range will be determined by a human factor, namely, the ability of the ear to discriminate between the commonly used A and N signals. These interlocking signals when they are exactly equal in intensity will produce a continuous tone. When the two signals are of unequal intensity, the pilot will hear either an A or an N standing out against the background of the rather continuous tone. The pilot's chief task in range flying is that of making an intensity discrimination of two tones. Thus he must be able to detect when the A is louder than the N, or when the N is louder than the A. What this amounts to is that the area between his ability to detect the A and his ability to detect the N determines the area in which he will fly. The more accurate he can make his discriminations the more accurately he will be able to fly in a straight line along a prescribed course. As the conditions become such that his discrimination is less accurate, however, he will tend to deviate from the indicated course.

We have already discussed some of the problems involved in intensity discriminations of tones in sonar operation. Many of the relations which we saw there apply equally to problems of the radio range. But there are new problems too. Let us have a systematic look.

The Factor of Intensity

Once again the most obvious thing which is going to affect the ability of the operator to use the radio range system is the intensity of the signal. We are not now talking primarily about the absolute intensity of the signal. We must deal with an intensity ratio -- the signal-in-noise ratio.

Signal-in-Noise Ratio. The next illustration (Fig. 52) shows us how intensity discrimination depends both on the signal-in-noise ratio and the overall intensity of the signal. Once again, we find that for every signal-in-noise ratio there is an optimal intensity -- indicated by the dashed line in this figure. For very strong signal-in-noise ratios, such as those shown at the bottom of the figure, the optimum is not very pronounced. But for very weak, or unfavorable, signal-in-noise ratios -- such as that shown at the top -- the optimum is more pronounced. It is easy to see here that the signal-in-noise ratio itself has a great deal to do with how accurately the operator can discriminate between the A and the N signals. Thus we find that when the signal-in-noise ratio is unfavorable (-10 db) the operator may need as much as a 2-1/2 decibel difference between the A and the N signals in order to hear them as being different. If the signal-in-noise ratio is very favorable, the operator may need less than 1/2 decibel difference between the A and the N signals in order to hear them.

Overall Intensity. We probably should point out here once again the meaning of these relations between overall intensity and signal-in-noise ratio. You will recall that in the question of speech,

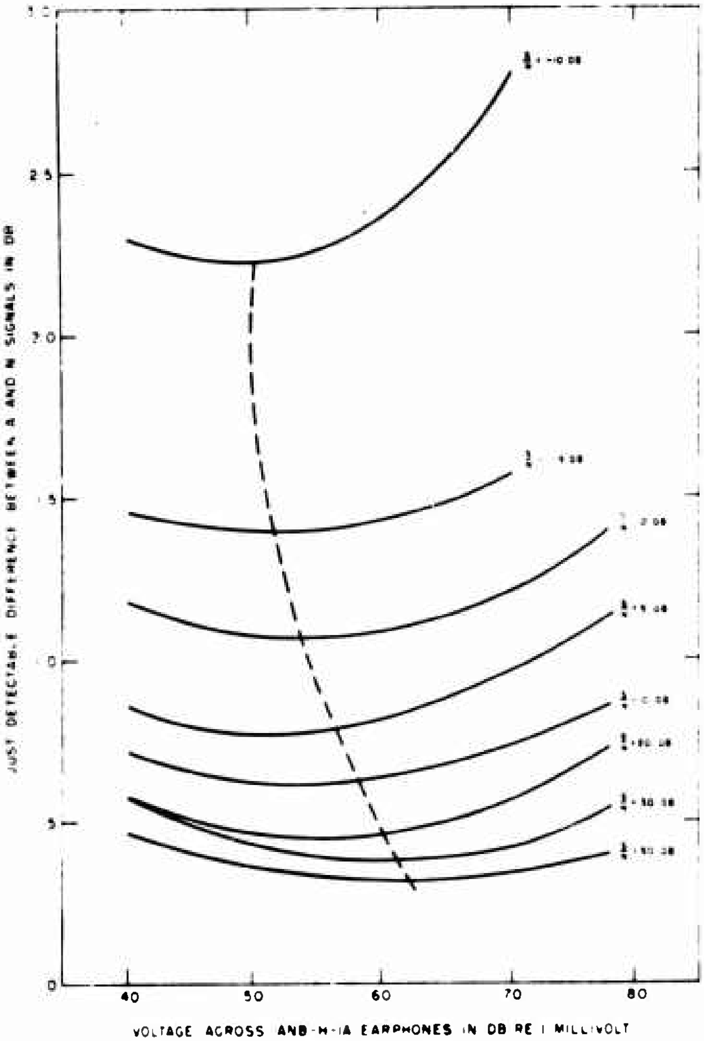

Fig. 52. The mean decibel difference necessary to detect the A above the apparently continuous tone as a function of intensity. (From Flynn et al., 1945.)

the best way to operate a receiver depended to a great extent on where the noise comes from. If the noise that is masking the tone (and producing the N of the S/N ratio) is in the radio receiver, then by changing the gain of that receiver, we change both the signal and the noise but leave the signal-in-noise ratio constant. We can do nothing about the signal-in-noise ratio -- we can only change the overall level. But we can change that to get it optimally set.

Receiver Gain. When, however, most of the noise masking the tone is occurring outside of the radio receiver and in the environment of the operator -- such as engine noise -- then we would want to turn the gain of the receiver to maximum in order to get favorable signal-in-noise ratio. We cannot affect the intensity of the surrounding noise, but we can affect the intensity of the signal so that we can change the signal-in-noise ratio to give us a favorable ratio.

And once again, when we have obtained a most favorable signal-in-noise ratio by increasing the gain of the receiver, we can obtain a more favorable overall intensity by the use of such a device as an earplug or wad of cotton.

Frequency Characteristics of the System

The frequency characteristic of a range system also, as in the case of a speech system, has a lot to do with the use and usefulness of the system. Would it be desirable in a case like this to reject certain noise frequencies while at the same time not rejecting the tone frequencies? Would it actually increase the ability to detect differences in the tone? You must recognize that this is a slightly different problem from that shown previously in the case of sonar. There we were concerned with the ability of the operator to hear the tone against the background of noise. Here we are concerned with the ability of the operator to discriminate between tones, both of which are against a background of noise.

Band-pass Filters. Experiments have shown us that the intensity discrimination can be improved by the use of narrow band-pass filters in the system. The frequency usually used with radio ranges is approximately 1000 cycles, and in this particular system a band-pass filter was inserted which rejected all frequencies below 900 and above 1100 cycles per second. Fig. 53, as you can see, clearly shows that the use of such a filter did improve intensity discrimination between the A and the N signal. This improvement becomes less with better signal-in-noise ratios, and probably eventually there would be no difference at all between the case with the filter and without the filter. Obviously if the overall signal level is so large with respect to noise that the noise is having no effect at all, then we should not be able to get any improvement in intensity discrimination by the use of a band-pass filter.

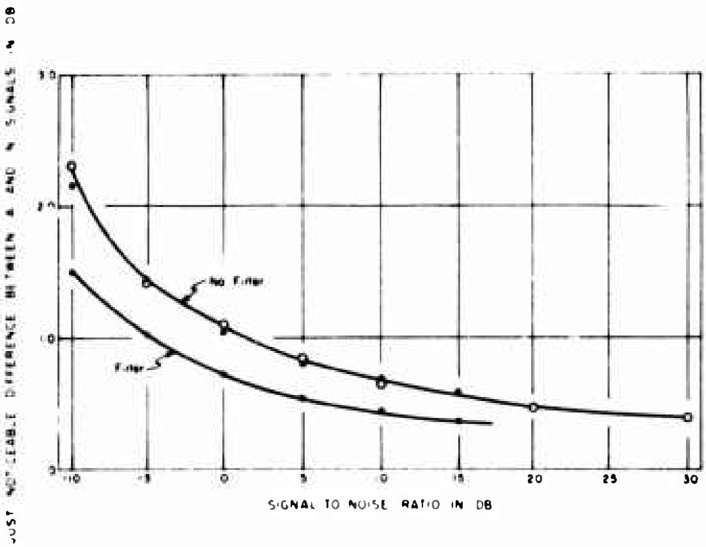

Fig. 53. The effect of a narrow band-pass filter on the detectability of the A and N signals. (From Flynn et al., 1945.)

Design of Earphones. So now we see that the use of a narrow band-pass filter does improve intensity discrimination in the radio range system. Here we have an excellent case whereby we can predict something about the design of specific equipment. Knowing that filtering does improve intensity discrimination we would predict that the use of resonant earphones would improve intensity discrimination also. We can choose phones which are highly resonant, or we can use phones which are very flat in their frequency response. With the highly resonant phones, we usually gain in intensity at the resonant frequency. The results which we have just discussed would indicate that the resonant phones, if the resonance is at the proper frequency, would be better than flat phones for this particular task.

Actually two different types of earphones have been compared in terms of their efficiency in receiving radio range signals. Fig. 54 shows a comparison of those two different earphones. The ANB-H-1A phones are relatively flat phones. The TH-37 phones, on the other hand, are very highly peaked at about 1000 cycles. We see from these curves that intensity discrimination is better with the peaked phones than with the relatively flat phones. This is exactly what we would have predicted, and this is exactly what has happened.

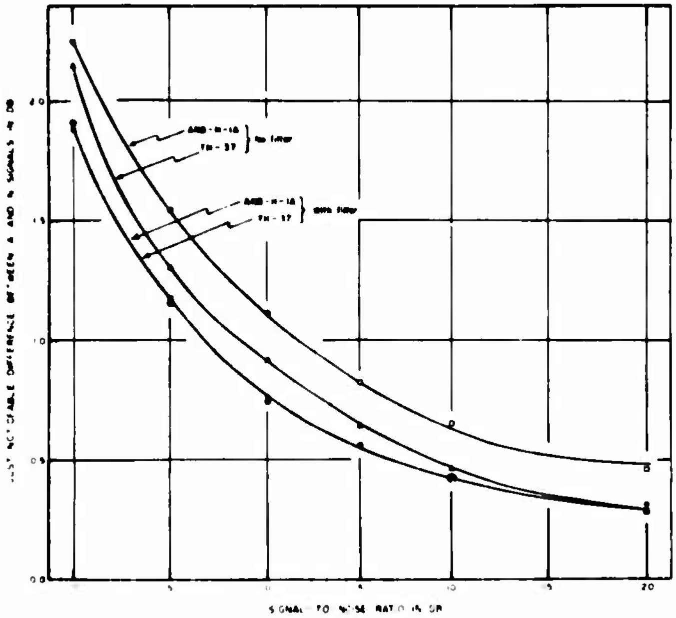

Fig. 54. A comparison of earphones and narrow band-pass filter for detectability of the A and N signals. (From Flynn et al., 1945.)

The curves at the bottom, however, show that if the filter is inserted in the system with the phones, then there is no difference between the phones. The filter is a little better than the phones in discriminating against noise in favor of signal. For this particular job, then, resonant earphones are better than flat earphones. A narrow band-pass filter, however, is better than either of them.

Expanders and Limiters

There are a couple of special things which can be done to the radio range signal to make it an even better signal than it is. One of these things is to use an expander -- a device which amplifies large signals more than it does small signals. The general effect of this device is to make differences more different. This is, actually, a form of non-linear amplification, and in any system where it is not desirable, it would be called distortion. The question quite naturally arose as to whether the use of an expander would appreciably improve the ability of an operator to distinguish between A and N signals. Fig. 55 shows that it very definitely does. We see here that the ability to distinguish between the A and N signals is considerably improved when an expander is used in the system.

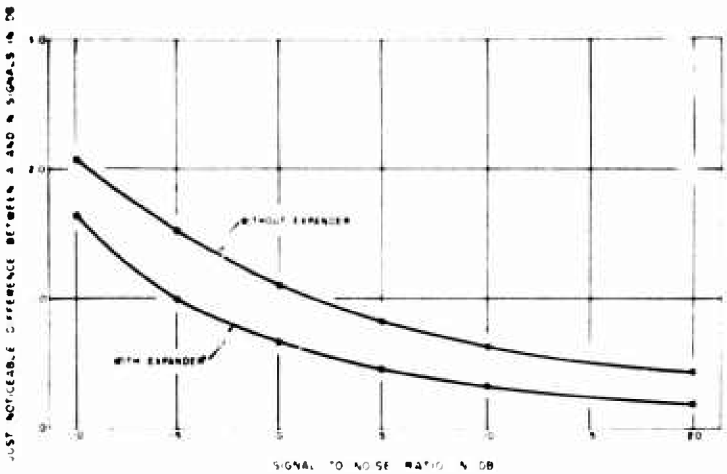

Fig. 55. The effect of a signal expander on the detectability of the A and N signals. (From Flynn et al., 1945.)

The use of the expander, particularly with the more intense signals, has reduced the difference threshold to less than one-half its former value. The width of the area in which the plane will fly is cut approximately to one-third of its former value -- assuming the pilot can fly where his ears tell him to.

Pitch Modulators

It is also possible to help ourselves out in some situations by using a gadget called a pitch modulator. This device translates the difference in energy between the A and N signals into a difference in pitch. This sort of trick can help in some situations, but we will not go into intimate details now.

Now, in brief summary, the efficiency of a radio range system is dependent upon the signal-in-noise ratio of the system, it is dependent upon whether filtering is used in the system, or whether peaked or resonant earphones are used in the system. Efficiency can also be improved by using such special devices as signal expanders, or pitch-modulated units. And that constitutes a once-over-lightly for radio range problems.

SPECIAL AUDITORY SIGNALS (FLYBAR)

We should like next to discuss a third and special type of auditory signal, one which has been developed during the late war. This special type of signal is what we have called "Flybar," and it consists of the combination of auditory signals which a pilot may use in aiding him to fly his aircraft. The signals may combine different sorts of indication, and may combine anywhere up to three indications. But more of that in a moment.

Uses of Auditory Signals

You all know that "blind flying," so called, is presumably very hard on the eyes. Many a pilot who could fly contact all day and still have energy for vigorous social pursuits at night finds that blind flying for a few hours is tiring enough to give him a strong interest in lying down.

Indications in Blind Flying. A pilot with instrument training soon comes to react almost automatically to three fundamental blind flying instruments which keep the plane level, right side up, and on a straight course. But even with just these three instruments the physical task of keeping visually posted all the time is hard on the constitution. It would, therefore, be of rather obvious advantage if we could construct some type of auditory signal which the pilot could use instead of, or along with, these various visual indications. It would take a great load off his eyes, to say the least. And it might make him better company when the day's flying is over.

Other Uses of Auditory Signals. While we are going to talk specifically about this problem of Flybar, this is not the only circumstance in which special types of signals can be used. There is in progress now, at our laboratory, a series of experiments designed to give us a little more understanding of the interrelations between various types of signals. We would like to know a little more of the fundamental nature of these signals, so that we can predict what types of signals would be useful in various circumstances. One other rather obvious circumstance in which auditory signals could be used, is that for target indication to fire control radar. The present procedure usually requires the use of transmitted speech to indicate in what direction the fire control radar should point. We may be able to get those signals there considerably faster, and even with more accuracy, by the use of some special sort of signalling system.

Flybar. But getting back to Flybar, let us tell you a little of the story of its development during the war. In the first place, we should point out that the word Flybar is the combination of the words "flying by auditory reference." In tackling this problem during the war, we decided to limit ourselves to the three basic indications needed to keep a plane straight, right side up, and at the right altitude. The three indications we chose were bank indication, turn and either air speed or altitude indication. We set our tests up in such a manner that we could test one of these signals at a time or, if we chose, two or three of them being used simultaneously. The purpose of these experiments was to determine how many of these indications could be used, and also whether all three indications could be presented by ear at the same time.

Indications. We should also point out that in a signalling system of this sort there are essentially two problems. In the first place, we have to present a signal that will let the pilot know if and when he is controlling his plane correctly. It is sometimes quite handy for him to know whether or not he is right side up and whether he is flying in a straight line. In the second place, it is handy if he knows how right side up, how straight, how level he is flying. He is much happier and much more likely to get where he wants to go if he knows the directions and amounts of his incorrectnesses.

There are good reasons for having something more than the crude either-or, correct-or-incorrect type of information coming from our indicators. You can imagine how a pilot would perform and feel in instrument weather if his only turn indication, for example, was a bright red light that flashed in his eye or a gong that sounded in his ear every time he departed a degree or two from true north. In instrument flight, the pilot has to make continual corrections for the sometimes inherent waywardness of his plane and for the vagaries of the elements. He cannot make these corrections with any efficiency at all unless he has good information about how much correction is needed and in what direction. And he could not make a desired instrument turn unless his instruments tell him how much he has turned and how much he is turning at any given time. We see, then, that the pilot needs to know (1) when he is performing correctly, (2) the direction of any incorrectness and (3) the amount of incorrectness. We want to get these three sorts of information from our auditory instruments.

Development of Experimental Flybar

Auditory 'Realism.' In the preliminary experiments in the Flybar problem the first thing that became obvious to us was that the auditory signal ought to sound as much as possible like what the plane is actually doing. If the plane is turning, the auditory signal ought to sound as though the plane is turning. Likewise, if the plane is going too fast, the auditory signal ought to sound like the plane is going too fast. This, strange as it seems, makes the task very, very difficult. It is extremely difficult, not only to provide sounds which sound like what the plane is doing, but also to provide sounds which can be accurately discriminated one from the other. As soon as the problem of Flybar is mentioned, we think that it is the simplest thing in the world to indicate a change in direction. All you have to do is to give a different intensity in each of the two ears and that will sound as though the plane is going in one direction or the other direction. And we could indicate not only direction but also amount very easily.

Intensity as a Signal. Our first experiments indicated that this was far from being the true state of affairs. We see in Fig. 56 that the difference in intensity between the two ears must be on the order of six or seven decibels for the pilot to know, consistently, that he is not flying straight. This was rather surprising, but nevertheless it was true. Thus we would have to have an area of 12 db -- 6 db for each side of the turn -- to indicate the null point, that is, to indicate the area in which the plane is flying correctly. This obviously was too much, and the use of differences in intensity between the two ears had to be discarded almost immediately. More recently, we have also found out that individuals have big discrepancies between their two ears in terms of relative loudness. This means that some pilots, flying by loudness cues, will fly in nothing but circles when they think they are going straight. Loudness in the two ears has very little to do with physical equality in the two ears. This again is unfortunate, but true.

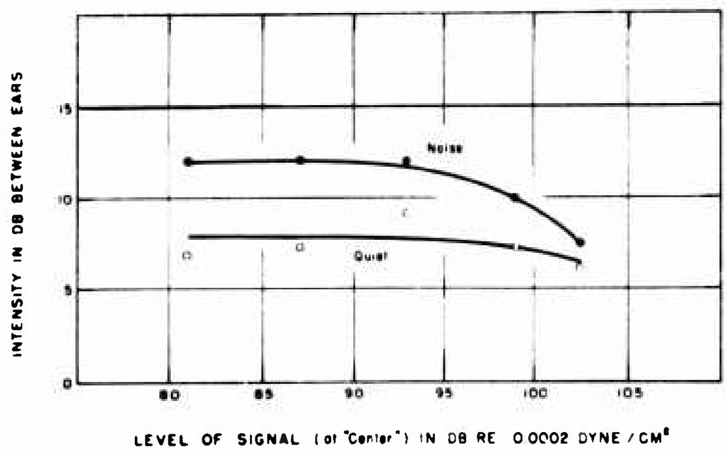

Fig. 56. The interaural intensity difference necessary to detect an apparent signal displacement. (From Forbes et al., 1945.)

Other Types of Signals. We immediately had to discard the notion of using intensity differences. What we did was to try successively several different types of signals, and compare the use of these auditory signals with the use of visual signals. In the case of the visual signal, the operator had to keep a spot on an oscilloscope in the right position both in the horizontal and the vertical dimension. For the third visual indication, we used a simple meter. These spots and the meter were controlled by a rudder and stick such as those used in regular aircraft. An error score electronically produced indicated how successful the man had been in keeping all signals at the null point.

Three-Tone Signals. One of the sets of signals used a three-tone combination. One tone was very low, one was very high, and an intermediate tone varied to indicate air speed. When this tone became high with respect to the other two tones, it indicated that the air speed was too great; and likewise when this intermediate tone became too low, it indicated that air speed was too low. When the middle tone approached either the high or the low tone, beats could be heard -- indicating that the pilot had reached the limits of safety in variation of air speed. This same tone was heard in both ears. When we wanted to indicate turn, we interrupted the tones in either one ear or the other depending on the direction of turn. The rate of interruption indicated the amount of turn. In order to indicate bank, three stepwise low tones were introduced into either one ear or the other, depending on which side was banked low, and the frequency of this tone indicated the amount of the bank. We later found that this signal was not very satisfactory, mostly because the subject tended to listen to either one or the other of the signals when all three were presented simultaneously. When using only one signal at a time, the system worked fairly well.

Two Tones Modulated. Another type of signal consisted of two tones heard in both ears when the plane was on course, but heard in only one ear when the plane was off course. These two tones were frequency modulated by a sawtooth modulation waveform. The rate of this modulation indicated the rate of turn. The direction of the modulation indicated the direction of the bank. Thus if the pitch was going up in one ear and going down in the other ear, it indicated that the wings were tilted in that direction. Air speed was indicated by means of a separate put-put which sounded very much like the motor of the airplane. The rate of this put indicated high or low air speed as compared to a standard rate.

Sweeping-Tone Signal. A third type of signal which turned out to be fairly satisfactory consisted of a sweeping tone from one ear to the other. The tone changed in intensity becoming louder in one ear as it became weaker in the other ear, giving an illusion of movement of the tone. The direction of this illusory movement indicated the direction of turn, and the rate of this illusory movement indicated the rate of turn. At the same time that this tone was being changed in intensity from one ear to the other, it was also being changed in frequency. Thus if a tone started with a high frequency in one ear ending up in the other ear with a low frequency, that indicated that the side of the first ear was high in bank and the other side was low. The tone sounded as though it were sweeping across the horizon, starting high and ending low. That tone sounded exactly like what would be happening to the plane if it were turning in one direction with wings banked. If it were turning in the wrong direction with respect to the bank, then the frequency and intensity would be reversed. Air speed was still indicated by the use of a put-put, with the exception that we now introduced an alternating rate of put-put which always provided a constant standard for the operators. This provided a more accurate estimation of the plane's rate.

Evaluation of Flybar

Fig. 57 shows the comparison between the visual indications and the auditory indications when one, two and three controls are used simultaneously. There is very little advantage in the visual signal over the auditory signal when only one control is being used.

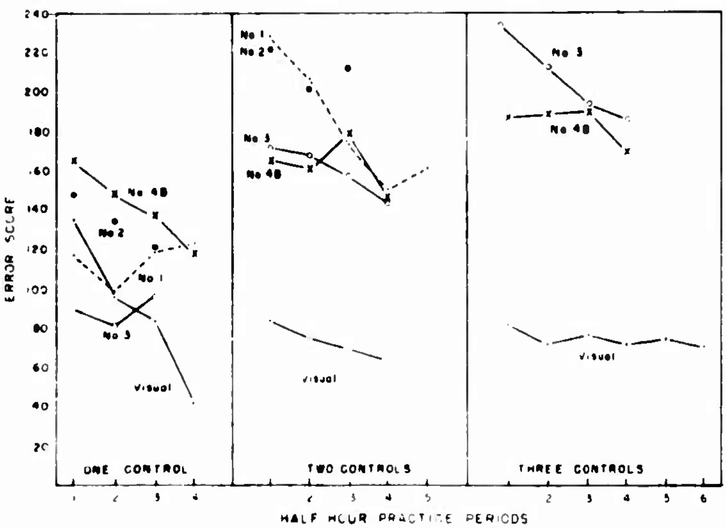

Fig. 57. Comparison of Flybar and visual signals on the airplane pursuitmeter. (From Forbes et al., 1945.)

The advantage of visual over the auditory becomes greater, however, when two or three controls are used. Actually, this advantage consists in the auditory signals becoming somewhat worse, while the visual signals stay about the same. These tests did show us, however, that there is a possibility of using auditory signals. There is a very good possibility of using at least one signal, and at least some possibility of using two or more signals. The task imposed on these operators was very rigid, probably more rigid than that imposed on pilots flying actual aircraft. Therefore, we took this best combination -- the one entitled 4B here -- and installed it on a link trainer.

Link-Trainer Tests. We found that in using the link trainer, pilots were able to fly the link almost as well with auditory signals as with visual signals. In most of the cases, pilots were just as efficient with the auditory signals as with the visual signals. That is to say, they were just as efficient in maintaining a straight course. We did not require the pilots to make good turns, or good banks. They simply had to fly a straight course.

We had some men who were just learning to fly blind, and we were able to compare the rate of learning with auditory signals and with visual signals. Once again, we found that pilots were able to learn just as rapidly with the auditory signals as they were with the visual signals -- even when they were using all three signals simultaneously. Table V shows a sample of some of the results we obtained. We see here the variations in altitude and in air speed when the pilots were using visual indications and when they were using auditory indications. The auditory indications are just as good in enabling the pilot to keep a constant air speed or a constant altitude as the visual indication. This was indeed very heartening, and these results are in essence no different from results obtained with the other indications. These results are a sample of the sort of data we obtain. It should be emphasized that these data were obtained with trained pilots -- not scientists who were very familiar with the auditory signals, but who could not fly. These were men who were more used to flying with visual instruments than they were with auditory instruments, and we found that they could fly just as well with the auditory instruments as they could with the visual instruments.

Flying Tests. We even went so far as to install some of these signals on an actual dive bomber. This dive bomber was tested -- this time obviously with trained pilots -- and once again we found that the pilots could use these signals. They had turned out to be satisfactory.

Future Research. The answer now is that auditory signals can be used to provide indications as a substitute for visual indications. These experiments, however, were done during the war and with the usual rush produced by that war. We still need to have more precise information about how well a man can estimate extent or direction by the use of various types of auditory signals. How precisely can he estimate changes in air speed with different types of signals being used to indicate air speed? Likewise, how precisely can he estimate a bank when a moving signal is being used for a bank? We need to know such questions as how much frequency change we need to indicate bank, and how much difference in frequency change is needed to indicate twice as much bank or only half as much bank. These are essentially problems of scaling or of establishing metric values for tonal signals. That is the problem with auditory signals which we do not have with visual signals.

Table V

Summary of Airspeed Variations
During the Learning Series on the Link Trainer
(From Forbes et al., 1945)

Trial	Range of Altitude in Feet	Number of Airspeed Observations: At or Below 120 MPH	Below 150 MPH	Above 170 MPH	Range of Airspeed in MPH
1	200	2	7	1	80
2	400	1	3	2	100
3	500	0	2	6	40
4	1000	0	0	3	25
5	800	0	4	7	30
6	250	0	1	0	25
7	300	0	7	5	45
Performance of Pilot B -- Using Auditory Indication 4B					
1	300	0	4	1	55
2	600	0	2	7	40
3	350	0	6	5	45
4	600	0	10	2	45
5	300	1	12	0	70
6	100	0	17	1	45

With visual signals we can mark scales right on the meters. It says 1, 2, 3, 4, or 5. With Auditory signals, however, we can not say 1, 2, 3, 4, or 5 unless we do actually *say* them. If a change in frequency, or a change in intensities is to indicate a precise amount, we must determine exactly how much seems to be twice as much, or half as much. These are problems in what we call the development of psychological scales, or psychological quantity.

Fortunately, these are not unanswerable problems. A considerable amount of work has been done on these problems, and a fairly heavy program is now in progress to determine various limits of error and various indications of amount and direction which may be used. We need to determine such things as the interaction between the repetition rate and the apparent pitch of the tone. We need to find out such things as how rapidly can one use the sweeping tone such as that used here before one can no longer distinguish direction of sweep. After awhile, if the sweep rate becomes too high, the tone will simply seem to alternate from one ear to the other. We must determine what those limits are if we are to use such a signal successfully.

And that takes us through much of the area of auditory displays, spoken and non-spoken. In the next lecture we will turn to the subject, "How we see."

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VIII: HOW WE SEE

The last couple of lectures in this series developed the theses (1) that the ear is a fairly important sort of appendage to have around, and (2) that a knowledge of its working has an intimate bearing on the design and operation of psychophysical systems. Now, the eye is important. This lecture and the next will attempt to document that importance and will be concerned with some of the basic facets of visual functioning.

The Eyes are Important. No one will object if you believe in the importance of the ear. But it is probable that the eye is more important -- in life and in psychophysical systems. That complicated mechanism which is a man ubiquitously needs and uses his eyes as his major source of contact with his environment. The eye furnishes him with his primary means of knowing things, of finding his way about in life. And if the human organism gets himself involved as a functioning part of a psychophysical system, his effectiveness is very often determined entirely by the acuity and efficiency with which he can use his eyes. We can document that point very easily.

Take radar for example. We are told that radar is the eyes of the fleet. But radar never sees. It's a man who sees. And if his eyes -- either because they are inherently poor or are placed at an undue disadvantage by poorly designed equipment -- if his eyes fail at a critical time, then radar fails, the ship fails, the mission fails. And again, think of the demands imposed on the eyes of the pilot who is "flying blind." This job is primarily a visual job.

Problems in Vision. You can see without our belaboring the point further that visual problems are numerous and crucial in psychophysical systems. How large should we make the markings on a dial? How should dials and indicators and scopes be illuminated? How can we handle the eye in order to get the most information from it at night? These are simple-sounding questions but their answers have far-reaching practical implications. To deal adequately with these and a dozen similar questions we will need to take a systematic look at the eye and the way it works. The taking of that look is our job.

VISUAL ACUITY

A good way to start our discussion is to define an important measurement used in investigating visual functions. This is the measurement known as visual acuity. There are two different ways to measure acuity, one commonly used by physicians and one by laboratory scientists. The two measures are obtained in much the same way and one can generally be translated into the other. Your visual acuity is simply a statement about the smallest object you can see in a standard situation.

The Eye Chart. All of you, having suffered through at least a few annual physicals, are familiar with the doctor's eye chart. And you know the corpsman uses it to decide if you are fit for one more year of active duty. Some of you can probably recite the chart from memory. Used properly, which it often is not, this measuring device compares your visual acuity with what is supposed to be that of the average person. If, at 20 feet from the chart, you can see what the average person can see at 20 feet, you have 20/20 vision. If you have to move up to 15 or 10 or 2 feet to see what the average person can see at 20 feet, you have 15/20 or 10/20 or 2/20 vision. That is not so good. If you can see at 60 feet what the average person can see at 20, you get a 60/20 score. That is remarkable. These measurements can be made, of course, by changing the size of the letters rather than by moving you back and forth, but the principle is the same.

Actually, the chart method of measuring acuity has disadvantages. In actual use the illumination is allowed to vary and the dirtiness of the chart is not always constant. These factors can interfere seriously with the accuracy of the measurement. Also this measurement is for distance acuity only. A person may have excellent acuity at 20 feet and very poor acuity at 13 inches. Or vice versa.

Visual Angle. The other type of measure, commonly used in the laboratory for measuring visual acuity, expresses the size of the smallest object which you can see in terms of the visual angle subtended by this object at the eye. This kind of measure has its advantages because it is expressed independently of the distance at which the object was seen or the test was conducted. It gives us a single, simple number to work with. In general, the average person can just barely see an object which subtends one minute of visual angle. This corresponds to 20/20 vision. A person with 10/20 vision can just barely see an object which is two minutes of visual angle in size. Just to give you some realistic notion about how big one minute of visual angle is, we have been told that the stripes on a commander's sleeve subtend just about one minute of visual angle at a distance of 100 feet. Visual acuity is a basic visual measurement that will keep cropping up from time to time in our discussion of the basic laws of vision.

Retinal Angle. We all use our eyes so much that we commonly overlook certain peculiarities about seeing and would never notice them if they were not pointed out to us. Every once in a while, for example, somebody writes a popular article about the eye being just like a camera. In such a discussion the author usually compares the photographic film with the retina, that back part of the eye on which the images of outside objects are formed. If you stop to think about it, however, this analogy is not correct in one very important respect. A photograph is usually sharp and in focus over its entire surface. The edges of the photograph are clear. But that is not the way the eye sees things. If, for example, you stare steadily at one letter on a printed page, it is impossible for you to read letters two inches away; or if you all look directly at the loud speaker above the stage to the right of the speaker, and keep looking steadily at that loud speaker, you cannot tell how many fingers he has raised. So the eye does not see everything as clearly as a photograph all over its visual field.

This variation of visual acuity in different parts of the eye is plotted in Fig. 58. In this illustration, zero degrees represents the straight-ahead direction which strikes the fovea in the eye. You can see that visual acuity drops off very rapidly as we go out toward the corners of the eye. As a matter of fact, when you are looking straight ahead, your visual acuity five degrees to the right or to the left of this central line of sight, is just half as good as it is right smack in the center of your eye. When we go out to the edges of the eye, as far as 40, 45, and 50 degrees from the central line of sight, visual acuity is only about 1/20 of what it is directly straight ahead.

The Blind Spot. Now one thing more before we get off this illustration. You notice that there is a blacked off area in the figure. This is labeled the "blind spot." Even though most people do not realize it, everyone has a blind spot in each of his eyes. It is located about 15 degrees from the central part of the eye, on the side of the eye nearer to the nose, and is about seven degrees wide and about five degrees high. It is the place where the nerves and blood vessels come into the eye.

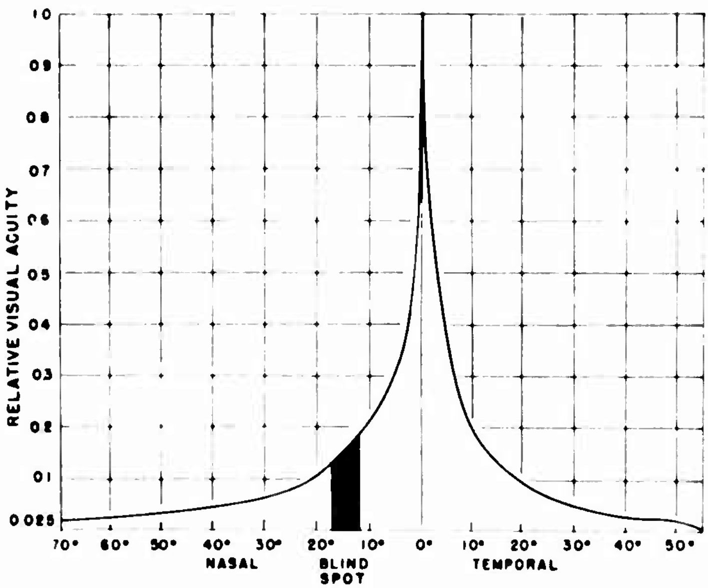

Fig. 58. Daylight visual acuity of various parts of the eye. (From Wertheim, 1894.)

This area of the eye is absolutely blind. You cannot see anything at all in this area, and yet we are sure that as most of you sit there trying to find a hole in your visual field, you do not see any such blind spot. But it would be a very simple matter for us to demonstrate it to you in the laboratory.

There is an interesting story about this blind spot. It was discovered by a man named Mariotte in 1668. When the Royal Society demonstrated this phenomenon to King Charles II, he used it to see how his friends would look with their heads cut off.

Seeing is Deceiving. These two very simple facts, the variation in visual acuity in different parts of the eye, and the presence of the physiological blind spot, may go unnoticed by very careful observers for years and years. Usually when people have these things pointed out to them their natural reaction is "Sure, but how come? How come I never noticed it before this?" Well, there are two answers to this question. The first is that seeing does not simply involve the eye; it involves the eye and the brain, and the brain is a very imaginative thing indeed. It plays all kinds of tricks on us. It tends to fill in the blind spot for us, and tends to give us an idea that what we see is a perfectly clear, sharp field whenever we look at things. There is a very common saying that seeing is believing, but before we get through with this lecture, we hope to show you that in some cases seeing is deceiving. Sometimes our brain makes us see things that are not really there even when the brain is free from the allegedly evil effects of alcohol.

EYE MOVEMENTS

Another reason that we do not notice a lot of very obvious things about our seeing process, is that the eyes are never still. When we photograph somebody's eyes in the laboratory, we find that they are restless. They are always moving and looking from one place to another. This constant restless motion of the eye presents the brain with a whole lot of overlapping pictures which give us the impression of a complete clear visual field.

Eye Movements. Scientists have spent a lot of time studying eye movements and have classified them into certain basic types. It is not necessary for us to go into all the types of movements that the eyes make, but it is important for us to know a little bit about the way the eyes move. The average person has an idea that when he is reading a book or newspaper his eyes make nice, even, smooth movements in following the lines of print. Actually that is not the case at all. If you do not believe it, watch the way your wife's eyes move when she reads the newspaper tomorrow morning. You will find that what actually happens is that her eyes move in a series of jerks. They literally hop over the words in the sentence. From actual measurements in the laboratory, we know now that in reading the eye is moving about 10 per cent of the time; the other 90 per cent of the time it is stationary. We know, too, that the eye does not look at every word, but that it tends to stop at every second, third, or fourth word depending on how difficult the reading material is.

Saccadic Movements. In Fig. 59 are shown three lines of print which were read by a subject in an experimental laboratory. The vertical lines on these three lines of print indicate where his eyes stopped in reading and the numbers above these vertical lines indicate the number of the stop. In the first line, for example, the eyes of this subject stopped first at the second "r" in "arrows." Then his eyes went back to the "e" in "The", then to the "y" in "boy" and so on. These small jerky movements of the eye in reading are called saccadic movements. An important point about these rapid saccadic movements is that when the eyes are in motion they receive only blurs and streaks. The eye actually does not see when it is in motion.

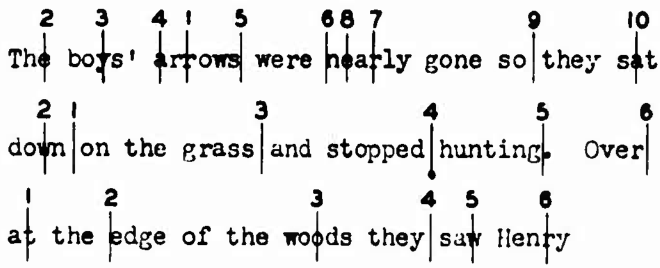

Fig. 59. Location of successive fixation points of the eyes of one subject in reading three lines of test. The vertical lines indicate the fixation points; the numbers above show the order in which the points were fixated. (From Buswell, 1920)

Applications

Well all this, you say, might be very interesting to the scientific psychologist, but what has it got to do with psychophysical systems research? It has a lot to do with seeing in certain kinds of situations.

Radar Detectability. For example, take the detection of targets on radar scopes. Certain recent studies by the Operations Evaluation Group have shown that radar operators may sit and look at a PPI for as long as 15 minutes and not see a new target which has appeared on the scope. This may seem a little hard to believe, but actual experiments show it to be true.

One of the reasons why we suspect this situation happens is: There is a very bright sweep line, so called, on the PPI's of most radar sets. This sweep line is continually rotating around the radius of the radar scope. We think that the radar operator's eyes follow this radar sweep around in this typical series of jerky rapid movements -- trying to keep pace with the radar sweep line. Since we know that the eye does not see when it is actually in motion, the probability of detecting a new target pip on the face of the scope depends an awful lot on the way in which the eyes move, and where they happen to be pointed at any particular time. Although we have not actually performed these experiments yet, we think that further study of the basic movement patterns of the eye will clarify our understanding of why targets are or are not picked up on the radar scopes under certain conditions.

Visual Search. This knowledge about eye movements also came in very handy in certain scanning problems during the war. The RAF, for example, worked out a series of search-scan patterns for aircraft observers so that they could increase their probability of detecting life rafts on the open sea. The ocean is a mighty big place and if you search in a random, haphazard pattern, your chances of picking up a small object are pretty slim.

Visual Displays. Now if we go back to the first thing that we told you about the eye, the way that the visual acuity of the eye varies in different positions, we find that this fact, too, is of considerable importance in visual displays in psychophysical systems. If a radar operator or CIC officer is always primarily looking at one point on a radar scope or a plot board, numbers, symbols and digits out on the edge of his visual field have to be much larger in order for him to see them. It is one of those things that we have to take into account when we design display systems for our psychophysical apparatus.

DAY AND NIGHT VISION

Now look at another set of facts about vision. From the standpoint of its function, the visual apparatus may be considered as two separate systems. One part operates most efficiently in ordinary illuminations, such as those that prevail throughout the day and in normally lighted rooms at night. When the illumination is decreased to about the level of full moonlight, around 0.01 effective foot candles, the other part of the eye takes over.

Rods and Cones. If we were to take the front part of the eye off and poke around inside with a microscope, we would find that there are two different kinds of nerve endings inside the eye. Anatomists and physiologists call these rods and cones. The cones are found densely packed in the central part of the eye, the fovea. Toward the edges, in all directions from the center, the density of the cones decreases, and only a very few are found in the extreme edges. The rods, on the other hand, are entirely missing in the central part of the eye. Toward the edges in all directions out to about 20 degrees from the center, the density of the rods gradually increases. A lot of experimental work points pretty conclusively to the cones as the structural elements, or nerve endings, which are associated with daylight vision, and to the rods as those associated with night vision. Individual rods and cones differ in sensitivity so that most types of nerve endings operate over a fairly wide range of illumination. In general, however, vision at starlight levels of illumination is mediated almost exclusively by the rods while vision in daylight is largely a function of the cones.

Spectral Sensitivity. Now one important difference between the rods and cones concerns their relative sensitivity to light from different parts of the spectrum. If colored lights containing equal amounts of radiant energy are viewed in daylight illumination, they do not appear equally bright. Red and blue will appear dark, orange and green appear intermediate in brightness, and yellow-green will look brightest. This state of affairs is shown in Fig. 60 by the curve labelled "cone vision." If we decrease the overall intensity of the energy from the different parts of the spectrum until only the rods are functioning, the visibility of the colors will be proportional to the values given by the left hand curve in this illustration -- the one labeled "rod vision."

The Rod-Cone Shift. The practical significance of these data is that red and blue lights of equal size and intensity at cone levels of illumination and at night do not remain equally bright as we increase our distance from them. This results from the fact that the amount of illumination at the eye decreases and a proportionally greater number of rods is stimulated. Violet, blue and blue-green lights outlive other colors in visibility as the distance between the light source and observer increases at night. This effect is known as the Purkinje phenomenon. The magnitude of the shift in sensitivity of the eye to lights of longer and shorter wave lengths, respectively, is enormous and may amount to a factor of as much as

1000. These facts were especially useful during the war and they account for the fact that violet, blue and green light could be much more readily detected at night by a distant enemy observer whose eyes were dark adapted. Red, orange, and yellow lights, on the other hand, are not so easily detected at night by someone who is far away.

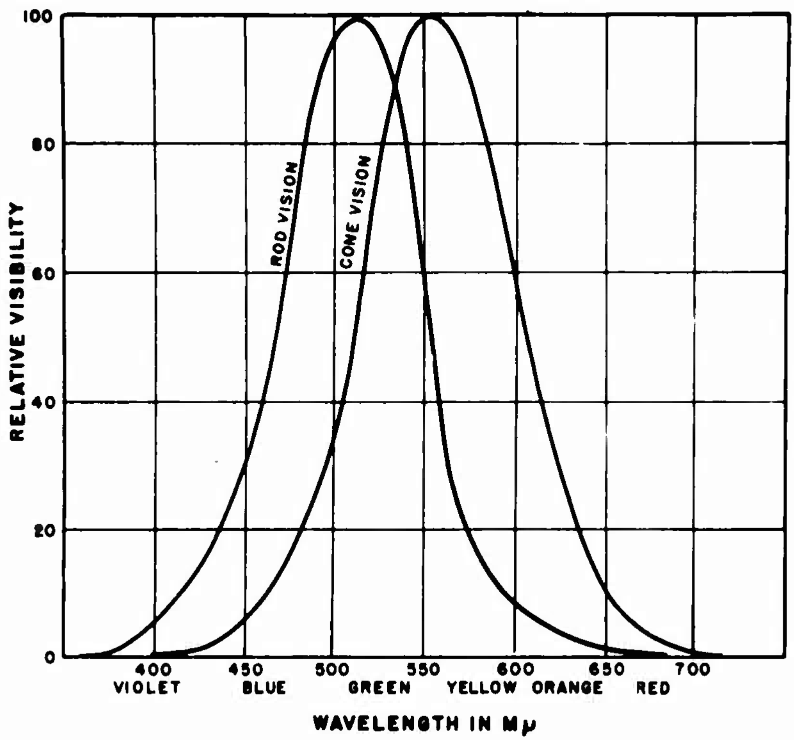

Fig. 60 The photopic and scotopic visibility curves of human vision. (Adapted from Troland, 1934.)

Color Vision. Another important difference between the rods and the cones involves their sensitivity to color, as color. True perception of color is not possible with the rods, as may be clearly demonstrated by trying to determine the colors of objects at star-light illuminations. It is possible to distinguish between light and dark colors at night only in terms of the intensity of reflected or transmitted light. Under these circumstances all colors appear as a series of lighter or darker grays. In short, when the illumination has been decreased to about that of half full moonlight, it is impossible to tell colors as colors. If the brightness or intensity of a color at night is above the threshold for cone vision, however, then and only then, can it be perceived as a true color.

Red Goggles. The relative sensitivity of the rods and cones as shown in Fig. 60 has provided us with a very important aid to night vision. As you can see, the rods are stimulated only very little by red light so that by wearing goggles with red lenses in ordinary illuminations, it is possible to dark adapt the eyes and still see well enough with the cones to read or write. You can look at it this way -- when you have red goggles on, the rods in your eyes, for all practical purposes, are in complete darkness. The use of red lighting and red dark-adaptation goggles during the war must be familiar to all of you, and we need not spend any more time on this topic.

Visual Acuity at Night. Now you recall that we said that the cones which are responsible for our seeing in daylight are most densely packed in the central part of the eye, and that they decrease in number as we go out toward the edges of the eye. The rods, on the other hand, those nerve endings concerned with seeing at night, are entirely missing in the central part of the eye, but they increase in frequency as we go out toward the edge of the eye. It is this distribution of the rods and cones which accounts for the ability we have to see with different parts of the eye.

In Fig. 61 is shown a curve of visual acuity at ordinary daylight illumination. This curve is exactly one-half of the curve which you saw in Fig. 58. Here again the zero degree mark represents vision in the direct line of sight. Now when we plot the visual sensitivity of the eye at night we get the other curve in Fig. 61. At night, the central part of the eye, the fovea, is virtually blind, but as we go out to 5, 10, and 15 degrees from the center, the eye becomes more and more sensitive. This chart, therefore, gives us more evidence about basic differences between rods and cones, and between seeing in daylight illumination and night illumination. In daylight, the central part of the eye is most sensitive. At night, the central part of the eye is almost blind. In daylight, visual acuity is very poor, relatively speaking, 15 degrees from the central line of sight, but at night the eye is most sensitive at 15 degrees from the central line of sight. Strange as it may seem, in order to see best at night, you must not look directly at something. You must use off-center vision -- you must look away from something in order to see it most clearly.

Dark Adaptation. If you go suddenly from bright illumination into darkness, the eye is not ready to go to work until it has had time to become adapted to the new illumination. If you step out onto the open bridge at night from a brilliantly lit ward room, at first you cannot see very much, but after several minutes dim forms and large outlines become visible, and, as time goes by, more details of the environment become perceptible. This increase in

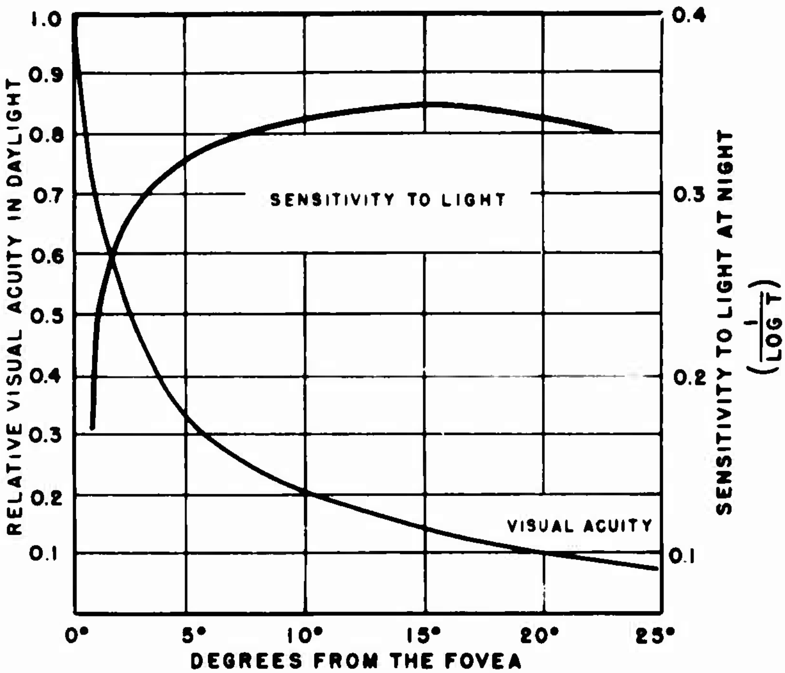

Fig. 61. Regional variations in daylight visual acuity (adapted from Wertheim, 1894); and in light sensitivity at night. (From Pinson, unpublished data, 1941.)

sensitivity of the eye at low levels of illumination is called "dark adaptation." You recall that we mentioned this process briefly in one of the earlier lectures. Dark adaptation follows a fairly definite pattern which can be charted by determining the minimum amount of light visible at various intervals after entry into the dark. The pattern of this dark adaptation process to different colored lights is shown in Fig. 62.

The Course of Adaptation. In general, the decrease in visual threshold during the first eight or nine minutes is due to an increase in the sensitivity of the cones, and, to a small degree, to the dilation of the pupil which increases the light-gathering power of the eye. The additional increase in threshold, which occurs after ten minutes, is due to the function of the rods. Most of the increase of the sensitivity of the eye occurs during the first thirty minutes, although after that time there is still a small but consistent increase in sensitivity. During these first thirty minutes, the eye's sensitivity increases roughly ten thousand times.

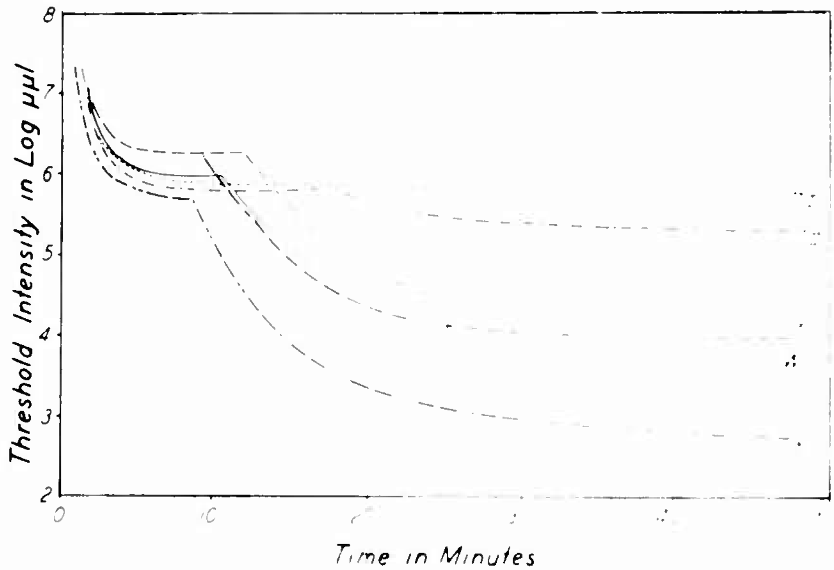

Fig. 62. The course of normal dark adaptation measured with red (R_I), reddish-orange (R_{II}), yellow (Y), green (G), white (W), and violet (V) light. (From Chapanis, 1947.)

<u>Color and Adaptation</u>. One more thing this figure shows very clearly is that the eye is much more sensitive to violet light than it is to any of the other colors. It should be clear to you by now that our eyes are really extraordinary instruments. They are so sensitive that they can pick up a lighted match ten miles away if the night is completely black and if there is no haze in the air. There is literally no single optical instrument which has the enormous range of sensitivity -- from full daylight to starlight -- that the eye does.

THE LAWS OF VISION

So far we have been discussing certain basic physiological facts about the eye. We should like now to shift our emphasis to four basic laws of vision. These four laws of vision tell us how visibility of objects is influenced by physical factors in the environment. As a result of a large number of scientific experiments we know now that in daylight, as well as at night, the visibility of an object, or the distance, or the ease with which it can be seen, depends on (1) the illumination on the object, (2) the size of the object, (3) the contrast between the object and its background, and (4) the length of time it is seen. As regards the first of these factors, namely, visual acuity and illumination, we have already had occasion in a previous lecture to discuss this function briefly. Fig. 10 shows the relationship. This curve tells us that when the illumination is decreased we cannot see so well, and it enables us to predict exactly how well we can see with certain amounts of illumination.

Illumination and Visibility

From a practical standpoint, the decrease in acuity at low illuminations and at night, means that identification must depend on the perception of generalized contours and outlines and not of small distinguishing features. Small guns and turrets, fixed landing gears, struts, antenna, wires, and so on, may be invisible a few hundred feet away. Aircraft and ships are least visible when viewed from dead astern, because their areas are smallest in that direction. For this reason night interception tactics require that enemy aircraft be followed from rear-above or rear-below rather than from rear-level. Similarly, small terrain features, a small building, smoke-stack or a bridge may not be visible at night and recognition must depend on rather large ground features -- surf and sand, large clumps of trees, rivers, lakes and large concrete installations.

Size and Visibility

The second law of visibility says that the larger an object is the more visible it is. This is a kind of common sense notion, and it is very easy to demonstrate, as we have done in Fig. 63. It is a lot harder to see things when they are smaller. This illustration actually is one kind of test which can be used to measure visual acuity. But do not lose sight of the basic law here: Visibility is related to the size of the object you are looking at.

Contrast and Visibility

Brightness Contrast. The third basic law of visibility says that objects are more visible when the contrast between the object and its background increases. In our discussion of contrast, however, we should distinguish between two types of contrast -- brightness contrast and color contrast. By brightness contrast, we mean how much lighter or darker an object is than its background. By

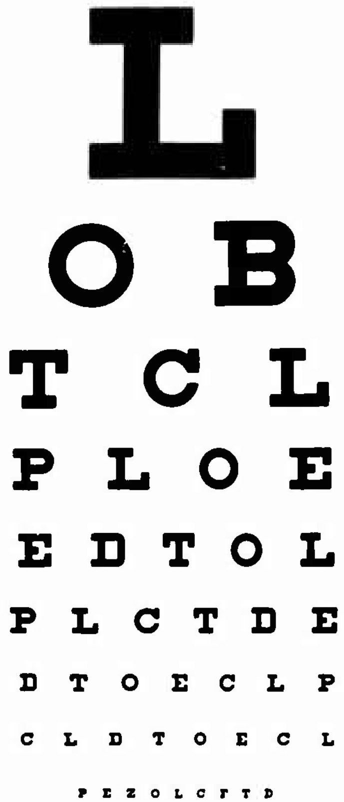

Fig. 63. If you hold the book five or six feet away, this chart illustrates a basic law of vision: visibility is a function of size of object. (From Fryer, 1946.)

color contrast we mean how much difference in color there is between an object and its background. The whole art of camouflage depends on methods whereby low color and brightness contrast are used to conceal objects by decreasing their visibility. Standard camouflage for naval aircraft consists in painting the underside a light color so as to present low contrast against the sky when seen from below, and the top side blue to match the sea when seen from above. When aircraft operate predominantly in one type of combat environment, as do naval aircraft, satisfactory camouflage can be achieved easily. If, on the other hand, the aircraft must operate under a wide variety of environmental conditions a camouflage for all of these conditions is difficult, if not impossible to achieve.

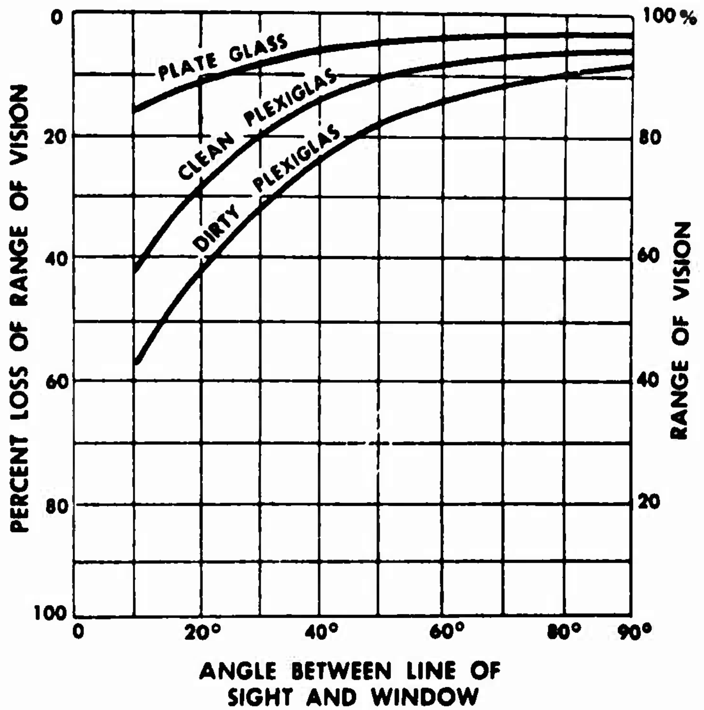

Fig. 64. Range of vision through glass, and clean and dirty plexiglass at various angles of incidence. From Olenski and Goodden, 1943.)

Color Contrast. Color contrast may also be used effectively to increase visibility. Of the various spectral components of white light, the short wave lengths, the blues and greens, are most easily refracted and scattered by the atmosphere and suspended dust. This scattering sometimes produces a troublesome diffuseness of retinal images and reduced visual acuity, particularly when dust concentrations are high, or when haze and fog are dense. Red, orange and yellow light are much less dispersed by these atmospheric factors. In some cases, therefore, it is possible to increase contrast and visibility by using a yellow lens to eliminate dispersed blue light. A number of good field tests have shown fairly conclusively, for example, that red and orange filters enable you to follow tracer against the sky longer than you can with the naked eye.

Color contrast obviously enters into the design of radar scopes, and the search for the most visible, or legible, color combinations on these radar scopes is still not ended.

Contrast and Aerial Visibility. Practical illustrations of the importance of brightness contrasts are shown in Fig. 64, which scarcely needs any interpretation. These data were obtained by subjects who looked through aircraft glass, clean plexiglass and dirty plexiglass. This figure shows that dust and grease on windshields act as an effective screen between the pilot and the outside world. Particles of dirt and grease scatter light haphazardly into the bundle of light rays which form an image of the object on the retina. This decreases the contrast and destroys the sharpness of the image. Diminished contrast also results from scratching or fogging of the transparent material, because each scratch or water droplet is a source of scattered light.

Contrast at Night. As another illustration of how contrast affects visibility at night, Table VI summarizes the average ranges at which aircraft can be spotted under winter skies. These data are taken from a British source. They show that when there are no clouds in the sky and the moon is full, an aircraft can be seen from below at a distance of about 1,200 feet. When the aircraft is seen against the clouds from above, with a full moon shining on the cloud floor, the contrast is increased markedly, and the plane can be seen about 6,000 feet away. Under the worst conditions, however, with a dark, clear, starlit night, and the aircraft being seen from above over land, the contrast is excessively poor, and an aircraft can be seen only if it is within 300 or 400 feet.

Contrast, Illumination and Size. Our best source of information about the way the eye responds to different contrasts, illuminations and sizes of objects, comes from an extensive study carried out during the war by the Office of Scientific Research and Development. This agency took over the Lewis Comfort Tiffany Foundation, which is normally an art school in peacetime, to conduct this study. In these experiments spots of light were projected on a screen some 60 feet away from a group of observers who reported whether or not they had seen the spot. A large number of such presentations were made with varying brightnesses of the stimulus, with stimuli of varying sizes, and with illuminations varying from full daylight to slightly less than the darkest night. In all, more than two million observations were recorded. Some 450,000 of these observations have now been analyzed and they constitute the largest single study of human vision which has been reported to date.

Table VI

AVERAGE RANGES FOR SPOTTING AIRCRAFT UNDER WINTER SKIES IN BRITAIN
(from Chapanis, 1945)

Full moon, no clouds, aircraft seen from below	1,200 ft.
Moon on cloud floor, aircraft seen from above against clouds	6,000 ft.
Moon on cloud floor, aircraft seen from below against clouds	500-700 ft.
Dark clear starlit night, aircraft seen from below	600-900 ft.
Dark clear starlit night, aircraft seen from above over land	300-400 ft.

Let us take a quick look at some of the data explained in this experiment. Shown in Fig. 65 are a series of curves showing the least perceptible brightness contrast which can be seen by the normal eye at various illuminations. The different curves in this slide represent the data for test objects of various sizes. A total of approximately 220,000 observations went into the plotting of this series of curves. Two relationships are shown very clearly by this series of curves, the first one is that as the illumination decreases, the brightness contrast of the just barely perceptible object must be greater. If we translate this into other words, it means that when it gets darker, things have to be a lot blacker or lighter than their backgrounds in order for us to see them. If the illumination is high, on the other hand, then we can see objects which are just a little darker or lighter than their surroundings.

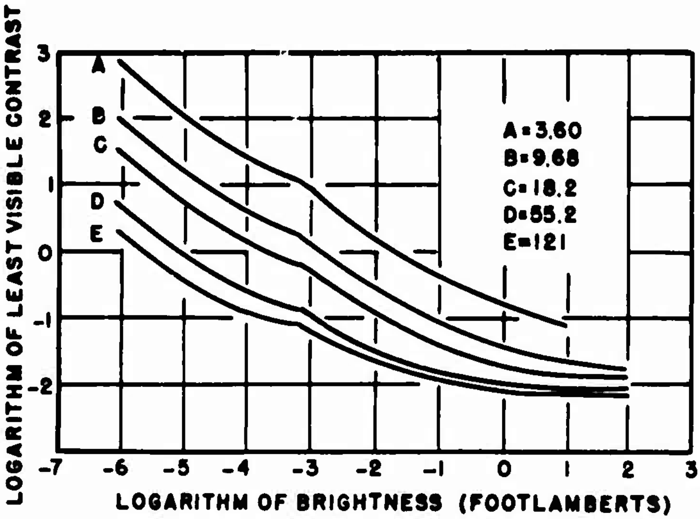

Fig. 65. Least visible contrast as a function of brightness and size of object. (From Blackwell, 1946.)

The other relationship clearly demonstrated in this graph is that at any illumination small objects have to have more contrast in order to be seen than do large objects. This latter relationship is more clearly demonstrated in Fig. 66 where the size of the object is plotted against the brightness contrast of the just perceptible object. In this case the different curves represent the data obtained at the various illumination levels.

Time and Visibility

The fourth law of visibility says that an object is more visible the longer you have to look at it. Again this law is so reasonable that it hardly needs illustration. Magicians make use of this principle all the time and it accounts for the saying, "The hand is quicker than the eye."

Each of these four laws of vision is easily understood when we consider them one at a time. A difficulty arises, however, because they are all interrelated, so that predicting visual acuity under a given set of circumstances may become fairly involved. We know, for example, that a reduction in any one of these four factors -- illumination, size, contrast, or time, may be compensated for by an increase in one or more of the others. For example, an object which is so small as to be just below threshold visibility may be made visible by increasing the illumination on it, or by increasing the contrast between it and its background, or both.

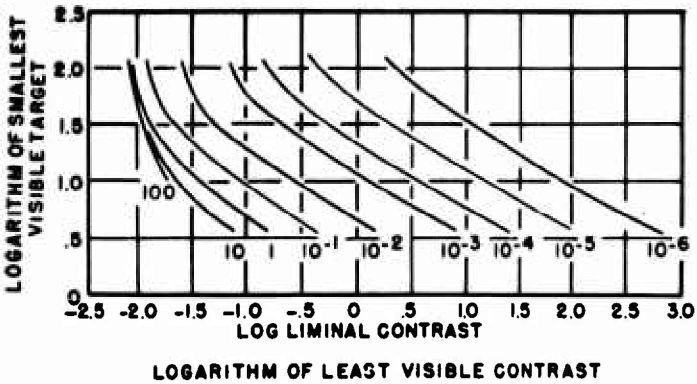

Fig. 66. Least visible target size as a function of contrast and brightness. (From Blackwell, 1946.)

Interrelationship of Factors. Fortunately for us, these four basic factors have all been thoroughly investigated in their various interrelationships, and Fig. 67 represents these relationships between various combinations of size, contrast and brightness for threshold visibility and for a constant time of exposure. We are trying to show so many interrelationships here that it is necessary to use a three-dimensional diagram, and even then we do not quite get in all of the information that we would like. The area above this three-dimensional curve is the region of clear seeing; the area below the curve represents the region of the invisible. By means of this curve we can tell from the size of an object, from its contrast, and from the amount of illumination on it whether or not that object will be clearly seen or not seen. This plot of the boundaries of normal vision was derived from over 200,000 separate measurements, and it forms the basis for many of our predictions about visibility under many practical conditions.

Brightness of Surround. In our discussion of the four fundamental laws of vision we were concerned with the size, the brightness contrast and illumination of an object along the central line of sight. Many practical problems in illumination engineering require that one other factor be considered, namely, the brightness of the area surrounding the visual task. For all practical purposes the visual field of the eye represents the amount of space that you can see. This visual field is limited by the physiognomy of the face. Above, it is limited by the eyebrows, to one side by the nose,

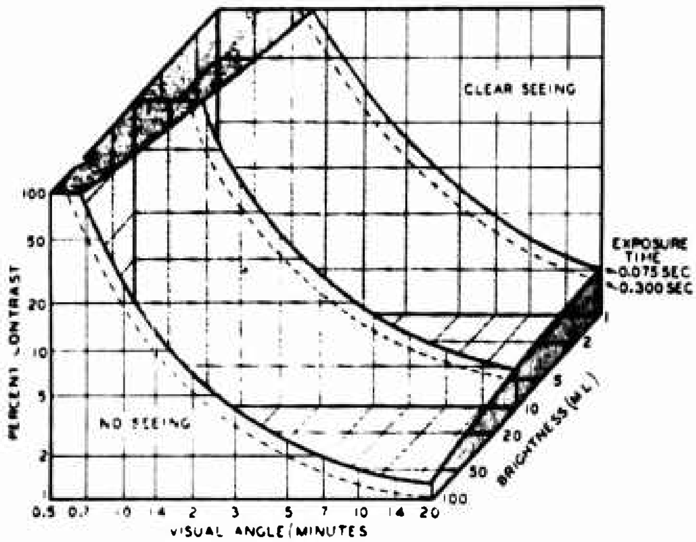

Fig. 67. The curved surface represents the relationship between combinations of size, contrast and brightness for threshold vision. (From Luckiesh and Moss, 1944.)

and below by the cheek bones. For the average observer, the visual field is about 160° in size horizontally and about 120° in size vertically. For most engineering problems we can divide this visual field into three areas as shown in Fig. 68. The central field is fairly small in size and it is where we have our most accurate vision. That portion of the visual field which surrounds the central field up to 60° constitutes the surroundings. Finally, around the surrounding 60° portion is the periphery of the visual field.

Visual Acuity a Function of Surround Brightness. Now, here is the point of this business. We can change the visual acuity of the eye by merely increasing or decreasing the brightness of the surroundings. The results of one investigation undertaken to explore this function are shown in Fig. 69. This figure shows that the sensitivity of the eye is greatest when the surrounding area is the same

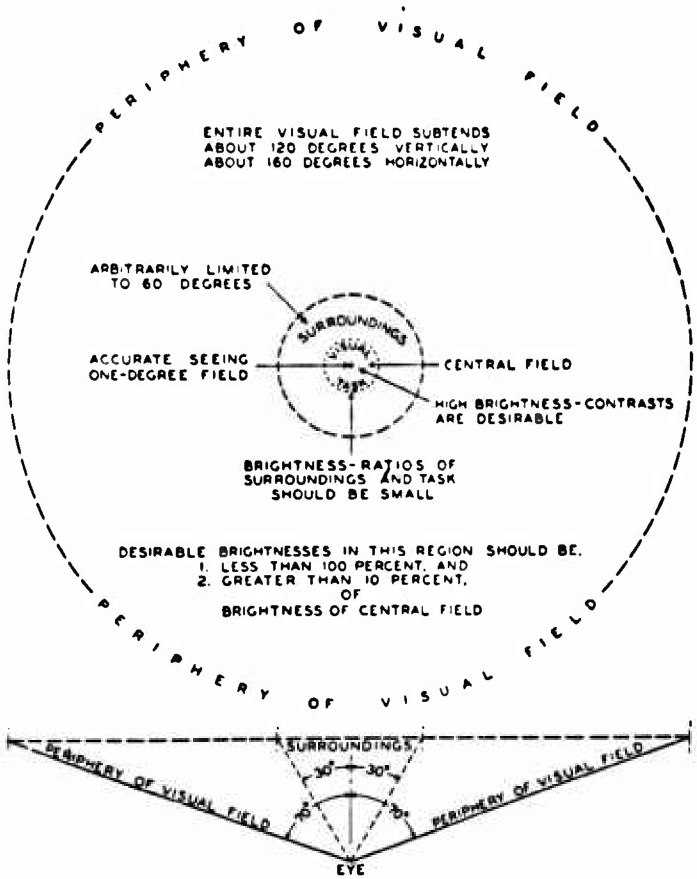

Fig. 68. The illuminating engineer has to consider the entire visual field in the design of interior lighting. (From Luckiesh, 1944.)

brightness as the central field. This means, for example, that if we are looking at a dial, our eyes are most sensitive when the large area around the dial is the same brightness as the dial. If we make the surrounding area five times brighter than the dial, visual acuity is reduced to about 44 per cent. If we make the surrounding area 1/5 as bright, that is, darker than the central portion, visual acuity is decreased to 77 per cent. Visual acuity is best, therefore, when the surrounding area is equal in brightness to the object at which we are looking. If the surrounding area is not equal in brightness, visual acuity is not as good, and we get our greatest loss when the surrounding area is brighter than the visual task.

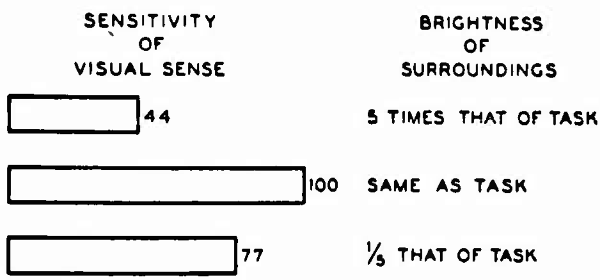

Fig. 69. For best vision the area surrounding a visual task should be as bright as the visual task. (From Luckiesh, 1944.)

As a practical illustration of this principle, it appears, on the basis of some preliminary work, that detectability of targets on radar scopes actually improves if the illumination in the CIC room is kept a little higher than is usually the case. Detectability is best when the eyes are adapted to the same brightness level as the radar scope. This appears to be true in the laboratory, <u>but</u> --

Glare

And the big "but" is this: Another factor which must be considered in the design of brightnesses and illuminations for interior work spaces is the effect of glare. Glare applies to light entering the eye from any visible light source or bright area. In general it reduces the sensitivity of the eye and reduces the visibility of an object or task. Usually when we try to increase the illumination in the CIC room to get better detectability of radar scopes, we find that we have increased the glare so much that we are worse off than when we started. There are too many shiny surfaces around.

Glare and Visibility. Glare, we know, is also distracting and annoying and may even cause extreme discomfort and pain. Glare sources that are particularly annoying are headlamps at night along the highway, bright light sources in the direct visual field, or reflected images of light sources from polished metal surfaces inside. As a result of many years of research on this problem certain fundamental laws concerning glare have been well established. The first of these is that glare reduces visibility directly as the brightness of the glare source. The impairment of visual acuity, therefore, is directly dependent on the candle power of the glare source

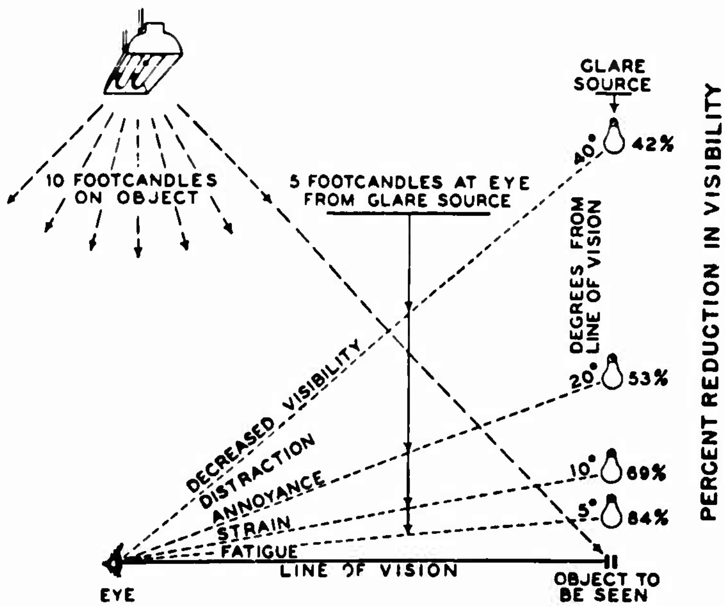

Fig. 70. Glare becomes worse as it comes closer to the direct line of vision. (From Luckiesh, 1944.)

toward the eye and inversely proportional to the square of the distance of the glare source from the eye. A second relationship is that the effect of any glare source becomes less as the angular distance from the direct line of vision increases. This relationship is shown in Fig. 70. This illustration shows the eye looking at an object with the direct line of vision represented as a horizontal line at the bottom of the figure. Shown in the upper left hand corner is a lamp furnishing ten foot candles of illumination on a test object.

If we introduce a glare source 40 degrees above the direct line of vision the effect is merely one of decreased visibility. If we bring this same glare source down to within 20 degrees of the direct line of sight, the effect of the glare is directly annoying. As we bring it down to 10 degrees there is a distinct effect of strain, and within 5 degrees the effect is downright fatiguing. The percentages on the right tell us how much effect the glare source has on the eye.

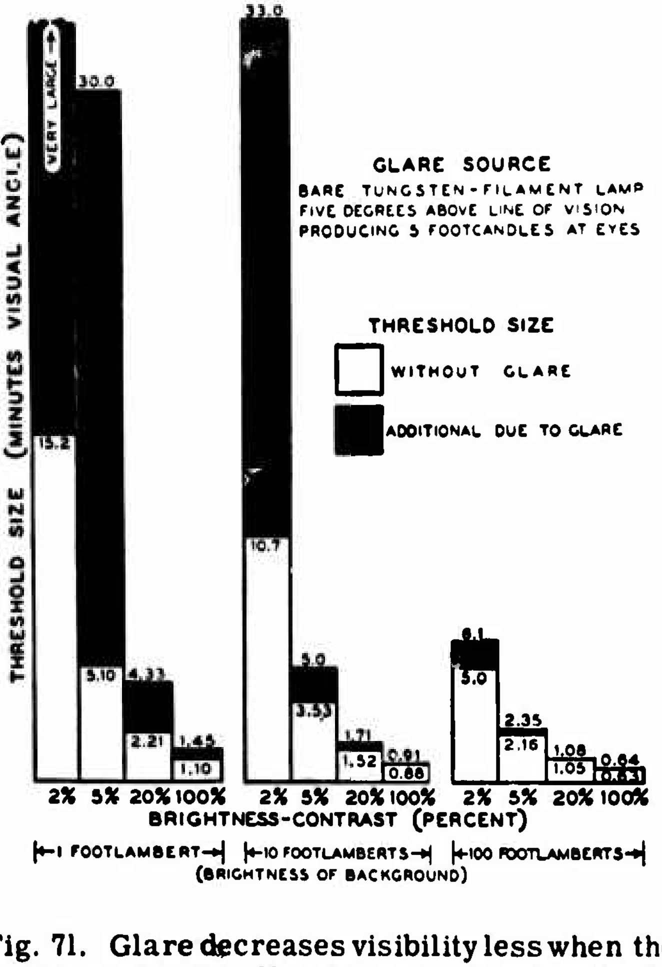

Fig. 71. Glare decreases visibility less when the brightness level and brightness contrast are high. (From Luckiesh, 1944.)

Glare and Brightness Level. Another relationship we know is that the effect of any glare source decreases as the general brightness level increases. If we increase the illumination on the object from 10 to 100 foot candles the effect of this same glare source is considerably less, as shown in Fig. 71. Then, finally, we know that we can evaluate the effect of several glare sources if we weight each one for its distance from the primary line of sight. All of these factors are important for the illumination engineer in designing illumination for the interiors of work spaces.

OPTICAL ILLUSIONS

Earlier we said that seeing really involves both the eyes and the brain. In many cases the brain takes the picture that is formed by the eye, distorts it, and makes us see things that really are not so. Some of these discrepancies between perception as registered in the brain and the actual picture which is registered on the eye go by the name of optical illusions. Undoubtedly all of you have seen a number of these optical illusions, but it might be fun just to look at one or two of them.

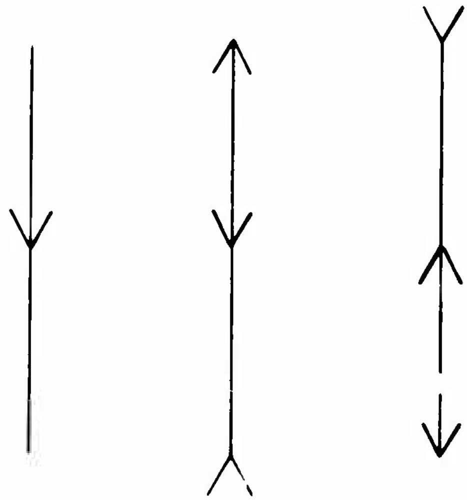

Fig. 72. The Müller-Lyer illusion. (From Glasser, 1944.)

Müller-Lyer Illusions. Shown in Fig. 72 are a number of illusions which go by the name of the Müller-Lyer illusion. In this figure all the horizontal and vertical lines are exactly equal in length and all are divided exactly in the middle. Practical applications and illustrations of this illusion are found very frequently in architecture, and in the kind of hats women wear.

Vertical Illusion. Another common illusion is the illusion of the vertical as shown in Fig. 73. In this illustration the height of

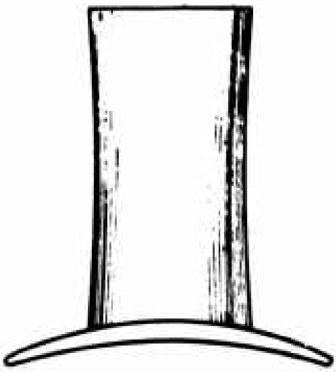

Fig. 73. The illusion of the vertical. (From Glasser, 1944.)

the top hat is exactly identical with the width of its brim, but certainly most of you will agree that it looks a lot taller than it does broad. This figure illustrates a very common illusion -- the universal tendency to overestimate figures in the vertical dimension and underestimate them in the horizontal dimension. That is why the carrier Midway, for example, does not look anywhere near as long as the Chrysler Building is tall, yet they are practically identical in length.

Perspective Illusion. Another very common illusion is the illusion of perspective as shown in Fig. 74. In this case, the three men are identically tall but the one on the right appears to be considerably taller than the one on the far left. This illusion appears to arise because the human eye has been trained to associate perspective with distance. This illusion is largely a matter of experience, therefore, and we know that children, who have not yet been trained to associate perspective with distance, almost universally say that the three men are the same size.

Applications. By now, we are sure that most of you are thinking that all of these illusions are very cute, but what have they got to do with anything in psychophysical systems research? A goo illustration of how important some of these illusions may be in practical situations comes from a study being conducted by the Institute of Research at Lehigh University. A group of psychologists there is working on a contract with the Watson Laboratory, Army Air Forces, primarily to investigate certain psychological aspects of radar presentation and control as they relate to systems for the

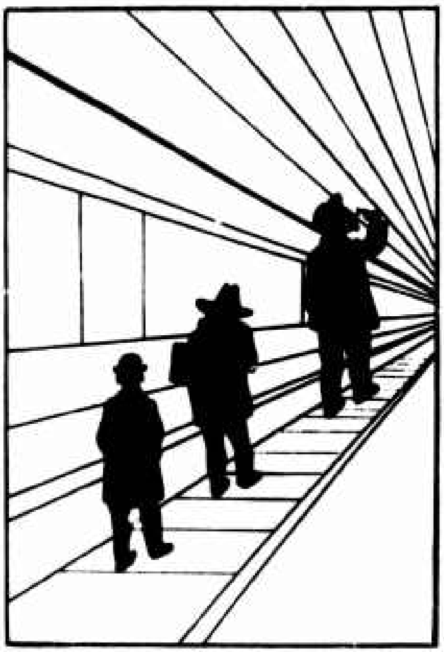

Fig. 74. The illusion of perspective. (From Glasser, 194ı.)

ground control of aircraft. In one of their experiments, these investigators studied a sector-type radar presentation used to estimate and control the glide path of an aircraft approaching an airport in a blind instrument landing. They studied three of these sector-type presentations as shown in Fig. 75. In the first presentation, the gently sloping line in the center of the scope represents the normal glide-path pattern. The vertical spacings on the right hand margin of the scope represent deviations in feet from this normal glide path. The bright blob above the glide path and about in the center of the scope is an aircraft making an approach on the landing strip.

Because of the triangular structure of this type of radar presentation we have a situation which resembles very closely the conditions for the perspective illusion which we showed you a moment ago. These investigators had a number of radar operators estimate the distance of the aircraft above and below the glide path and they discovered, sure enough, that as the aircraft came in closer to the point of the triangle, the operators tended to greatly

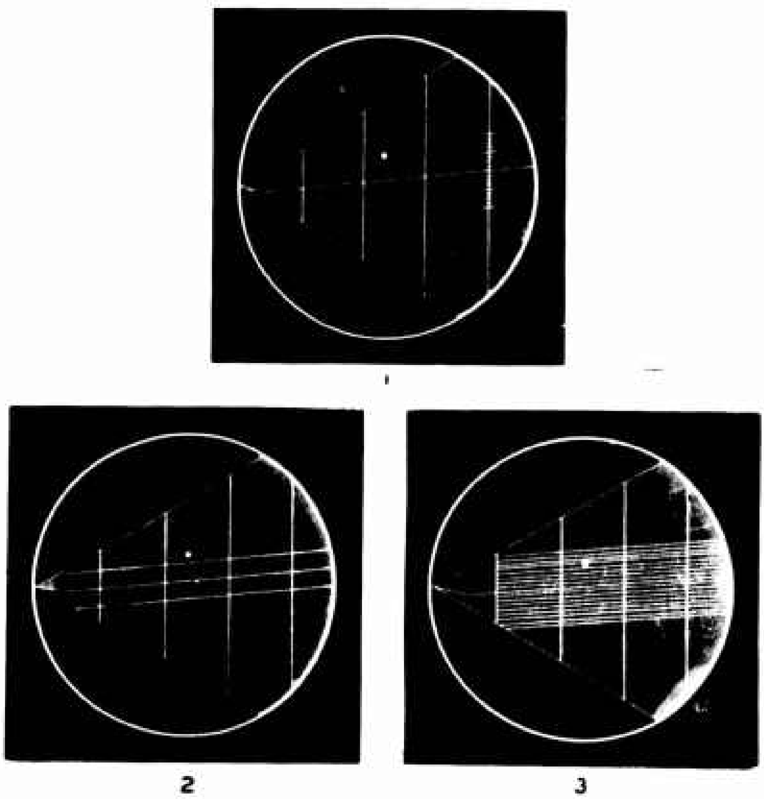

Fig. 75. Sector-type radar presentations. Numbers 1 and 2 are subject to the perspective illusion; Number 3 is not. (From Ford and Jenkins, 1947.)

exaggerate their estimates. There was a very strong tendency for the operators to overestimate the amount of deviation of the aircraft from the glide path. Even when these investigators put in two extra reference lines as shown in the second radar presentation, the operators still persisted in overestimating the amount of the deviation of the aircraft from the glide path. The illusion was so strong that it overcame the effect of the two additional reference lines. They finally had to use a radar presentation as shown in the third sector before they could completely eliminate the tendencies to overestimation.

In summary, we have tried in this lecture to present some basic information about how we see. In our next lecture we shall look at a number of specific seeing problems as they relate to psychophysical systems.

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IX: DISPLAY PROBLEMS IN PSYCHOPHYSICAL RESEARCH

In our last lecture we had a long look at some of the basic laws of vision. We asked ourselves the question, "How do we see?" and we found the answer fairly complicated. We found that we see differently with different parts of the eye. We found that the way we see depends on whether we are using our day eyes or night eyes. We found that seeing is very much dependent on the amount of illumination around us, on the brightness contrast of objects, on the size of objects, and on the length of time we look at them. And at the conclusion of our last lecture, we found out that in many cases seeing is not believing, but deceiving. We saw that this is so because seeing involves both the eyes and the brain, and the brain in many cases plays tricks on us. It makes us see things that are not there, or it makes us misinterpret what we do see.

In this lecture, we would like to take up where we left off last time and look at a number of specific visual display problems encountered in psychophysical systems.

Kinds of Displays. In every psychophysical system there has to be some kind of a display somewhere or sometime in order that the operator or observer can know what is going on. Ordinarily the word "display" implies vision. But we use the term in a broader connotation since a display can be of a number of types. It may be a visual display, an auditory display or a tactual display. You have already heard a lot about various types of auditory displays. Tactual displays have not been used very much in psychophysical systems, but they do occasionally become pretty important. The feel of a joystick in an aircraft, for example, may tell the pilot something about the kind of maneuver he is making. The shapes of certain kinds of knobs also give an operator information about the control he is operating. The position of a series of controls also gives the operator information about what is going on.

Visual Displays. In this lecture, however, we are concerned primarily with visual displays. The psychologist calls these display problems "perceptual problems" because they demand more than just seeing. The eye and the brain are involved.

Perception and Displays. In perceptual problems, the observer not only has to see things but he has to interpret what he sees. He has to relate what he sees to what he already knows. He has to make judgments and decisions on the basis of what he sees. When a target pip shows up on a radar scope, not only does the observer see that there is a bright spot there but he also, for example, tries to interpret the position of the spot in terms of the distance of a target. He performs a complex mental judgment about the range of the target by knowing what distances the range rings on his radar scope represent. All of these words I have been using -- perceive, interpret, judge, estimate -- all of them indicate some higher mental function being carried on by the brain at the time that the eyes are seeing. We have already discovered that the brain is a mighty fallible piece of machinery and it should not surprise us very much, therefore, to discover that our study of visual display systems might just as well be labelled "Studies in human error."

Examples of Perceptual Errors

Let us look at the record of some of these errors. It is instructive to do this because it gives us some idea of the kind of problem we are up against. An Army investigator recently collected a number of stories by pilots on errors they made involving the reading or interpreting of some aircraft instrument. Here are some of the verbatim accounts.

1. "One night when I was instructing in the basic flying school, a cadet was given instructions to let down for a landing. That was the last that was heard of him that night. The next morning he called up from a point about 15 miles from the field. What had happened was that he had started to let down and read his altimeter as 1,300 feet when actually it was 300 feet. He had crashed into a forest and been knocked out for an hour or so. Afterwards he had walked away and finally gotten to a telephone."

2. "This cadet started practicing spins at 18,000 feet. Of course, spins do not break as fast at that altitude. The cadet thought the ship was not coming out of the spin. He had been instructed to bail out of the spinning ship if it ever got down to 3,000 feet. He looked at his altimeter, and it read 13,000 feet. However, he thought it read 3,000 feet and bailed out. It took him a long time to get down to old Mother Earth. We lost one AT-6 on that deal."

3. "A buddy of mine was flying at 1500 feet and looked up

and there was a bunch of trees in front of him....After it was all over and the plane had crashed, he said, 'Well, I guess I must have hit a tree.' The thing was that he had read his altimeter wrong. It was really indicating 500 feet which was just the height of the terrain at that point.''

4. These are all documented stories from people who were there. There is one other incident we would like to tell you about. There may be some doubt about its ultimate veracity, but it will illustrate how errors in perception and judgment can cause trouble. An instructor in Naval Aviation, after a large evening and six successive training hops, found it impossible to stay awake. The cadet was fairly competent and after his allotted time in the air brought in the SNJ, parked it on the line, cut his engine and left. The instructor slept peacefully. Some incidental noise happened and he awoke with a start, heard no engine noise, saw a zero on his airspeed indicator. He bailed out and broke his shoulder.

5. In order to dispel any idea that pilots are the only people who make errors of this sort, here is another kind of example. Field artillery and tank destroyer outfits use what is known as a panoramic telescope to get an accurate sight on targets. When the cross hairs in the telescope are accurately lined up on the target, all the operator has to do to find the bearing is to read a continuous scale underneath a pointer. (We ought to point out incidentally that the Army reads bearings in mils -- 6400 mils to a circle.) Even so, it looks like a pretty simple job. In one study conducted by the Applied Psychology Panel, 14,000 tests were made with this telescope. Of these 14,000 observations, nearly one in twenty was in error, and of these errors, over one-half were errors of 100 mils or greater. These errors were big enough so that occasionally shells would be lobbed over onto the wrong side of the line.

6. Just one more example to show you that this sort of thing can happen with Navy equipment too. In one short series of experiments performed in our laboratory, men were required to operate a VJ remote radar indicator and to read the bearings and ranges of single targets showing up on the radar scope. Four per cent of the bearings turned in during this experiment proved to be seriously in error. They were not measly little one or two degree errors, but 10 degree errors and 100 degree errors. The operators were not green. They knew their business. They were experienced, and they recognized their mistakes as soon as they were pointed out to them.

Well, there you have it. There is the problem. People will persist in misreading scales, in misreading dials, in making errors, even when their eyes tell them that it is not so. The problem is there all right, and it looks like a pretty tough one to crack. Let us see what the psychophysical research scientist can do to reduce these errors. We will find as we get into this problem, though, that we do not have all the answers yet. In many cases we will only be able to ask the questions.

LEGIBILITY

One fairly obvious factor in these problems and these errors is legibility. In our last lecture, we talked a lot about the visibility of things. Even if we do have a bunch of letters, all of the same overall size, of the same degree of contrast, and with the same amount of illumination on them, the letters are not equally legible. Certain letters and numbers are more easily confused than other letters and numbers. What can the scientist tell us about these?

Letter-Legibility. When we start investigating this problem, we find out that the simplicity or complexity of the outline of a number markedly affects its legibility. Different amounts of shading, and different numbers of hairlines in the design of numbers also affect their legibility. So does the amount of white space included within the outline of numbers and symbols. And finally, emphasis or lack of emphasis on certain parts of numerals and symbols affects their legibility. On the basis of certain researches, we know now that the letters which are the easiest to read are the A, E, N, H, I, J, L, N, P, T, U, V, X, Y, and Z. We also know that lower case letters are a lot easier to read than capital letters. A group of letters which needs special attention is B, C, D, G, K, Q, R, S, V, and W. The B, for example, is a lot more legible if we put a little overhang on the top and bottom. The same is true of the letter D. We can improve the differentiation between C and G if we have well-marked gaps in the letters and put a well-marked cross-piece in the letter G. The Q needs a definite, strong, oblique stroke in order that it will not be confused with the letters O or C, and the W needs a high center prong so that it won't be confused with M. S is a difficult letter no matter what one does. It is always being confused with other letters.

Number-Legibility. Insofar as numbers are concerned, 1, 2, 3, 4, 5, and 7 are a lot easier to see than the numbers 0, 6, 8, and 9. We know that the 2, 3, and 5 should have very large open spaces in them in order not to be confused with other numbers. And we also know that a 3 with a flat top is much less easily confused with 8 or 9.

Some dial designers apparently think that you can make a number more legible by making the strokes very strong and bold. They think that the heavier the line the more legible the letter. Actually this is not true, and on the basis of some preliminary investigations it appears that a good working rule is that the line thickness should be about one-seventh the height of the letter for white letters on a black background. If black numbers are used on a white background, the letters have to be about twice as thick. In general, white letters on a black background are more legible than black letters on white.

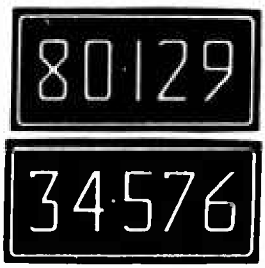


Fig. 76. The most legible kinds of numbers for day vision. (From Berger, 1944.)

The Most Legible Numbers. A psychologist at Cornell University recently carried out an extensive investigation to discover the most legible kind of number for automobile license plates. We need not concern ourselves with the details of his experiment except to note that he tried a large number of shapes and thicknesses. His results are of considerable interest because the numbers he found to be most legible do not resemble the kinds of numbers we ordinarily see around us. The most legible numbers for daylight are shown in Fig. 76; the most legible luminous numbers for nighttime in Fig. 77. The printer did not make a mistake -- luminous numbers are more legible at night if they are thinner. This research was done with large numbers viewed at fairly great distances (30 to 100 yards), however, so we do not know if the results can be applied to numbers on dials.

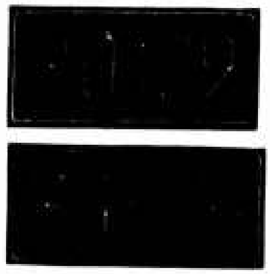


Fig. 77. The most legible kinds of luminous numbers for night vision. (From Berger, 1944.)

Legibility-Research. Well, the story about legibility is not all told. We still do not know all the answers, and Purdue University psychologists have some further work under way to investigate exactly what the factors are which contribute to making certain letters and numbers more legible than others. When the answers do start rolling in, we hope that we will be able to design letters and numbers which will be much more legible than those now widely used. It is not impossible that we will be able to decrease the number of reading errors by as much as 50 per cent in some cases.

DIAL DESIGN

But there is more to the legibility problem than just the legibility of the numbers. The dial itself is important. Should the dial be round, semicircular, or long and narrow? How many marks should there be on it? The specific designs which make dials most legible are still incompletely understood. We made a start on these problems during the war, however, and we have some fairly definite conclusions on some questions.

Dial Markings. A couple of years ago an Army Air Forces psychologist studied a number of different dial designs in an attempt to discover some of the factors which increase the legibility of these dials. One of his rather surprising results was that the fewer the number of markings, the better the legibility. In Fig. 78, for example, we can see three of the dials studied by this man. These happen to be aircraft tachometer dials. You might suppose at first glance that the one on the extreme right would give the most accurate readings since it has so many scale divisions. Actually it turned out that with very short exposures, or quick glances at these dials, pilots tended to be a lot more accurate with the dial on the extreme left. The cleanest dial from the standpoint of design, the one with the fewest dial markings, actually gave the best results. The actual percentages of error in reading these dials for an exposure of 3/4 second were 34% for the dial on the extreme left, 41% for the dial in the middle, and 44% for the one on the right.

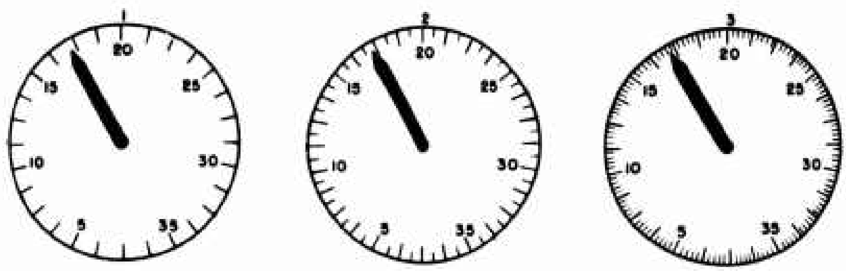


Fig. 78. Legibility decreases as the number of lines increases. (From Loucks, 1944a.)

Dial-Numbering. A second interesting conclusion this army psychologist reached from these researches was that the numbering of small subdivisions tended to decrease the accuracy with which an instrument could be read during a short exposure. Most accurate results were obtained when the major subdivisions of the dials were numbered with clear legible numbers, and the intermediate numbers were omitted.

Pointer-Width. Another thing he found was that a reduction in the width of the pointer did not improve accuracy. Then, too, he found that an increase in the height and thickness of the numbers did not necessarily improve their legibility. When the numbers were too thick, they were seen as blobs, and could not be read easily.

Dial-Rotation. He also found that the starting point of the dial did not have any significant influence on its legibility. This fact is of considerable importance since instruments can be rotated so that the pointers will lie in a given position under normal operating conditions -- a fact we will take up in a minute. Finally, he discovered that mid-division lines which change in value from one part of the scale to another prove very confusing and increase the number of errors considerably. Most slide rules, since they have logarithmic scales on them, violate this important psychological principle of legibility. In the case of the slide rule, however, it is not quite so important, because we usually have enough time to study the scale and get our settings accurately.

Dials or Counters?

Sometimes it may be worth while to ask the question, "Is there some other kind of a device that will work better than a dial?" This is a proper kind of question when we are interested in exactly what the scale or dial reading is at any particular time. An example of this is a bearing dial. We really want to know what the bearing of a target is to the nearest degree. In many cases it does not help if we know merely that a target is off our starboard bow. What we really want to know is that it is at bearing 069. But as we have already indicated, we find quite a sizable proportion of errors when people read these bearing dials. It is quite natural for us to ask, therefore, if there is any better way of presenting precise information so that people will not make mistakes.

Experiments. One idea that occurred to us was this: Instead of having a dial, why not fix up a special little gadget which will tell us exactly in numbers what the bearing of the target is? In one of our experiments we tested four pieces of radar equipment -- the SG and the SR radars, and the VF and VJ remote indicators. In this experiment, too, we also tried a bread-board model of a direct-reading bearing counter. Fig. 79 shows the type of bearing scale that appears on one of these radars, and Fig. 80 shows the bread-board model of our direct-reading bearing and range counter.

Results: Time. In this experiment we used five subjects with a total of 1,250 observations for all subjects and all pieces of equipment. Let us look at what we found. In Fig. 81 are plotted the average times required by the five operators to read bearing and range information from the four standard radar units and from the experimental bearing and range counters. You will notice that it took these operators on the average about 3.5 seconds to read a

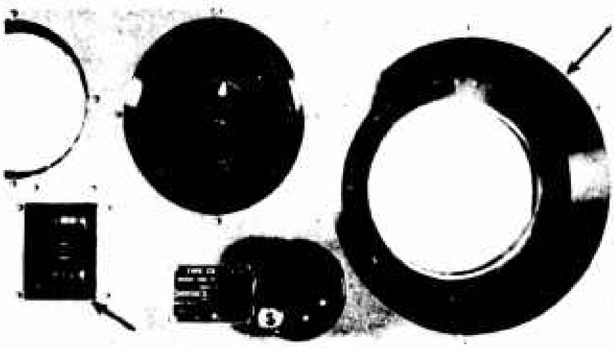


Fig. 79. Bearing dial (right) and range dials (left) on the SG radar. (From Chapanis, 1946.)

bearing and range from the standard radar units. And you will also notice that it only took them about 1.8 seconds to read a bearing and range from the experimental counters -- a saving of about 47% in time.

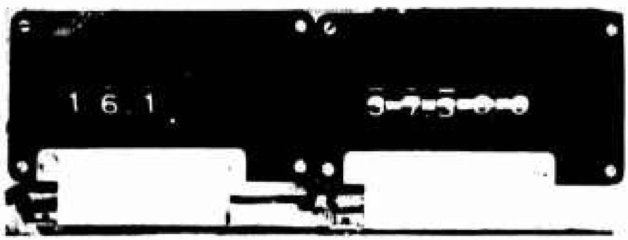


Fig. 80. Experimental direct-reading bearing indicator (left) and range indicator (right.) From Chapanis, 1946.)

<u>Results: Errors</u>. Now let us look at the <u>errors</u> made by these operators in reporting targets from these various pieces of equipment. In Fig. 82 are shown the total numbers of bearing errors made by the five operators in reading 250 target settings from the four standard radar units and from the experimental bearing and range counters. The results are so clear-cut that we really do not need to comment very much about them. There were a lot

fewer errors when operators read their bearings from the direct-reading bearing counter than when they read their target bearings from the conventional circular scales.

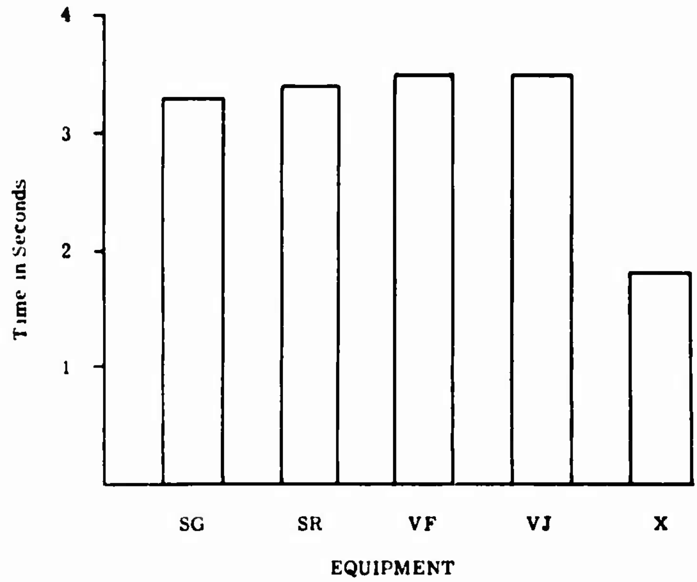


Fig. 81. Average times required by five operators to read bearing and range information from four standard radar units and from experimental bearing and range counters (X). (From Chapanis, 1946.)

'Operational' Tests. This first experiment, however, was a kind of elementary approach to this problem, because the men were not actually operating the equipment at the time they made their readings. This was a test merely of the efficiency with which they could read these various scales. Then, too, we only used a bread-board model of the direct-reading counter. In order to be sure that this difference in favor of the direct-reading counter would still hold up under actual operational conditions, we constructed a direct-reading bearing counter and hooked it up to the bearing crank on a VJ remote indicator. When we got through we had a gadget that looked like the instrument in Fig. 83.

Ordinarily a radar operator reads his bearing from the circular dial around the PPI in the center of this instrument, then he looks down to a range counter below the PPI. In our experimental setup, however, we put the direct-reading bearing counter directly over the PPI and then hooked up another set of range counters directly to the right of the bearing counter. In this case you will notice that the bearing of the target is at 345 and the range is

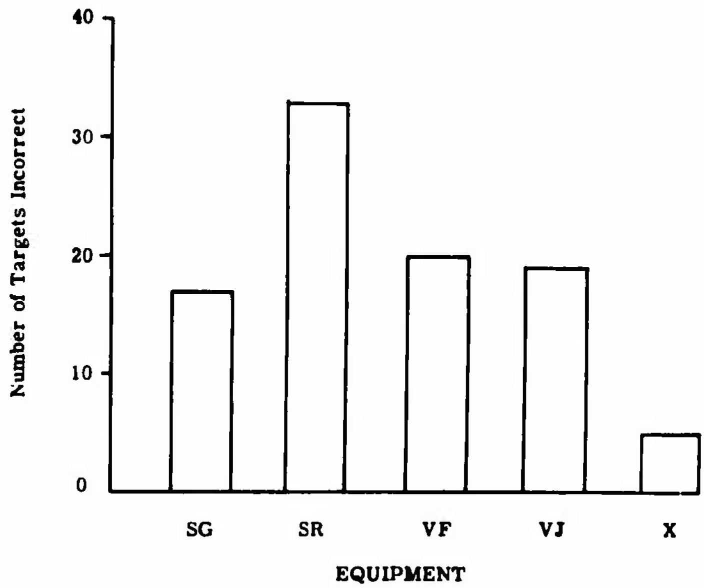


Fig. 82. Total number of bearing errors made by five operators in reading 250 target settings from four standard radar units and from experimental bearing and range counters (X). (From Chapanis, 1946.)

9,600 yards. We ran a series of 160 trials on this experiment in which the radar operators were required to hunt for new targets, operate the bearing and range crank, and read the scales to give us the bearing and range of the target. We found that when these operators used the normal procedure of reading the bearings on the circular dial around the PPI, it took them about 12.8 seconds to do the entire job. When they read their bearings from the direct-reading bearing counter, however, it took them about 11.1 seconds, a saving of 1.7 seconds per target in favor of the bearing counter. In this case, it happened to turn out very nicely, because this was exactly the amount of saving that we found in the earlier experiment.

In this experiment we did not really run enough trials to get a large number of errors, but it is interesting to note that 4% of the readings made from the bearing dial were seriously in error. With the bearing counter, however, only slightly more than 1% of the targets were in error. So the results in this case look pretty clear-cut. If you want to get accurate readings from your dials, a direct-reading counter can increase both your speed and your accuracy.

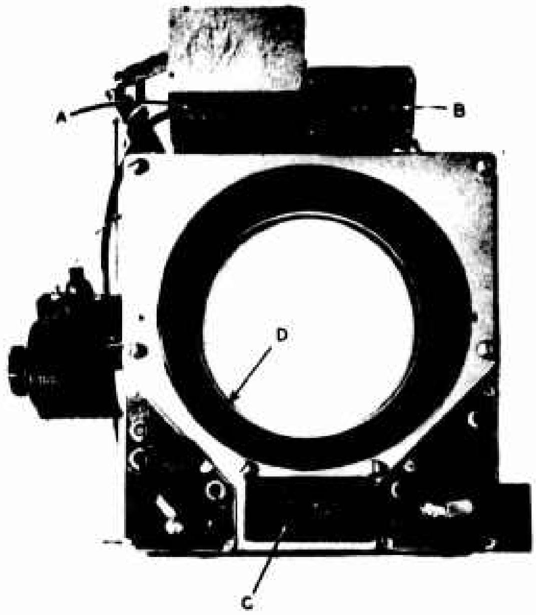


Fig. 83. Top view of a VJ remote indicator showing the direct-reading bearing counter (A); an experimental placement of the range counters (B); the conventionally located range counters (C); and the bearing scale (D). (From Chapanis, 1947.)

Disadvantages of Counter. But this does not mean that we should run out and change all our dials to this direct-reading type, because it does have certain disadvantages. One of them is that it is a lot harder to use a direct-reading counter of this sort for setting information into your equipment. The reason for this is pretty obvious. When the bearing counter is used for setting information into a piece of equipment, the numbers on the dials rotate so rapidly that the operator has to stop every once in a while to find out where he is. In the case of the bearing dial, however, the dial is stationary, and the bearing cursor moving within it furnishes the operator with a very helpful cue.

All in all, then, these experiments indicate that a direct-reading counter is more efficient, both in time and accuracy, than an annular scale for presenting bearing information which must be read from instruments. The counter-type of indicator, however, is less efficient if settings must be reproduced or set into the equipment.

THE PATTERNING OF DISPLAYS

In many types of dial display systems, the operator is not interested in knowing exactly the dial reading at any one time. In aircraft, for example, the pilot does not care particularly whether the manifold pressure is 37.5 pounds per square inch or 38 pounds per square inch. All that he really wants to know is whether or not the manifold pressure is within a normal, safe operating range. For this reason many aircraft instruments have a small, narrow green band painted along the outside edge. This green band indicates the normal operating range or safe range.

'Unpatterned' Dials. Even with this additional help, however, there is another factor which tends to add to the confusion of the operator, and it is possible that we can make his job considerably simpler by using a principle known as patterning. In Fig. 84, the nine dials on the left hand side of the figure represent a hypothetical group of dials such as we might find in an aircraft instrument panel. This is not a patterned group of dials. The safe ranges for each of these dials is indicated by a small black band around the edge of the dial. If you hunt around, you will discover that two of the dials indicate that something is amiss. Two of the dials are not pointing at the normal safe operating range.

Alignment Patterns. Suppose now that we had patterned this system of dials. One possible type of pattern is shown by the group of nine dials on the right hand side of the figure. In this case, the normal safe operating ranges are indicated at the top of the dial. We had to shift the number scales around to make the dials do this, of course, but that is not the important thing. The important thing is this: So long as everything in the aircraft is perking along smoothly, all the needles on the dials will be pointing straight up, and we think you will agree that it is much easier to spot the two dials that indicate something is wrong. So far as we know, this system of patterning dials has never been experimented on systematically, but we certainly think that it deserves a try.

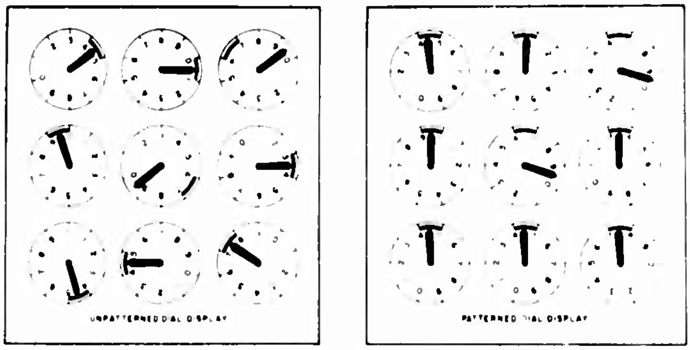


Fig. 84. Patterning of dials may help an operator to perceive which instruments are not functioning smoothly.

Another type of patterned dial display is shown in Fig. 85. This one is under experimental investigation at the present time. You notice that in this case we have transformed our circular dials into rather long, narrow dials. The safe operating ranges for all of these dials have been lined up, so that when the aircraft, for example, is flying under normal operating conditions, all of the pointers will be lined up in a row. If one of the instruments indicates that something is wrong somewhere with the aircraft, the needle which is out of line with the others tends to be detected very easily. This type of a patterned dial display makes use of what the psychologist calls vernier acuity. Translated into English, this means that small misalignments in a straight line pattern are extremely easy to pick up.

Direction of Dial Changes. Another important principle of dial design which affects legibility is this: The direction of the increase of the scale on the dial should be consistent. Now in Fig. 86 there are two pairs of dials, one above the other. The upper pair are to be read together. One of them is a coarse reading dial and the other a fine reading dial. Now here is what we would like you to do: try to read the exact number that the pointer indicates on both upper dials. Try to read these dials accurately and fast. Then look down to the next pair below and see which pair of dials you

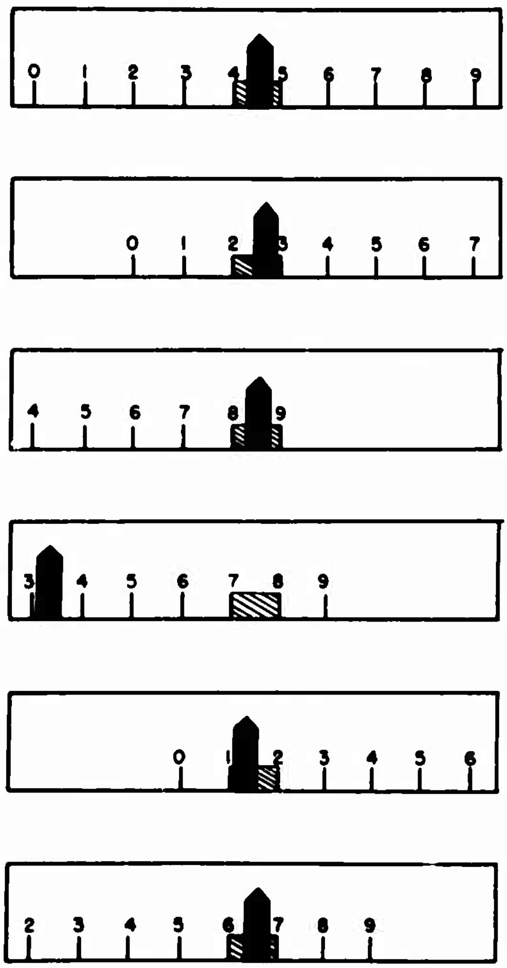


Fig. 85. Another type of patterned dial display.

consider easier to read. Although we know of no actual experimental work on this problem, we think you will all agree that they ought to be one way or the other. We have seen both kinds on Naval equipment.

As an example of how bad these things can get, there are three radio receivers on the panel of the B-314. On two of them, the controls and dials are rotated clockwise to increase the frequency; in the third receiver, they rotate counter-clockwise. In the same aircraft, the copilot's air-speed indicator is rotated clockwise by a corresponding motion of the setting knob, but the pilot's meter has a reverse action. The situation is further complicated by the fact that these adjustments vary from one aircraft to another. The pilot, therefore, has to determine the action of his instruments by trial and error each time he flies another plane.

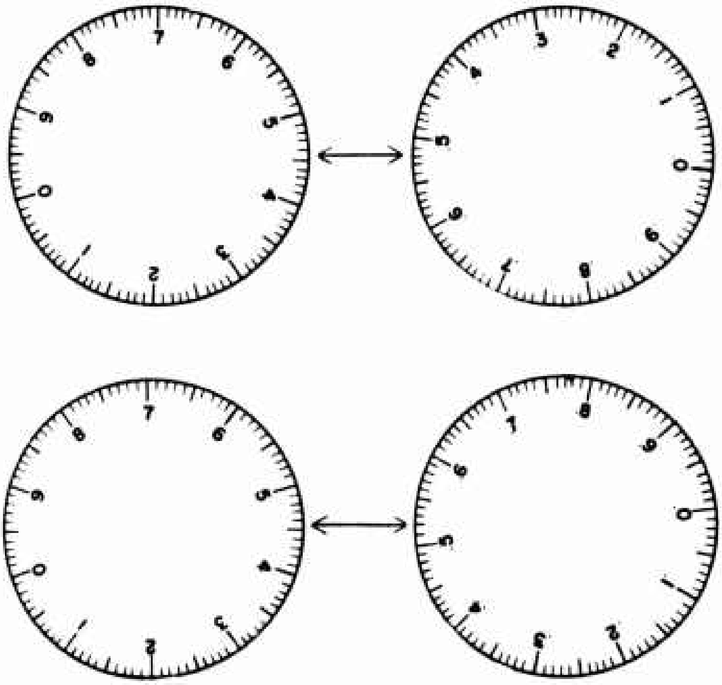


Fig. 86. Which pair of dials is easier to read?

Standardization

Which brings us to another very important problem -- standardization. When our basic research has progressed far enough so that we know what makes dials good, and when and where to use what kind of dials, we will have to standardize. It is a lesson industry learned, but the services appear to have been very slow in picking it up.

Aircraft Instrument Panels. One important principle here is that grouped dials and groups of dials which are used for the same function should be standardized in location, from one situation to the next, from one airplane to the next, or from one ship to the next. The problem is an especially pressing one in the case of aircraft, but it holds equally well in the case of radar systems and CIC. An investigator from Northwest Airlines recently conducted a large survey of pilot opinion among a representative group of the Airlines Pilots Association. The results of this survey show that most pilots agree that a very necessary and vital step in the design of instrument panels is the standardization of instrument locations. Most pilots felt that it really did not make very much difference what the final arrangement was so long as the dials were clearly visible and so long as their location was consistent from one plane to the next. In spite of this unanimous opinion on the part of the pilots, however, another recent survey showed an almost complete lack of uniformity in the arrangement of dials on commercial two-engined aircraft now being built. The problem is one which certainly needs a lot of prompt and careful attention.

Radar Equipment. Recently we have been doing a lot of research on the VJ remote radar indicator. On this equipment the bearing control is on the left, the range control on the right. This is a sensible arrangement since operators normally read target locations in that order -- bearing first, range next -- left to right. Well, we got a brand new piece of equipment a few weeks ago -- hot from the factory -- and where do you suppose the bearing and range controls were? In case you have not guessed by now, they were backwards -- range control on the left, bearing on the right. We think you will understand if we say that our subjects who are trained on the VJ are always a little confused when they turn to the new equipment.

One thing the experimenter can always expect when any kind of standardization of dials is agreed upon and used, is that there will be a large number of complaints from people who are not used to this particular arrangement of the visual display system. It is one of those things you have to expect, and it is really not a serious disadvantage, because the eventual benefits which result from the standardization far outweigh any minor inconveniences which result from another training period.

DESIGN OF TABLES AND GRAPHS

All of our visual displays associated with psychophysical systems are not necessarily dials or scales of one type or another. In many cases we have to use tables and graphs which present numerical data of various sorts. An interesting group of experiments has been done on this problem -- again by psychologists working for the Army Air Forces. The results these Army people obtained provide us with some extremely useful information concerning the design of tables and graphs.

Coordinates. One question we can ask immediately is whether or not it makes any difference if the X of graphs is always along the abscissa, that is, the bottom, and the Y along the ordinate. In Fig. 87, for example, are shown two graphs of the equation $Y=X^2/C$, where C=60, 70, 80, 90, and 100. Although it is not essential for

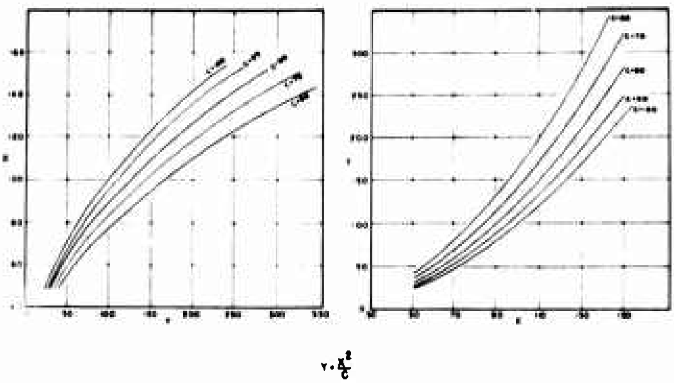


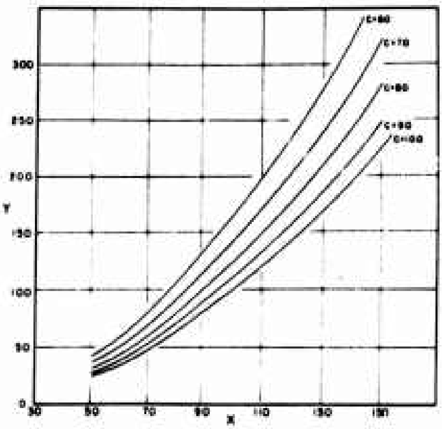
Fig. 87. Interchanging coordinates does not affect your ability to read a chart. (From Carter, 1946b.)

our understanding of the problem, we might tell you that in this case the X represents indicated stress, Y indicates actual stress, and C represents various parameters of temperature in degrees Centigrade. In one of the two graphs shown in this figure, the one on the right, the X, the indicated stress, is indicated along the abscissa. In order to read the corresponding actual stress, one would have to enter the graph along the abscissa, read up to the temperature, and read across to the actual stress value. In the other case, the graph has been reversed; the X and Y coordinates have been switched.

Does it make any difference whether or not we have a graph as shown on the right or on the left? The answer to this question in this case turned out to be negative. When the subjects had a chance to work with the graphs awhile, it did not make the least bit of difference which way the graphs were arranged.

Graph vs. Table. Another question we might ask is this one: Does it make any difference if we have a graph or a table as shown in Fig. 88? The table, in this case, is a small sample of the actual values that appear on the graph. Both the table and graph present

		Y				
X	C=	60	70	80	90	100
50		42	36	31	28	25
60		60	51	45	40	36
70		82	70	61	54	49
80		107	91	80	71	64
90		135	116	101	90	81
100		167	143	125	111	100
110		202	173	151	134	121
120		240	206	180	160	144
130		282	241	211	188	169
140		327	280	245	218	196
150		375	321	281	250	225



$$Y = \frac{X^2}{C}$$

Fig. 88. In general, a table is easier to use than a graph. (From Carter, 1946a.)

the same information, and the question is, "Which one enables us to get the information out fastest and most accurately?" The results of this research were fairly clear-cut. The conclusion is that it it a lot better to use a table than a graph, provided that you can get all of your data into the table. In general, it was found that a large table, even if it ran to several pages, was much better to use than a complicated graph with a large number of curves on it. This conclusion is valid so long as the table contains all of the values which will be used in normal practice.

Interpolation. In some cases, however, it is necessary to interpolate. It was discovered in these researches that interpolation in graphs or tables is an extremely difficult job for most air force pilots and even for college students, supposedly more accustomed to this sort of thing. They made a lot of errors in what seemed to be simple interpolation problems. The general conclusion reached in this study also shows that if a large number of such interpolations have to be made, the graph works better. If for example, the temperatures come in odd numbers which do not appear or which cannot be tabulated in the table, then it is a lot more efficient to use the graphic type of presentation.

DESIGN OF GRIDS AND RANGE RINGS

Now let us look at one other entirely different kind of display system. Let us look at the PPI's of radar scopes.

Number of Range Rings. You know that most types of PPI's have fixed range rings which serve as reference points for estimating the range of targets which appear there. An important question very frequently put to us is this one: "How many range rings are best?" Offhand you might say that you can estimate the range of targets more accurately on the PPI which has the largest number of range rings. Actually, experiments show that there is no increase in accuracy with more than five range rings when the operators are working fast.

Range Rings Must Be Easily Identifiable. The main reason for this seems to be that the use of a great number of range rings is not valuable unless the operator can immediately identify each of those rings. If the operator has to look at, say, the fourth ring, but is not immediately sure whether that ring means 4000, 5000, or 6000 yards, then the value of all the additional rings is lost. In order to be sure of the identity of that particular ring, the operator is forced to count when he has a large number of rings showing. This counting procedure involves a loss of time and apparently some loss in accuracy. When only four range rings are used, however, the operator can look at the second ring and know immediately that that ring is 5000 yards because he can see as many as four rings at one time, all of them in the proper relation to the whole picture. When more rings are introduced a point is reached where the operator can no longer see each ring in relation to the whole picture.

Coding Range Rings. This situation is not entirely hopeless, however, because in this same research, it was discovered that we can improve this situation considerably by using alternate solid and dotted rings. This relationship now enables the operator still to see each of the major solid rings in reference to the whole picture, and dotted lines in between are then referenced only to the major rings, the solid ones, and not to the picture as a whole.

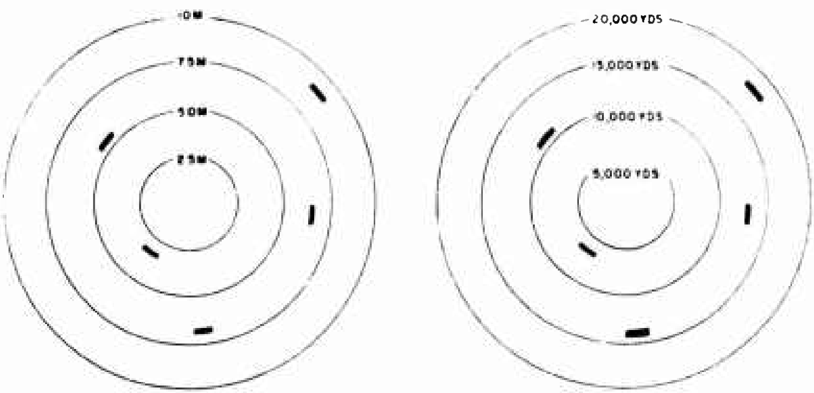


Fig. 89. Can you estimate the ranges of the targets just as well in the two cases? (From Chapanis, unpublished data.)

Another trick that we can use to simplify the procedure of estimating ranges with a large number of range rings is to use colored rings. In this way, the quality of the range ring immediately identifies it in relation to the whole picture without the whole picture having to be seen. So, for example, if the third ring is red or green or blue, it enables us immediately to identify it with a particular range. The operator does not have to read a number to identify it, but any part of the ring has an immediate range meaning because of its coloring. This kind of coding can be of great help in the design of plotting surfaces, and more research is now under way in our laboratories to investigate different types of coding in an effort to discover the one which enables operators to estimate most quickly and accurately the ranges of targets.

Range Intervals. Another kind of problem which is also important in the case of PPI's with fixed range rings on them is the problem of what to call them. What range intervals should these range rings represent? In Fig. 89 are shown two PPI's each containing four range rings. The one on the left has the range rings identified as 2 1/2 miles, 5 miles, 7 1/2 miles and 10 miles. The PPI on the right also has four range rings. In this case, however, they are identified as 5,000, 10,000, 15,000, and 20,000 yards. Both scales, therefore, represent the same amount of distance because, as you know, 2 1/2 nautical miles equals 5,000 yards. So the scales are the same. Does it actually make any difference what we call these range rings? Do you get equally accurate results in both cases? It is interesting to note, for example, that the 2 1/2 mile scale does actually appear on one standard radar now in use, namely the VJ. The 5,000 yard interval also appears on a number of standard radar equipments, the SG, for example.

In a large research project now nearing completion at the Systems Research Field Laboratory, it was discovered that it does make a lot of difference what you call the range interval. The 2 1/2 mile scale, for example, gave errors which were nearly twice as great as those which were obtained when the range rings were numbered in 5000 yard increments. This is a kind of semantic problem. It is a problem in number names and number divisions. We do not quite know why it is so hard to work with a 2 1/2 mile scale, but there seems to be no doubt that the 2 1/2 mile scale is really extremely difficult to use.

The Best Range Intervals. This research program to which we refer tested a lot of other scale intervals. In fact, the scale intervals tried were 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10,000 yards and 2 1/2 miles. Over 5000 observations were made in this research with 11 different radar operators. The results obtained so far are quite consistent. It turns out that the 1000 and the 10,000 yard scales give the best results. Actually we should not be surprised at this finding, since we are used to dealing with our decimal number system in everyday life, and of course, the 10,000 yard scale is the same as the 1000 yard scale with another 0 added to it. It is also interesting to note, however, that the next best range interval was 2000 yards; then came 5000 and 4000. After that the errors began to increase considerably. Nine thousand, 8000, 7000, 6000, 3000, were bad, and 2 1/2 miles was actually the worst of all those tried in this experiment.

Obviously in designing range rings for actual pieces of radar, we have to consider other things than the scales which are most easily read. We have to consider the maximum range that we want to get on our radar and the ranges at which the radar will be used.

most frequently. But this research does give us some help in this design problem by showing us that certain numbers are much more easy to work with than others.

SUMMARY OF PRINCIPLES

In closing, we should like to summarize what we have said by listing some general principles which are important for visual displays. These principles describe, in general terms, our accumulated knowledge about these factors.

1. Every display should be designed for quick perception. This is a basic requirement for the intelligent operation of any kind of a psychophysical system. Numerical information used in operating the equipment, check lists, maps, tables, graphs, control markings, PPI's, scales, and dials, should be easy to read. Scales and pointers should be designed for legibility. Visual warning devices should attract immediate attention.

2. Every display should be designed so that the meaning of the indication is immediately apparent. The operator must not only be able to see an indication quickly, but he should be able to comprehend and understand immediately the significance of the display he is looking at. He should not have to think about the display and interpret the meaning in terms of a set of complicated rules. His interpretation of what the display tells him should be easy and natural.

3. A display should provide information that can be read precisely and completely. An instrument or display which is accurate to .1% from a mechanical point of view is of very limited value if the operator can read it with only 10% accuracy. Precision in visual displays can be improved by a number of means -- by increasing the illumination, by increasing the size of the display or by redesigning entirely the type of instrument face.

4. Single displays in an entire display system should be as simple as possible. They should present only as much information as the user really needs. If a pilot needs to know his absolute altitude to the nearest 25 feet, it is not important to give him an altimeter which is designed to be read to the nearest foot. Or, if a radar operator can read the position of a target on a PPI only to

within plus or minus 200 yards, it is not important for him to have range dials which read to the nearest 20 yards. In many cases we have to ask ourselves whether a dial is really necessary. In some cases all that may be required is an all-or-none indication, an indication that something is working safely or normally, or not working safely. It has been frequently suggested by engineers that visual displays can be simplified by combining several indications on a single dial. However, when two different instruments are combined, it does not necessarily follow that the result is simpler. In fact, the combination may actually be more difficult than the two individual dials. In most cases the only way we can be really sure that a new type of display is simpler or easier than an old type is to conduct actual research on the two types.

5. Different displays and controls should be easily distinguishable. During the war, for example, there were a considerable number of accidents due to the fact that pilots retracted their wheels when they intended to raise their flaps. These errors were the result of the fact that both controls were located side by side and were identical in appearance and shape. It has also been reported very commonly that the clock and altimeter in many types of aircraft have been confused because of their similarity in design, shape, and numerals. At critical times these errors could easily cause serious accidents.

6. Displays which provide related information or which are referred to in rapid succession should be grouped together. It is the opinion of many pilots that associated instruments in aircraft should be located close to each other in order to minimize eye movements and fixation times.

7. Controls and instruments should be designed so that they move in the expected direction.

8. Last, but not least, displays should be standardized -- from one equipment to the next, from one aircraft to the next, from one ship to the next.

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X: THE FUTURE OF HUMAN ENGINEERING

This is the last of a series of ten lectures on psychophysical systems research. In the first nine lectures, we surveyed the methods, the facts and the principles that are available today. We purposely played down the research that is now in progress and the problems which are before us for further study. But to scientists -- to almost anybody -- the future is more exciting than the past. What we do not know is always more interesting than what we know. And we live in high hopes that what we do tomorrow will far surpass what we could do yesterday. So in this last lecture we want to look at the horizons, at the future of psychophysical research and human engineering.

In presenting the past of this field of research, we have not been entirely fair to all of our scientific colleagues. Because we who lecture to you are concerned with information systems research, we have tended to give examples and facts from our own fields of interest, strive as we have to present a balanced picture. So it will be too in this concluding lecture, for we shall, of necessity, emphasize our own specialty. We will conscientiously try, however, to take the broad view of the problem. Rather than make specific forecasts about particular problems and applications, we shall try to cover the broad areas which have been summarized in previous lectures, and we shall stress the potentialities of such research over a long range of time -- not two or three years, but rather twenty or thirty.

PROBLEMS AND PROJECTS IN PSYCHOPHYSICAL RESEARCH

Now let us give you a fleeting picture of the problems and projects which will engage our attention in the future. Let us see what is going on now, what needs to be done, and what can happen as a consequence of our present and future activity.

Getting Together the Facts that We Know

Research is not the only need -- though it is an important need -- in the field of human engineering. There is much that we already know that must be put in usable form. As we explained in the first lecture, pure experimental psychologists and time-and-motion engineers had been working for many years before the last war. The time-and-motion people have done a good job of writing textbooks, of setting up special courses and of training people to use their particular techniques. The experimental psychologists, however, never dreamed that much of what they knew could be useful to human engineering problems. So they have never assembled their material in a form that engineers can easily get at. One of the first things we have to do then, is to put into usable form what is already known.

Textbook of Human Engineering. This series of lectures is one step in putting together information which was formerly scattered here and there. These are not lectures out of a textbook. There is no textbook of human engineering. For the most part, these lectures have been new combinations of facts found bit by bit in technical journals, in classified war reports, in parts of different types of textbooks and in the results of our own research. But these lectures are just an icebreaker. They make the first cursory attempt to pull together the facts and principles of psychophysical systems research. In the next three years, we hope to expand and document these lectures so that a full-fledged textbook, giving a comprehensive and detailed treatment of the field, gets written. In preparing such a text, we shall be helped by the many Summary Technical Reports of war research already prepared, but not yet published. We shall be helped by the vigorous research that is now going on. Do not expect this textbook too soon, however, for it will take time to get all the material together, to digest it, organize it and get it published. Two to four years is about as soon as you can expect it.

In passing, we should like to call your attention to a book just published: Human Factors in Aircraft Design by Professor Ross McFarland. This is a comprehensive meaty text giving an account of both psychological and physiological factors in aircraft design. It is the closest thing we have to a human engineering textbook for aircraft.

Handbook of Psychophysical Functions. An essential step in the development of any technology which is generally useful is the collation of facts into handbook form. You now have a handbook of Physics and Chemistry, serving as a bible of millions of college students and a most valuable reference for many research workers and engineers. There is no such handbook for psychophysical functions. We wish we knew as much about them as we do about physical functions, but what is already known somewhere by somebody is appreciable. What is needed is to collate what we know into tables and charts that can be made available to design engineers everywhere to be used in the design of the displays and controls which human beings must see and manipulate.

Such a handbook is now in preparation at Tufts College. Psychologists at Tufts have a contract with the Human Engineering Section of the Special Devices Center to do this job, and they have already made a good start on it. The job will take two or three years, and after that will require constant revision to keep it up to date. But when you first see it, it will be a handbook prepared primarily for you and other engineering personnel in the Navy, though it will have general usefulness, we are sure, in other military and industrial situations.

Summary Technical Reports. A moment ago, we mentioned summary technical reports of war research. These have been written in both the armed services and in the Office of Scientific Research and Development. After the war was at an end, many people spent months putting together in coherent form the results of research and development during the war. Most of these reports are to be published within the year. Among them you will find several volumes and chapters dealing with psychophysical research. In a summary report of the Applied Psychology Panel of the OSRD, you will find several sections dealing with human engineering problems in gunnery, radar and voice communications. In a summary report of the Acoustics Section of OSRD, you find a substantial part of a volume dealing with human engineering problems of voice communication. And a similar report by the Underwater Sound Division of OSRD will tell you about human engineering problems of design and operation of equipments in, and connected with, submarines. There are others to come out, but these, we know, will be important sources of information.

Getting Together the Methods We Know

In addition to summarizing what we already know factually about human engineering problems, it would help a lot if we could get into the hands of engineers the appropriate manuals explaining what is known about methods in human engineering research and tests. Plans are more or less formulated for a number of such manuals. Slowly, but surely, in the years to come, these manuals will be published and will aid various design groups in various ways: setting up high, but realistic, design requirements for human operation; seeing the stages in design in which human engineering problems should be turned over to research groups; and setting up appropriate psychophysical tests for appraising equipments for human use. Just as samples, let us run through a few of the methods manuals that will be or should be written in the next few years.

Time and Error. First is a manual that we at Johns Hopkins published a little while ago. It is called the "Calculation of bearing and range errors due to delays in transmission of radar information." Actually, the manual has more general application than its title implies. It gives formulae and charts telling how a target of any speed, any altitude, on any course at any range and at any bearing moves as time elapses. There is nothing new in this manual that any competent person could not figure out if he took the time and trouble. Its value, however, is that it does all the work for you. By looking in the appropriate tables and charts, you can see quickly, for example, what a given amount of elapsed time would do to the error of any target-indication system. From this manual, it is possible to set up quickly and surely for any assumed tactical conditions, the speed and accuracy requirements of an information system.

Equipment Appraisal. Second are manuals for appraising equipments. As we have shown you in earlier lectures, it is a good idea to have every equipment given a human engineering appraisal. To be sure we know what a gadget will do and how well it will do it, we should have actual people operating it under realistic conditions while we measure precisely its performance. So far, the only safe way to run such tests has been for a research man to take considerable time and trouble to tailor-make a special experiment for each equipment. And to a certain extent, human engineering testing methods will always be rather specific to classes of equipment.

But it is possible to set up manuals for testing each class of equipment. The Psycho-Acoustic Laboratory has prepared such a manual for articulation-testing communications equipment. We are now in the process of preparing a manual for psychophysical testing of remote radar indicators. And one can expect similar manuals to be prepared by others for other classes of equipment. With such manuals it will be possible to make the psychophysical appraisal of instruments more routine than it now is, thus saving the time of research personnel and making psychophysical tests more economical and more generally available than they are today.

Statistical Methods. Another kind of manual which is needed is one on statistical methods for studying man-machine activities. As you saw in our second lecture, the statistics involved in human engineering are not of the sort ordinarily used by design engineers. They are not used much either in most branches of physical science. They stem from the kind of problems met mostly by psychologists, biologists and agriculturists. Even these standard -- if peculiar -- statistical methods need revising and streamlining for human engineering purposes. But once worked out, these statistical methods not only serve to keep us on the right path in psychophysical tests and research, but they become a powerful tool in finding out things one can measure, in putting our finger on the trouble spots in man-machine combinations, and in letting us predict accurately the overall error in our systems. When there is time, we hope to expand in manual form the statistical techniques which we reviewed briefly in the second lecture.

Methods for Arranging Systems. Quite similar in status is the problem of systems arrangement. As you saw in the fifth lecture, we already have standard techniques for going about the arrangement of any system of equipment and men. Again there are special problems to be solved for each and every system, but there are certain general procedures which apply to every problem in systems arrangement. Nowhere can you find these procedures laid out in detail -- we gave you only a skeleton outline in the fifth lecture -- and when there is time, we or someone else ought to describe these procedures in a form that others can follow to solve day-by-day problems of psychophysical systems layout.

Human Engineering Design. We still have much to learn about the design of controls and displays. But we already possess a considerable body of knowledge in this area. If we could put together a manual giving the principles, and outlining a check-list of requirements to be met in the design of any engineering equipment, if we could put this manual in the hands of designers, there is very good reason to believe that better designs would happen. A manual something like this has already been prepared by the Engineering Division, at Wright Field, for standardizing certain features of cockpit design in Army Aircraft. This manual is called the Handbook of Instructions for Airplane Designers and it contains a large number of specific human requirements prepared by the Aero Medical Laboratory. We need something similar for the design of all instruments which men must see and operate.

Undoubtedly there are many other manuals which ought to be written, utilizing existing knowledge and putting it in the form that engineers can use. We have given you examples from our particular problems in human engineering. To write all these manuals in the next two years would require more man-hours of research personnel than are now available for all aspects of work in human engineering. So patience is necessary. Manuals like these will be prepared, slowly but surely, and eventually you may expect a series of them from different laboratories covering various aspects of human engineering problems.

What We Must Learn Through Research

Now let us turn to the research programs in human engineering, either already underway or being planned for the near future. What may we expect of them? In answering this question we could easily take two or three lectures describing the problems and possibilities of psychophysical research. Such a lengthy description would undoubtedly bore you, and perhaps more confusion than enlightenment would result. So we will deliberately telescope into a few minutes what is extremely interesting to us, and we shall give you only a few highlights. Again, we shall tend to emphasize our own research more than that of others, for we know it better, but we shall try to represent as best we know it the work of all laboratories -- Army, Navy, industrial, and academic.

Training Devices. In the psychologist's vocabulary, the word 'transfer' is important. It means the amount of carry-over from the learning of one task to performance in another. Transfer is the key problem in the design of training devices and programs. A training device is just as good and only as good as the amount of transfer from the device to the real McCoy. So the design of training devices centers around the psychological features which will transfer the operator's training from the device to the McCoy.

In terms of transfer, most trainers do not train, or, if they train, they train only on the trainer, not on the operational gear. That is what a lot of experience with industrial and military trainers shows. Your Human Engineering Section in the Office of Naval Research has recognized this problem, and has instituted a program of research involving several laboratories to do fundamental research on the principles of transfer. What kinds of training transfer and what kinds do not? How should trainers be designed to give the maximum in transfer? These are questions that break down into a number of more specific ones, but we will not go into them here. Let us note simply that fundamental research on these questions is in progress. We expect it eventually to establish the advantages and limitations of training devices and to give us the human engineering requirements for the best kinds of training devices.

Simultaneously, of course, a short-range program of psychophysical tests is being carried out to appraise present training devices and new ones as they are developed. Several university and service laboratories are now studying, under controlled conditions, a variety of training devices. They will find out before too long whether the devices do train, and, if they train, how to get the best results in the least time out of them. Because present-day alleged trainers do not give much transfer to actual gear, there is much improvement to be made. This improvement is more likely to come from fundamental research which we described above, rather than from routine tests of present-day trainers.

Gunnery Systems. The Naval Research Laboratory has taken the lead in setting up a Psychology Section in its Fire-Control Division. The group at the Naval Research Laboratory is typical of many groups now springing up to do this sort of work. In the main, the scientists themselves are psychologists, but these experimental psychologists work hand in hand with the engineers responsible for the actual design of equipment. The engineers also build the equipment necessary for the more precise and fundamental studies of tracking behavior.

This group is studying such things as the speed of correction movements made to a visual stimulus. How fast can a man correct a tracking error? How much hunting behavior is involved in getting the equipment back on the right track? Is the time required for correction a function of the magnitude of correction, or is the speed of correction a function of the magnitude? Actually, this research group has found that within quite wide limits, the time required for a correction is independent of the magnitude of the correction. The greater the correction, the faster the movement of the operator, so that total time required tends to remain constant. These are the sorts of problems that are being investigated.

Airplane Cockpits. Toward the latter part of the war, both the Army and Navy became concerned about the design of displays and controls for human use in airplane cockpits. And they each set up groups to work in this general area. Though their work has been drastically impaired by shortages of personnel, it continues vigorously today. The airplane cockpit is not a single problem. Like the Combat Information Center, it is a system of instruments and men, and the varied problems of displays and controls call for many-sided research. In a previous lecture we looked at a few of the facets of this set of problems.

Controls. The human engineering of controls, their design and arrangement, is the subject of fundamental research in many laboratories. Here we can do little more than list the factors that are being studied. One study concerns the shapes of controls that can easily be discriminated. Another, the number of different sizes of controls that can be identified. Another is the basic study of the design of cranks: what size handles they should have, what radii, what resistance, what gear-ratios for different tasks, and how they should be grouped for efficient operation. Other studies include the best position for telephone type switches. Actually there are more than a half-dozen studies in as many different laboratories on one phase or another of the design and arrangement of controls. We will have to see where the present studies take us, before we know how much research will be required to lay down basic rules for engineering application, but it looks now as though substantial gains will be made in the next two or three years.

Speech and Hearing. Though tremendous advances were made during the war in the design of speech-communication systems for best and worst intelligibility, the possibilities are not yet exhausted. Fundamental research proceeds apace, under contract with the Navy, investigating the best ways of packaging speech in radio and interphone systems.

The Psycho-Acoustic Laboratory at Harvard is doing the largest part of that research, but in this field they are not alone. The Bell Telephone Laboratories, in New Jersey, are also involved in this research. These laboratories are probing deeply, for example, into the problem of distortion -- particularly frequency distortion --

and its various effects on communication.

Other problems are being investigated. Do noise-cancelling devices do what they are supposed to do? Does the use of a noise suppressor which suppresses only high-frequency noise really increase intelligibility, or is such a device useful only for listening to worn-out recordings of Bing Crosby?

Another whole area of research which we have not mentioned before is that concerned with the selective intelligibility of different word sounds. Are some speech sounds inherently better than others in the presence of noise, or with a distorting speaker? That work is progressing to the point where we now know that some combinations of sounds -- such as sister, and sewer -- ought not to be used where peak clipping is apt to occur. All that research is continuing, and, in the future, our predictions about intelligibility will be increasingly more precise.

Auditory Detection. We talked some about auditory detection of sonar signals. We know a lot about those problems, but not enough. We still need to know about problems of confusion in identifying sound signals, and about the annoyance effects of certain types of masking noise. But we have already made auditory detection pretty efficient.

Techniques of visual detection have improved just as signally. Now we have the problem of determining which of two methods of presentation is better -- visual or auditory. And, if it is visual, is A-scope presentation better than PPI? Many problems involving sonar are quite different from those involving radar, mostly due to the much slower times. We get into really serious problems of the visual detection of very small areas, and following spiral sweeps, rather than the circular sweep of a radar PPI. The Naval Electronics Laboratory at San Diego is at present thoroughly immersed in these and other problems, and they should be coming up for air in a couple more years.

Auditory Signaling. One currently wide-open set of problems is those related to Flybar -- the use of auditory signals to indicate positional and other information. As you recall, Flybar was developed enough during the war to indicate that it could work, but the best system had not been developed. Our own laboratory is continuing that work, not only in relation to Flybar, but in relation to the more general problem of the use of auditory signals under any circumstances.

We need to know not only what signals can be used -- and that is the main aim of our research right now -- but we need also to know the circumstances under which it is to our advantage to use auditory signals. For example, if a man has to attend and react to only two meter indications, is there any need at all of auditory signals? If the two meter indications are far apart, can audio take over one indication, and let the eyes handle one?

Likewise, is the use of auditory signals limited to cases where simple monitoring is necessary, or can such signals be used for precise adjustment of controls? Can we ever develop Flybar to the point where a pilot can make a perfect turn without looking at his meters? We do not know these things yet.

Or one more question: What about the time it takes to react to auditory signals? Is the time required to make adjustments to an auditory signal in all cases so much longer than the time required with visual signals, that we must limit the use of auditory signals to those cases where only slow adjustments are required? How rapidly can information be poured into the ears as compared with the eyes? These are all fundamental problems, and we can only hope to have the answers some time in the indefinite future.

Visual Displays. When we look to the future with regard to problems of visual displays we find that here again there is much to be done. In our eighth lecture, we found that our basic knowledge about the workings of the eye is fairly complete. We know a lot about the private life of the retina and can predict fairly well when things will be visible and when they will not -- so long as the things we are looking at are fairly small test objects in the laboratory. When we start throwing a lot of small visual objects together in displays, then we find that we cannot predict so well what a man will see and what he will not. Our last lecture, as a matter of fact, asked more questions than we were able to answer.

The perceptual problems associated with visual displays are the ones which need a lot more investigating. When we clutter up the visual field with lots of numbers, pointers, circles, x's and lights, we soon find out we are still in possession of considerable ignorance about seeing. We still do not have the final answer on the legibility of numbers and symbols. We have a few solid facts in this area. We know, for instance, that the S is harder to read than the E. We know that if letters are too thick we cannot see them well. But we need to get beyond these limited specific facts. We need a lot of basic rules and formulae for telling us how we can design the most legible numbers and symbols. Until we have such fundamental principles, research in this area will continue to be an inefficient rat-race of specific tests and comparisons.

We still do not know all the factors that the design engineer needs when he is planning to make a new kind of radar. What kind of phosphor should he use? How big should the radar scope be? How many range rings should there be on it? How fast should the sweep go around? How big should the target pips be? Should the radar scope be round, or would some other shape be better?

Tactical Information. Another group of problems, characteristic of radar systems and CIC, stems from the complicated kind of job we have asked the CIC to do. Somewhere, some time, someone has to know an awful lot of things about the battle scene. He has to know these things in order to make some intelligent decisions about what to do next. Let us look at what he has to know. He has to know where the targets are. This turns out to involve three separate items of information: (1) In what direction, (2) How far away, and (3) How far up? In addition to knowing where, he has to know who. Are the targets enemy or friendly? He has to know How many and What kind. And finally he has to know in what direction the targets are moving.

That makes a total of at least six items of information. Six items of information are not very hard to put on a plot board and remember, so long as these six items of information are concerned with a squadron of slow-moving ships -- or even a squadron of slow-moving planes. But even in this last war we began to approach the limits of human understanding and comprehension in battle. In the Empire strikes, for example, we did not suffer too many casualties so long as the Nips came in from one direction or even from two or three directions. Our radars and our out-moded methods of plotting information enabled us to keep up with the pace of the battle.

Systems Overloading. But, when the Nips started sending in their Kamikaze planes from ten and fifteen directions at once, then we really began to suffer. The system literally broke down because of overloading. In some of our experiments, we found that a good team of men could keep up with and have accurate information on as many as six different raids. But that was yesterday. Our problem is, HOW CAN WE KEEP UP WITH AS MANY AS THIRTY SIMULTANEOUS RAIDS? How can we plot onto a single surface seven items of information for each of thirty separate raids? Even if we had some super gadget to do all the plotting for us automatically, how could three or even four gunnery officers standing around such a plot be able to keep pace with the proceedings?

The problem is not purely a military one. Commercial air traffic has increased nearly seven times in the last five years. Let us look ahead about 50 years and imagine what kind of problem the air traffic control officer at LaGuardia Field will have when a heavy fog settles over the place and 100 planes converge on the field from Mexico, London, Paris, San Francisco, and Albuquerque. How are we going to get all that information to him? How can we present this information to him so that he can see the total picture? There are, after all, only a few channels that we can use in getting this information into his brain.

High Speeds. Then let us complicate the problem some more. We have been talking about horse-and-buggy targets -- targets that crawl along in the sky. Our engineers are now talking about 1800 miles an hour. They are thinking about airplanes that will have travelled ten miles closer by the time you can reach up and wipe the sweat off your brow. What would you do? How would you want this information brought to you, how would you want it displayed, if you were a CIC officer and had 15 targets converging on you at 10 miles a second?

That is the problem of the future. This is a Buck Rogers age we are living in. And we need to look at these problems with a Buck Rogers frame of mind. We need some broad, imaginative engineers and scientists to tackle these problems. In many cases we will need to throw out bodily a lot of nice, simple ways of doing things. We need new, bold, even reckless ways of looking about us. It is natural -- and very dangerous -- to regard as good our existing and habitual ways of going about our business. We must fight against the Maginot-line mentality -- the mentality that clings tenaciously to the old and customary regardless of the changed and forever changing demands of the environment. The fact that the

Declaration of Independence was written in laborious longhand should not make us frown upon the modern typewriter. And the fact that a very recent war was fought and won in one way should not give us too much faith in existing weapons and in the techniques for using them.

In visual displays as in almost everything else, tomorrow will bring differences. A restless, probing, inquiring orientation to tomorrow's problems is the only real insurance against being caught with our plans down.

DANGERS AND HANDICAPS

Lest we wax too eloquent about the possibilities of human engineering in years to come, it would be well to take a good look at the black side of the picture. There is a black side. There are too many conditions prevailing today -- and likely to continue for many years -- which will make progress in human engineering difficult. Let us look at them carefully and with adaptive realism.

Who Shall Lead Them. The first entry in the gloomy side of the register is the problem of personnel. Who is going to do all this research? For some jobs you can go out and choose any warm body and put it to work. But as the job becomes more complicated, the required abilities become rarer and the training becomes more protracted. You are familiar with this situation in the Navy. In research the problem is equally serious -- if not more so.

Good research people have always been scarce. They will probably always continue to be scarce. But the present scarcity is more stringent than ever before, and the stringency is as great or greater in experimental psychology than in almost any research field you can name. There are many reasons for this but here we have time to state only the basic and discouraging fact.

If you went out tomorrow to hire a dozen experimental psychologists to work on a project in psychophysical systems research, you would probably find, if you know one end of an experimental psychologist from the other, that there are not more than a hundred such specialists in the country whom you would consider hiring. Of this small number, you would be lucky to persuade even one to leave his present research and his present commitments. There are already many positions in experimental psychology -- and good ones -- currently vacant. They will remain so for a long time. Many, many important experiments will just not get done until the supply of psychologists catches up with the demand. There is no immediate hope that such an adjustment will happen.

Short-sightedness. Another great danger or handicap in human engineering research is short-sightedness in the use of research funds to support research. In love, people learn very quickly that the longest way around is the shortest way home. But in industry, where the eye is on efficiency and profits, and in government, where the eye is on Capitol Hill, people can not see that what looks like the round-about inefficient way may actually be the most economical in the long run. What we are talking about is the danger that psychophysical research men will be looked upon as testers, who can pull some magical tests out of the hat to test in a hurry some new idea some one has cooked up. Or the danger of asking for pay-offs in immediate applied research. To the practical man who wants an answer tomorrow and is not getting what he wants, the fundamental research man looks like he is just playing around. Many laboratories have been set up to do fundamental research, to produce new ideas, to be scientific leaders, only to have quick-and-dirty work, applied tests imposed upon them, to squeeze out all fundamental research, thus reducing capable research people to dull, hum-drum, unimaginative crank-and-knob-turning mechanics. That can happen to human engineering research too.

Consulting versus Research. Another aspect of the problem of short-sighted versus far-sighted research, is the danger of too much consulting and too little research. This danger takes two forms, one in the buyer and the other in the seller. The buyer -- that is, industry or government -- is prone to pay fancy sums to the man who knows a lot and can give quick answers to pressing problems. Consultants command fancy fees. But both industry and government are inclined not to pay for the process -- that is, research -- by which this information is acquired. Somebody else can pay for that. All too often, the universities which are poor and responsible for other educational problems, are the ones who pay for the increase in knowledge.

Fortunately, there is a great trend beginning before the war and accelerated since the war, for the buyer to support both the fundamental research and the quick answers which are based on it.

The farsightedness of the Office of Naval Research in this respect is to be complimented. To date, this office has gone further in supporting fundamental research than any other comparable private or public agency. But that does not rid us of the danger. For even though great strides have been made, there are many pressures on every side for the funds for research to be turned to those who will perform consultant services -- sell what they know without creating any new knowledge.

The other side of this danger lies in the seller -- the research man himself. He cannot consult and research at the same time. If he gives in to the considerable pressure to be a consultant, he almost inevitably must give up some or all of his research -- and the field suffers in proportion to the competence of the man.

Every Man A Psychologist. Almost every psychologist probably has had occasion to rue the day he chose the profession of psychology. Why? Because everyone else is a psychologist too. The trouble is that everyone, just in the course of growing up, in the course of being an officer, a doctor, or an administrator has had to deal with psychological problems. Each one has made his mind up. Each one has his own private solution to almost every psychological problem. The poor psychologist walks into a conference and finds that each member there has already decided issues which he, as a psychologist, thought he was being called upon to help settle scientifically. This is a great handicap -- and one that most other specialists do not suffer.

The psychologist must very often unsell somebody on a preconceived, armchair answer to a problem before he can win the opportunity to subject the problem to scientific study. This is not good duty. A further danger is that human engineering problems will always be brought to the psychophysical research men too late -- after most of the engineering decisions have been made, when the important matters affecting human performance are no longer subject to change.

A few months ago, for example, some people in ordnance came to us for help. They had decided how many guns there would be, how many remote radars there would be, just how projectors would work in conjunction with each of the remote radar indicators, and many other details of a gunnery system. All of these decisions involved human engineering problems, in fact the important ones in the system. When we asked them what we could do, they suggested that we might help with such questions as whether the markers should be squares, circles or arrows, whether the bearing indicators should employ match dial or pointers or what. All these were minor matters, not having much bearing on the functioning of the total system. Fortunately, what was a frozen design had not been built, and it was possible after some discussion to unfreeze the design to incorporate several changes stemming from human engineering principles. This experience is not unique.

THE NAVY AND PSYCHOPHYSICAL RESEARCH

In closing, we should like to point out the Navy's role in the use of psychophysical systems research. We have been talking all along as though we were the only ones who had anything to say about this research. Actually, as you all know, that is not the truth. You have as much to do about psychophysical systems research as we do, particularly as it applies to naval engineering problems.

Regardless of the applications of human engineering research, the work in the long run has to be a cooperative affair. The design engineer, in industry or the Navy, has the responsibility for actually designing the machine. The human engineer can tell him something about the best way to do it, but the human engineer himself does not do the design work. The particular research laboratory which we represent is concerned primarily with naval problems so let me point out the role you will play in determining the overall success or failure of this program.

Even though we are the ones who give the answers to some problems, you are the ones who put them into use. We may give you spot answers when you ask us questions concerning a very specific piece of apparatus. We also hope to provide general principles which will answer more questions than the spot answers. In either case, you put our work into practice. Some of the equipment you design yourselves, and there it will be easy to put these principles into operation -- after we have dug up enough of them. At other times, you are responsible for okaying the design of civilian design engineers, and there you may occasionally have to fight to keep the design in line with sound principles of human engineering.

Finally, you are naval officers, and we are just civilians. We have no intention of telling you how to run your Navy. That is your specialty. Ours is a specialty of doing research in the area of equipment design and layout. But in the long run, it is the commander of a ship who is responsible for the well-being of that ship. It is, and must be, his final decision about how that ship operates. The best target designating procedure is determined by the officers of the ship, and we can not say anything about the final decision. We can give you good information, however, about the best way to set up your working systems, and the best way to arrange your equipment on a ship. We hope that the information will be of use to you as command and engineering officers. We can only hope that our advice will be of aid to you, and that you will take advantage of the things we find out.

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* Available through Publications Board, U. S. Department of Commerce, Washington, D.C.

"Reprint January 1953,
Publication Press, Inc.,
500 Sands Point"