HUMAN ENGINEERING FOR AN EFFECTIVE AIR-NAVIGATION AND TRAFFIC-CONTROL SYSTEM

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Division of Anthropology and Psychology
Committee on Aviation Psychology
Washington, D. C.

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HUMAN ENGINEERING FOR AN EFFECTIVE AIR-NAVIGATION AND TRAFFIC-CONTROL SYSTEM - AND APPENDIXES I THRU III

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March 14, 1951

Dr. Douglas H. Ewing
Director of Development
Air Navigation Development Board, A-9
Civil Aeronautics Administration
Washington 25, D. C.

Dear Dr. Ewing:

The attached report, entitled Human Engineering for an Effective Air-Navigation and Traffic-Control System, is submitted by the Committee on Aviation Psychology in fulfillment of the obligation undertaken under Contract Cca-28483 between the National Academy of Sciences and the Civil Aeronautics Administration.

As indicated in the Editorial Foreword and elsewhere, the report and the long-range research plan embodied therein are not the work of a single investigator. They are the outcome of joint effort on the part of psychologists, engineers and others who, under the direction of Dr. Paul M. Fitts, The Ohio State University, combined their scientific and technical resources in reviewing past research, in analyzing the human problems in air navigation and traffic control, and in formulating recommendations with respect to research needs.

The report represents a pioneering effort in the way of formulating a long-range integrated plan for human engineering research to parallel and support long range planning for equipment and systems design. It is presented by the Committee on Aviation Psychology with the recommendation that steps be taken by ANDB towards the implementation of the proposed research program under conditions which will provide the closest collaboration among all scientific and technical personnel concerned with the development of an optimal air-navigation and traffic-control system.

Sincerely yours,

Morris S. Viteles, Chairman
Committee on Aviation Psychology

MSV:gnl

According to the author of an early 19th century text book in applied mechanics;-

> "We have been very much occupied in perfecting the machines and the tools which the worker uses in the economic arts. We have hardly attempted to improve the worker himself. However, if he were only considered as an instrument, a tool, a motor, he would necessarily be placed in the first rank of all instruments, all mechanical agents, since he has the immeasurable advantage of being an instrument who observes and corrects himself, a self-stopping motor which functions with the motivation of its own intelligence and which perfects itself by thinking not less than by work itself."[1]

In a broad sense, the viewpoint outlined above has been dominant in the application of psychology to the work-situation during the major portion of the 20th century. In the main, the objective has been to improve efficiency and safety by selecting, training and otherwise conditioning human beings for adaptation to existing equipment and working conditions. Particularly in the design and operation of machines and tools, the emphasis has been upon the adjustment of man to mechanical equipment, rather than upon the adaptation of the machines and tools to compensate for the physical and mental limitations of man as a working instrument.

During the past decade, primarily in response to military requirements, there has been growing withdrawal from this classical psychological viewpoint, and ever-increasing acceptance of the principle that "machines should be made for men; not men forcibly adapted to machines." This basic principle of "human engineering" is not new, particularly to industrial psychologists, although it has been consistently neglected, largely because engineers concerned with the development of the machine and scientists concerned with the individual who is to operate the machine have worked in almost complete insulation from one another. The resulting disregard of physiological and sensory handicaps; of fundamental principles of perception; of basic patterns of motor coordination; of human limitations in the integration of complex responses, etc. has at times led to the production of mechanical monstrosities which tax the capabilities of human operators and hinder the integration of man and machine into a system designed for most effective accomplishment of designated tasks.

The attached report concerns itself with the application of the principles and techniques of human engineering to the improvement of the air-navigation and traffic-control system. Its ultimate objective is to bring about rapprochement between design engineers and "human engineers" with the view of furthering the development of a man-machine system which will yield optimal results in the way of efficiency and safety in the movement of planes over the airways. The report is unique in a number of ways. Instead of dealing with over-all problems of machine and system design, attention is centered on those problems which are specifically pertinent to air navigation and traffic control. Furthermore, the viewpoint and conclusions embodied in the report reflect the mature and enlightened judgment of a large group of psychologists experienced in the field of human engineering who collaborated in its preparation, and the critical reflection of an even larger group of psychologists, engineers and others who reviewed preliminary versions of the report. Of particular significance is the fact that the report presents a long-range program of psychological research, to parallel the program of equipment and system development, which will permit an orderly and integrated solution of the human problems in the design of an optimal air-navigation and traffic-control system.

Although considerable talent and skill have gone into the preparation of the report, it is nevertheless not anticipated that there will be complete agreement with the conclusions reached from the survey of past research and experience. So, for example, questions may be raised concerning the viewpoint that men are extremely poor monitors of machines, and that emphasis might well be placed on the development of systems in which the essential responsibility for monitoring would be placed upon machines. However, the very fact that the issue is raised is, in itself, of importance, particularly since research procedures are available by means of which this basic question can be settled, leading to the establishment of fundamental principles concerning the respective roles of machines and men as monitors on factual grounds.

This and other problems are considered in the report. In fact, among the significant features of the report is a listing of areas requiring investigation in a systematic program of human engineering research, and of illustrative specific problems within each of these areas. In the preparation of the report, consideration was given to the possibility of establishing firm priorities with respect to both areas of research and to specific problems and hypotheses to be examined within each area. An informal survey of opinions of ten individuals who were involved in the preparation and review of the report suggests that *principles governing the efficient visual display of*

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[1] Dupin, Cours de Geometrie et de Mecanique Appliquee, cited from L. Walther, La Technopsychologie du Travail Industriel, Paris, 1926, p. 13.

information; essential information required in an air-navigation and traffic control-system; capacities for handling information in communication systems and maximum application of existing human engineering information represents areas which have high over-all priority ratings, in which a high level of research effort is needed, and which present the likelihood of important results and applications. On the other hand, *optimum conditions for the use of direct vision* is an area given a low over-all priority rating in terms of the initiation of research recommended in the body of the report. However, in spite of such ratings, there are diversities of opinion, and it appears to be the general view of those involved in the preparation of the report that the question of priority is one which can be settled only on the basis of detailed consideration of the immediate plans of ANDB; of available funds; of expenditures involved in projects of various types, and of similar items.

Comments prepared by a number of readers have focussed attention on the importance of the criterion problem. Safety and efficiency are described as the basic requirements of an acceptable air navigation and traffic control system. This means that the effectiveness of every link in the man-machine systems and the system as a whole must be evaluated to determine what it contributes to the satisfaction of these and, possibly, of other requirements. This, in turn, involves a consideration of the criterion situation, in terms of techniques available for the reliable and valid measurement of performance and of methodological problems involved in the development of new and more adequate criteria. In many ways, the problem of arriving at adequate criteria is at the core of the application of human engineering research techniques to the design and operation of an optimal air-navigation and traffic-control system. This problem is referred to throughout the report, and also in an Appendix, but the area is one which requires even more extended consideration as a preliminary to the design and initiation of specific studies within the long-range program of human engineering research described in the report.

The report, and the recommendations embodied therein are written from the viewpoint of human engineering, which is concerned primarily with the formulation of plans governing the design of machines for efficient human use, and with the effective integration of men and machines for the accomplishment of an over-all task. It seems well to note, however, as suggested by one reviewer of the report (T. Gordon), that "unlike machines, the output of the human is not always simply a function of input, the human system is affected by many factors other than the quality and quantity of informational data received through his senses. Human engineering, if it is to escape the dilemma of the old time and motion study engineering, must guard against exclusive use of the 'machine' model in its theory of human behavior." In other words, even the most effective program of human engineering does not eliminate the need for continued research on the selection and training of air navigation and traffic control personnel; on problems of morale and motivation; on the development of improved supervisory techniques; on the elimination of excessive fatigue and monotony, and on other human problems which arise in the work situation. It seems extremely probable that great gains in the efficiency of an air navigation and traffic control system can be secured through continued research on such problems, and planning in this direction must also be considered as part of an over-all program for the maximum utilization of human resources in the air navigation and traffic control situation.

Inherent throughout the report is a plea as well as a plan for active cooperation between engineers who design machines and scientists who study human behavior. This report will not have served its major purpose if it results merely in more or even better planned psychological research. Its purpose will be completely accomplished only if the research undertaken is conducted at the inter-disciplinary level, so that the ideas and experiences, the talents and insights of engineers, psychologists, applied mathematicians and other scientists; of pilots and controllers; etc. can simultaneously be focussed upon the development of improved equipment and man-machine systems optimally designed for efficient and safe air navigation and traffic control.

M. S. Viteles, Chairman
Committee on Aviation Psychology

March 14, 1951

PREFACE

The project that has led to the present report was first discussed in December, 1949, by Dr. Morris S. Viteles, Chairman of the NRC Committee on Aviation Psychology, Dr. Dean R. Brimhall, Assistant for Research to the CAA Administrator, and the Editor. Plans for the project were formulated in greater detail during the following six months at NRC Committee meetings and at conferences of the Editor with the Air Navigation Development Board and other agencies. Full-scale work began in June, 1950, under a contract between the National Research Council and the Ohio State University Research Foundation, with funds provided by the Air Navigation Development Board.

The report has been prepared primarily by a working group of ten psychologists, who are listed as joint authors. Each of these men is actively engaged in research in some area of aviation psychology and/or human engineering. They represent six private and two Government laboratories, and between them combine experience in all of the areas covered by the report.

The working group met at intervals during the summer of 1950, to study the long-range plans of the ANDB, and to familiarize themselves with operational problems, and with current research and development activities in air navigation and traffic control. In addition, individual members of the group visited various manufacturers, operational facilities, Government and private agencies, and conferred with members of various committees and professional societies. Late in August the group met for ten days of intensive planning and writing. The first draft of the report was written during this period.

Some degree of specialization and allocation of responsibility was necessary in collecting background information and in writing the different sections of the present report. However, the report is truly a group effort. The authors neither desire, nor believe that it is possible, to assign credit for individual chapters to particular individuals.

The report has undergone three major revisions since the first draft was prepared. The first revision included detailed changes recommended by the members of the working group. Subsequent revisions were made on the basis of suggestions of invited critics, a group that included psychologists, biological and physical scientists, and other specialists, in universities, Government agencies, and private organizations. Several of these critics made significant original contributions to various sections of the report. Their criticisms were extremely helpful in many respects, and have added much to the report.

The several drafts of the report were also reviewed by the members of the Committee on Aviations Psychology. The final form of the report, especially the recommended research program, benefitted greatly from the discussions at committee meetings. The editor also received valuable suggestions from the Committee as to qualified individuals who might be invited to serve as members of the working group and as expert critics.

In summary, the report represents the considered judgments of ten specialists in various areas of psychological research, plus the suggestions and criticisms of over twenty-five other experts in various fields of aviation, engineering, and research. Whatever beneficial influence the report may exert on future research will result largely from the fact that so many people of diversified competencies have contributed to its preparation.

Columbus, Ohio
March 14, 1951

Paul M. Fitts
Editor

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The members of the Working Group that planned and wrote the present report, and their respective laboratories, are listed below. These individuals are responsible for the overall organization and content of the report.

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The following individuals made significant original contributions to one or more sections of the report.

T. G. Andrews, Department of Psychology, University of Maryland, College Park, Maryland (Appendix III, The Criterion Problem)
David Bakan, Department of Psychology, University of Missouri, Columbia, Missouri (Contributions to Chapter VI, Problems of Direct Vision from Aircraft)
J. W. Black, Department of Speech, The Ohio State University, Columbus, Ohio (Contributions to Chapter VII, Voice Communication)
H. R. Blackwell, Armed Forces - NRC Vision Committee, University of Michigan, Ann Arbor, Michigan (Contributions to Chapter VI, Problems of Direct Vision from Aircraft)
Robert Miller, American Institute for Research, Pittsburgh, Pennsylvania (Contributions to various sections)

One or more of the early drafts were read by the following invited critics, who submitted evaluations and detailed suggestions for changes that were used in preparing the final report.

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Among the members of the NRC Committee on Aviation Psychology, the editor wishes especially to acknowledge the assistance of Dr. M. S. Viteles, the Chairman, and Dr. D. R. Brimhall, of the CAA, who advised, assisted, and encouraged the staff throughout all stages of the project.

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The editor also wishes to acknowledge the assistance provided by the Director and staff of The Ohio State University Research Foundation. From its inception the Foundation conceived of this project as a unique undertaking in research planning, and provided the administrative facilities that made it possible to draw on the scientific resources of the entire country in preparing the present report.

Columbus, Ohio
March 14, 1952

Paul M. Fitts
Editor

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SUMMARY

A. THE PURPOSE AND CONTENT OF THIS REPORT

In this report we submit proposals for a long-range program of human-engineering research on problems met in planning and designing equipment for an air-navigation and traffic-control system.

Content. We begin with a brief analysis of the essential functions of the air-traffic control problem. We then consider the basic question: Which of these functions should be performed by human operators and which by machine elements? Next we systematically review the status of knowledge concerning major areas of human capabilities as they relate to air traffic control. We end with a discussion of the application of research findings.

For the convenience of the reader the recommended research program is reproduced in a self-contained section which follows this summary.

Human-engineering research, as treated in this report, aims to determine man's ability to receive and transmit information, to make and execute decisions. It also aims to provide principles governing the design of tasks and machines in relation to man's capabilities, and to insure an efficient integration of men and machines for the accomplishment of an overall task.

For Whom Written. The report has been written primarily for (1) the Air Navigation Development Board, (2) professional psychologists, and (3) engineers and other professional people in the Civil Aeronautics Administration, the military services, the airlines, and industry. For these three groups, respectively, it is intended **(1) as a guide to research planning and budgeting, (2) as a survey of practical and theoretical psychological problems, and (3) as an overall view of the scope, methods, and applications of research on the human factor in the design of an air-navigation and traffic-control system,**

B. SOME BASIC PROBLEMS AND ASSUMPTIONS

Effective *long-range* planning must not be bounded by the problems of particular equipments and procedures in use today. At the risk of over-simplification, we have reduced the air-traffic-control problem to two basic requirements: *safety* and *efficiency*.

Opportunities for Exercising Control. Flights can be regulated by means of (1) take-off control, (2) enroute control, and (3) terminal-area control. The three methods have different potentialities, which are discussed in Chapter II. It is our conclusion that the greatest gains in safety and efficiency will be made in the next decade by solving the problems of terminal-area control.

Some Basic Initial Problems. It is possible to devise a fully automatic control system, with man serving chiefly as a monitor, or a system that will place primary responsibility in the hands of human operators, who would be assisted by effective data-analysis, data-transmission, and data-display equipment. To help in forecasting the most profitable direction in which overall planning should proceed, we have tried to provide, in Chapter III, some general answers about what men can do better than machines, and what machines can do better than men.

Men Versus Machines. It is our conclusion that humans appear to surpass present-day machines in respect to six abilities which are denoted as (1) detection, (2) perception, (3) improvisation, (4) long-term storage, (5) induction, and (6) memory. In like vein we conclude that present-day machines appear to surpass humans in respect to the following: (1) speed, (2) power, (3) routinization, (4) short-term storage, (5) deduction, and (6) performance of simultaneous operations.

Monitoring. We suggest that great caution be exercised in assumming that men can successfully monitor complex automatic machines and take over if the machines break down. Engineers should seriously consider systems in which machines would monitor men and prevent them from making dangerous mistakes.

Overloading. Both men and machines are likely to break down or become unstable if overloaded. However, in some ways humans may do a better job than machines under overload or stress conditions arising on the job--at least they may supplement machines in this regard, especially in situations where flexibility is an asset.

Flexibility. One of the greatest advantages of including human elements in a system is increased flexibility. For example, a proficient and well-trained human operator usually can adapt readily to the introduction of new equipment, to the sudden failure of equipment, or to the occurence of a unique and unforeseen problem.

C. A BASIC ANALYSIS OF THE HUMAN OPERATOR AS PART OF A COMMUNICATION SYSTEM.

Decision making, or choosing a course of action, lies at the root of the whole control problem. Decisions, in turn, depend on what information is available and how well it is assimilated. In Chapter IV we consider the information-handling capacities of the human operator, using concepts borrowed from modern communication theory. Research stimulated by this new orientation will, we feel sure, provide immensely useful results.

The Rate of Flow of Information. The flow of information to and from the human operators in a system depends on the way messages are encoded--the form which the information takes, the sensory channel through which it is received, the ratio of potential to needed information, and organization of the information.

We are certain that human operators will perform most efficiently only if the rate of flow of information falls within definite limits, but at the present time we can only make general estimate of what these limits are.

Perturbation and Redundancy. We must also consider perturbation--disturbances in the flow of information--and redundancy. For example, there is reason to believe that the exact repetition of a visual or auditory message is one of the least satisfactory ways of insuring its correct reception by a human operator. In short, redundancy should be achieved by repeating a message in a different way.

D. VISUAL INFORMATION DISPLAYS

We have used the term *visual displays* to include all those devices that exhibit information to the eyes. Chapter V is devoted to research problems relating to the design of such devices. The space which we devote to this topic is a direct indication of the weight we attach to it.

Pictorial and Symbolic Displays. Pictorial displays are easy to interpret and are especially adapted to the portrayal of relational information. On the other hand, they lack the accuracy of symbolic displays which are especially suited to the presentation of the discrete or single-item type of information. Still inadequately understood, however, are the general rules governing the many uses of these two kinds of displays and combination types. Enough work has already been done, however, to indicate that improvements in speed and accuracy of interpretation ranging from 100 to 1000 per cent are possible as a result of human-engineering research.

Displays for Transitory Data. One of the problems of displaying ever-changing, transitory information is the question of simplicity vs. complexity. We believe that there is an optimum amount of information that should be included in any one display, but the rules for achieving this optimum are not well understood.

A problem of special importance is the best way to display *the position and movement of objects in three-dimensional space*. Especially significant in this connection are recent findings which show clearly that novices can interpret the artificial horizon and *ILAS* indicators faster and with fewer errors if the motions are exactly reversed from those employed in present-day instruments.

Displays for Status Information. Displays of status information include maps, charts, and printed messages. Our inquiries show wide dissatisfaction with present weather maps. Pilots have difficulty in sorting out information they want from irrelevant data. They forget much of the information they need. They have difficulty understanding the symbols in which standard messages are coded.

Special Ground and Air Display Problems. Some display problems are especially critical for the ground controller and some for the pilot. For example, the pilot often acts as an error-reducing servo as he keeps his aircraft in stable flight. He responds to position, rate, and acceleration information. He compensates for his own time lag, which experiments in the air have shown may amount to as much as 1.5 seconds when he suddenly has to re-orient. The size, sensitivity, damping and direction-of-motion of his flight instruments are critical variables in this special air-display problem.

E. PROBLEMS OF DIRECT VISION FROM AIRCRAFT

Even with extensive use of electronic aids and automatic equipment, direct vision will continue to be an important factor in air travel, especially for landings at marginally-equipped airports, and for landings made by light aircraft carrying minimum equipment.

In Chapter VI we discuss three important groups of problems in this area: (1) Airport lighting and marking, (2) the adequacy of vision from the cockpit, and (3) the measurement of visibility in terms of what the pilot will see.

One of our conclusions in this section is that in view of the cost, the difficulty, and the hazards of trying out a great many different airport lighting systems by means of flight tests, further field trials should be deferred until adequate basic experiments on factors influencing visual orientation be completed by means of good flight simulators.

F. VOICE COMMUNICATION

Because it provides the quickest and simplest means of requesting and of providing many kinds of information, voice communication always has been, and probably will continue to be, an essential element in air navigation and traffic control. In Chapter VII we discuss some critical aspects of this topic.

Psychological Requirements for Voice-Communication Equipment. Voice-communication equipment is one of the weakest links in the present system (*see especially the results of our study reported in Appendix II*). Our inquiries suggest that the reasons for this state of affairs are to be found in inadequate engineering and in economic factors, rather than to lack of human-engineering data.

Improving the Voice Signal at its Source. There are several ways in which the design of communication equipment interacts with the speaker so as to affect his voice signal. For example side-tone--the experience produced by the speaker hearing his own voice--affects the intensity of the speaker's voice and the way he enunciates words. Such effects are worthy of more research.

The Eye Versus the Ear. We conclude Chapter VII with a comparison of the eye and ear as a means of communication. We conclude that the eye is maximally useful in judging spatial properties, or in obtaining information that can be displayed in spatial terms. The eyes can also search through information and single out appropriate items for attention (as from a table of data). The ears are generally superior in situations where time of occurrence, or rate of change, are important variables.

For most situations, however, the question of whether to use the eyes or ears is less important than such questions as: Is the information encoded in its most useful form? Does it have to be transformed before it is used? Should redundancy be introduced by providing a signal to both the eyes and the ears?

G. SYSTEMS RESEARCH, ANALYSIS, AND EVALUATION

Too often in the past important decisions about complex man-machine systems have been reached on the basis of hunches, guesses, and opinions. Even when systematic investigations were undertaken, the results often were inconclusive because the experiments were improperly designed and poorly controlled. In Chapter VIII we undertake to show that it is possible to obtain valid, objective results in experiments on man-machine systems.

Kinds of Systems Studies. System research tries to discover general principles that can be applied to the design and development of new man-machine combinations. *System analysis* aims at the measurement of the relative magnitudes of the errors contributed by the various sub-systems, and the arrangement of man-machine elements in their most efficient combination. *System evaluation* measures the efficiency of a total system so that it can be compared with other systems.

Sources of Error in Systems. One of the first steps in a system study is to identify the kinds of errors present and to locate their sources. We can distinguish four kinds of errors: *Qualitative errors* are errors of kind; *quantitative errors* are variations in amount; *temporal errors* are delays in a system; and *sequential errors* are those that occur when an operation is performed out of its proper sequence, or out of its most efficient order. In many contexts variability and error are synonymous.

Tests to Breakdown. Tests to breakdown are an important feature of system studies. The necessity for such tests is perhaps obvious. System A may perform slightly better than system B as long as the load on the system is relatively light, but with heavy traffic loads and excessive stress system A may break down completely whereas system B may still be capable of handling some information. For example, a human operator, while unable to do as much as an automatic system when the latter is functioning properly, may turn out to be superior under disaster conditions.

Qualifications for Human-Engineering and Systems Research. Special qualifications are needed by the persons who are to conduct human-engineering experiments. We review these qualifications in Chapter VIII. We also point out that many human-engineering investigations, especially those concerned with complex man-machine systems, call for a research team including men specialized in operating problems as well as in research.

H. CRITERION PROBLEMS

Requirements such as *safety* and *efficiency* define the goal, or *ultimate criteria,* for which the system is designed. However, the researcher usually cannot deal directly with ultimate criteria but must seek intermediate or proximate indices-of-merit for various parts of the system.

We discuss criterion problems at many places in the report and in Appendix III. We also stress the importance of determining what essential information is needed at each stage of control and for each subsystem, and how this information is used.

It is essential that intermediate criteria be related to, or predict, the ultimate criteria. They must reflect critical aspects of particular functions, aspects that contribute significantly to overall system performance.

Intermediate Criteria of Efficiency. Speed and accuracy in making specific decisions are two commonly used indices of efficiency. However, several other efficiency measures are available. One is the absence of *variability*. Another is the amount of *overloading* that can be tolerated before a process breaks down. *Manpower criteria* are also especially important.

Intermediate Criteria of Safety. Much work needs to be done in relating various sub-criteria to the ultimate safety of a control system. Speed and accuracy in making certain types of decisions, such as decisions to commit an aircraft to a landing, and the degree of precision required in certain types of information, such as weather data, need to be related to accident probability. Data are needed on how much each sub-system contributes to overall safety. At present, intermediate criteria of safety are not as well established as are those of efficiency.

The development of adequate criteria or indices-of-merit is a crucial aspect of human-engineering research, and one that deserves special emphasis.

I. PUTTING HUMAN-ENGINEERING DATA TO USE

The final step in an applied research program is the application of research findings to practical problems. Chapter IX reviews available ways of closing the gap between research and application.

Different methods of communicating research findings to engineers can be employed to advantage at different stages in the planning, designing, developing, and testing of equipment and systems. For example, published reports and handbooks reach a large audience and are readily available; but face-to-face contact with consulting or full-time specialists probably provides a more effective exchange of information and ideas.

In some instances the people who do research should be brought in as consultants on practical problems. In other instances it may be desirable to call on the staffs of consulting firms, who combine knowledge of the research literature with a wide grasp of the many practical problems faced by the project engineer.

J. IMPLEMENTING THE RECOMMENDED RESEARCH PROGRAM

An Intrегrated Program. One must never lose sight of the relation of specific problems to the overall system. For example, the optimum design for a new navigation display will be determined in part by the principles embodied in the design of other navigation and flight instruments.

Long-Range Objectives. We believe that many of the most important human-engineering problems of air-navigation and traffic-control will be solved only if continued support is given to long-range research. Therefore, in formulating the research objectives presented in this report, we have emphasized long-range goals, rather than immediate problems that are most pressing at the moment.

Research Facilities and Personnel. Facilities for research in the human-engineering field are limited, and there are relatively few scientists who are now trained to conduct research or to do consulting work in this area. However, continued support of a long-range research program should do much to stimulate the development of adequate research facilities, and to attract able young scientists into this important new field of research.

Research Planning a Continuing Process. Research planning, especially in a field as new as human engineering, must be a continuing process. The further definition of problems should be made a part of nearly all research projects.

Related Topics. This report does not deal directly with the many problems of personnel research - selection, training, manpower utilization, working conditions, and maintenance of proficiency. Nonetheless, the number of persons required to operate and maintain a system, and the difficulty of selecting and training them, are important factors that should be considered while a system is in the planning stage.

Related Research Programs. Many of the basic psychological problems that we have formulated are very broad. This is fortunate. It means that much of the information gathered in human-engineering research on other systems will support the program recommended here, and the latter will, in turn, supplement many of the human-engineering research programs already being supported by government agencies.

Concluding Statement. We are convinced that the human-engineering research program outlined here should fill a crucial gap in the development of an improved air-navigation and traffic-control system. This program should be promoted **(1) by giving additional support to the work of in-service laboratories that have human-engineering divisions, and (2) by supporting an extensive program of long-range contract research.**

THE RECOMMENDED RESEARCH PROGRAM

Recommendations for research are organized under nine broad Research Objectives and twenty-one specific Problem Areas. We believe that these recommendations, together with the discussions and summaries in the text, are sufficiently detailed and yet are framed in sufficiently broad perspective to permit the Air Navigation Development Board, its associated agencies in the Air Force, the Navy, and the CAA, and prospective contractors, to carry out an effective and integrated research program - a program that gives proper emphasis to research on specific problem areas as well as research aimed at a basic understanding of the capacities of human beings in complex communication and control systems.

Research Objective I. Determination of the Relative Abilities of Men and Machines to Perform Critical Functions in Air-Navigation and Traffic-Control Systems.

Basic research should be supported to provide the principles on which decisions about the most effective roles of men and machines can be based. The decision to develop a machine that will perform a certain operation usually implies a prior decision that a machine can do the job better, faster, or more reliably than a man. At the present time there are few rules that can be followed in reaching such decisions. Information is needed about such general topics as these:

a. What standards or norms of human performance can be expected when men are assigned certain air-navigation and traffic-control tasks and how much variability will there be between individuals in the performance of these tasks?

b. To what extent will the various human tasks require unusual human capacities and long training programs?

c. How can human performance be measured in terms that will permit the meaningful comparison of the effectiveness of men and of particular machines when carrying out certain tasks?

Collection and synthesis of known facts about human abilities will help to establish some of the needed principles. Some of the information necessary for answering additional questions can be obtained from existing records or can be collected during routine operations. In other instances it may be necessary to conduct extensive experiments to establish some of the principles that are needed in this area.

Illustrative Research Problems. In this report we have advanced arguments in support of the hypothesis that men cannot efficiently monitor automatic equipment. This hypothesis needs to be tested in various work situations, and it may be that the answer can be found by careful surveys of typical industrial situations, such as power plants or military lookout posts, where men are now employed as monitors. As *another example,* in this report we propose the hypothesis that under certain circumstances men may function better than machines under conditions of overload and stress. This hypothesis needs to be validated, and again the answers may be forthcoming from a careful analysis of records from the operation of automatic machinery, such as dial telephone systems, during wartime conditions, floods, partial power failures, etc.

Research Objective II. Determination of the Capacities of Human Operators for Handling Information in a Communication System.

To insure the effective integration of men and machines, it is necessary to establish some general principles governing the nature of the operator as a link in a control or communication system. Decision-making, choosing a course of action, lies at the root of the whole control problem. The selection of the correct course of action, in turn, depends on the information available. As one aspect of the research program, therefore, we recommend the study of human capacities for handling information and suggest that this study be approached from the viewpoint of communication theory.

Problem Area 1. Factors Influencing the Rate of Flow of Information. Studies are needed to determine the information-handling capacity of human operators. This capacity should be measured with reference to such factors as the way in which the information is encoded, the sensory channel used, the regularity or spacing of messages in time, the effects of mixing relevant with irrelevant information, and the effect of increasing the total amount of information required for a decision.

Illustrative research problem. Test the following hypothesis:[1] The presence of irrelevant information retards the rate with which a pilot or ground controller can handle relevant information.

Problem Area 2. Redundancy. Studies are needed to determine the optimum amount and form of redundancy that will insure the fewest errors by a human receiver of information.

Illustrative research problem. Tests of the following hypothesis are needed: The literal repetition of a visual or auditory message is one of the least satisfactory ways of insuring its correct reception - redundancy should be introduced by repeating a message in a different way.

Problem Area 3. Methods for Measuring Human Information Handling Capacities. Since this is a relatively new research field support will have to be given to the development of improved methods of measurement in areas mentioned. We have so little data to go on that our statement of this problem area is general in nature.

Illustrative problems. Messages used in current traffic-control operations should be analyzed in an effort to define basic message units. Units of measurement should be developed that will facilitate quantitative comparisons between such widely different means of communication as verbal language, printed language, abstract visual symbols, and scale-and-pointer patterns.

Research Objective III. Determination *of the Essential Information Required at every Stage in the Operation of an Air-Navigation and Traffic-Control System.*

Systematic studies are needed to determine the essential information required for making the decisions and carrying out the various tasks involved in navigating and in controlling traffic. Such analyses are needed in connection with most of the technical objectives that follow. These studies should include experimental investigations in the laboratory, job analyses, system analyses, operational analyses, and field studies of certain existing operations. They should cover both transient and status information and the information needed both by the ground controller and the pilot. They should be made for specific existing systems, and also, in so far as possible, for the basic functions common to all systems.

Illustrative research questions. What does a pilot need to know about weather? What information is essential in a pictorial display for airport taxi control? What information is essential in order for a pilot to orient by means of ground lights? What is the relative frequency of different types of air-to-ground messages such as "command-type" and "information-type" messages? What information should be included in a Human Engineering Handbook?

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[1] We have included at least one example under each problem area to illustrate the kind of research recommended. In many cases we state the example in the form of a specific hypothesis that can be subjected to experimental test. We do not imply, when we state such hypotheses, that we expect the tests to support the particular hypothesis more often than to reject it - in other words the fact that the hypothesis is stated in the negative or in the affirmative has no significance. We have selected as illustrations problems that we consider to be important, but we do not wish to imply that those particular problems are necessarily ones that should be given highest priority in each area. In the body of the text can be found many other examples of specific problems that need to be solved.

In specifying information needs research should answer such specific questions as the following:

a. What information is needed?
b. With what accuracy is it needed?
c. How much time is available to use it?
d. What decisions will be made and what actions taken about it?

Research Objective IV. Establishment of Criteria and "Indices-of-Merit" for Human-Operator and Man-Machine Performance.

The criterion problem arises in connection with all of the research problems dealt with in this report *(see Appendix III)*. The answer to the problem begins with the determination of a theoretical ideal level or "model" of desired performance. This ideal model should define the ultimate criterion for the system. Unfortunately, it is not often that the research worker can relate his experimental data directly to such an ultimate criterion. Instead he must make use of proximate or intermediate criteria or "indices-of-merit."

The development of satisfactory intermediate criteria is an important problem. At this level we deal with parts of the system, sometimes even with single instruments and specific ways of using them. It is essential not only that we measure the effectiveness of these specific operations, but that we relate our measures to the higher order or ultimate criteria in terms of which the entire system is being designed.

Investigators in the field of human-engineering have made some progress in establishing criterion measures. However, many new criterion problems arise whenever research is undertaken on a new system.

It is our belief that the criterion problem cuts across every aspect of human-engineering research, and that almost every investigator must devote careful thought and expend some research time on the criterion aspects of his special problem. We believe accordingly that it may be misleading to break up this general topic into specific problem areas and so we list no specific problem areas here. The criterion problem should be studied as an important aspect of each of the other research objectives.

Illustrative Research Questions. Questions illustrating the criterion problem can be grouped under three headings:

a. Questions about ultimate criteria: How can the ultimate objectives of a system be formulated more specifically and quantitatively? For example, is runway utilization the best single ultimate criterion of the efficiency of a traffic-control system?

b. Questions about intermediate criteria: What are the most satisfactory measures of the effectiveness of a communication system? A display system? An airport lighting system? How do the measures of the effectiveness of each of these systems relate to the ultimate criteria? For example, are pilot eye movements an index of the effectiveness of a proposed instrument-panel arrangement, and how do eye movement measures relate to the accuracy of instrument flight, to safety, etc.?

c. Questions about techniques of criterion development: What are the best methods of collecting data on what human operators do on the job? What are the best methods for determining the reliability of these measures? What are the best methods for determining the interrelations between intermediate criteria, and the relations between intermediate and ultimate criteria? For example, what is the most reliable method of obtaining and reporting information about accidents and near accidents?

Research Objective V. Determination of Principles Governing the Efficient Visual Display of Information.

A good display is one that facilitates the flow of pertinent information to a human operator.

The principles governing the design of such displays are still incompletely understood and much work is needed in this area.

Problem Area 1. Simplicity versus Complexity of Visual Displays. Studies are needed to determine the relative advantages of displaying a given amount of information (a) by means of a number of relatively simple instruments, and (b) by means of a single complex instrument. We propose as a general hypothesis that there is a limit to the amount of information that should be crowded into a single display. Research is also needed to determine the maximum number of different ways in which related information can be encoded and presented simultaneously.

Illustrative research problem. If one wanted to depict, by means of a symbol on a cathode ray tube, four things about an aircraft, it would be possible to do this by using the color of the symbol to depict one thing, its size another, its brightness another, and its shape still another - (its position, of course, would provide information along two additional dimensions.) Studies should be made to determine whether a controller can respond effectively to symbols which are categorized simultaneously in as many different ways as these.

Problem Area 2. The Display of Spatial Relations. Studies should be made to determine principles governing the effective display of information about the relative position of aircraft and ground objects in tri-dimensional space. Numerous questions of great practical importance must be solved in this problem area. These include the following:

a. *What coordinate systems and what type of projections should be used in showing spatial relations on bi-dimensional pictorial displays?*
b. *How should information about spatial relations be encoded on symbolic displays?*
c. *What combinations of symbolic and pictorial displays are most effective?*

Illustrative research problem. Test the following hypothesis: In a semi-pictorial airborne approach and landing display it is better to show azimuth and elevation pictorially, with range presented symbolically, than to show azimuth and range pictorially with elevation presented symbolically.

Problem Area 3. Coordination of Displays and Controls. Studies are needed to determine the display characteristics that are necessary when the action taken in response to displayed information is a manipulation of controls, and when this movement in turn results in a modification of the display.

This problem area is particularly critical for the pilot. The pilot sees the movement of displays relative to his own eye and the rest of the cockpit; yet he must interpret this information in terms of the movements of his aircraft relative to the earth.

Problems which arise here involve direction-of-motion relations between displays and controls, the question of what is responded to - displacement, acceleration, or some higher order, and the optimum sensitivity of displays. Such problems have been receiving some research attention, but as yet few general design principles have been established.

Illustrative research questions. Should flight instruments be designed in accordance with the "fly-to" or "fly-from" principle? In a pictorial display of the aircraft's track over the ground should the aircraft appear to move and the ground appear to remain stationary, or should the aircraft's location appear fixed and the ground appear to move? When should azimuth stabilization and when should heading stabilization be used? How accurately can controls be positioned in response to derivative information? What is the optimum sensitivity for a heading or bank indicator? Principles that will settle questions of this sort must be established to achieve the level of pilot performance required for precise navigation and traffic control.

Problem Area 4. Displays for Quantitative Reading. Studies are needed to determine principles for designing displays so as to increase precision, and reduce the incidence of gross errors,

in reading scales. Considerable research has been completed on scale reading precision, and on the nature and magnitude of interpolation errors, but relatively few studies are available on the origin of gross errors such as "reversal" errors, and on ways of minimizing such errors.

Sources of possible confusion in shifting from one instrument to another, or in interpreting different kinds of scales, should be investigated thoroughly. The potential value of studies planned to eliminate the causes of gross errors is indicated by the results of recent experiments which showed that by changing the face of the conventional altimeter the frequency of 1000-foot errors could be reduced by a factor of more than 10.

Illustrative research problem: Determine whether the principles of combining a single sensitive pointer and a counter to provide a "long scale" instrument can be applied generally in the design of many different kinds of instruments.

Problem Area 5. Displays for Check-Reading and Monitoring. Studies are needed to determine principles governing the display of simple yes-no information so that the eye can quickly detect deviations from a null or desired condition, picking out a deviating instrument from among a large number of normally-reading instruments. We have expressed doubts about the suitability of a human operator for most monitoring tasks. However, there will continue to be many jobs in which pilots and ground controllers will devote part of their time to check reading, which is an aspect of monitoring. It is essential that they have properly designed displays for this purpose.

Illustrative research problem. Conduct test of the following hypothesis: There is an optimum visual angle for viewing any monitoring display, and speed and accuracy of check reading will be impaired if display size is too large or too small.

Problem Area 6. Display of Status Information. Studies are needed on methods of encoding and displaying weather information, on ways of representing landmarks and terrain features on maps, and on ways of summarizing information on charts and display boards. Much improvement can and should be effected in this problem area. A few projects are being supported by the military services, but these should be supplemented by studies relating especially to the traffic controller and civilian pilot.

Illustrative research problem: How should the changing weather picture be displayed so that it is readily available to the pilot in the form in which it is needed?

Research Objective VI. Determination of Optimum Conditions for the Use of Direct Vision.

Even with extensive use of electronic aids and automatic equipment for all-weather flying, direct vision will continue to be an important factor in many flight conditions, especially for flights to small, marginally-equipped airports, and for light aircraft carrying minimum equipment. Therefore, some research should be continued on problems of direct vision.

Problem Area 1. Airport Lighting and Marking. Systematic studies should be made of such questions as the following:

a. *What cues are most important in permitting a pilot to orient with respect to the runway when he sees a pattern of lights from the air?*
b. *What is the best way of indicating position along the runway?*
c. *What factors influence ability to shift quickly from instruments to ground displays, and from ground displays to instruments?*
d. *What is the interaction between approach-light design and the design of cockpit instruments?*

We believe that work on these problems should be carried on chiefly in the laboratory, through the use of simulators. However, this should be accompanied by some carefully planned flight test work to check on the validity of the criteria employed in the laboratory research. (see Research Objective IV).

Problem Area 2. Vision from the Cockpit. Studies should be continued to determine by scientific means the required field of view from the cockpit, and the required quality and angle of transparent sections. The efforts of the CAA Technical Development and Evaluation Center along these lines should be supported. Every effort should be made to see that manufacturers meet the vision requirements that are already known.

In addition to studies of requirements for direct vision through the windscreen, the possibility of providing supplemental views of the terrain and other aircraft through the use of reflective or refractive optical systems should be investigated. Such studies will be closely related to those on the use of pictorial displays of space relations (such as television displays.)

Illustrative research question. How does the accuracy of manual landings in marginal weather vary as a function of the field of view through the windscreen?

Problem Area 3. Measurement of Atmospheric Transmission. Studies should be continued to determine better ways of measuring and predicting the conditions of visibility that will exist during a landing approach, and of improving visibility through the choice of the type and spatial distribution of energy in airport light sources.

Illustrative research problem. What ways of measuring visibility from the ground agree most closely with actual visibility of airport lights from the cockpit of an approaching aircraft?

Research Objective VII. Determination of the Psychological Requirements for Communication Systems.

Communication is an essential element in air navigation and traffic control. Many of the psychological requirements for good communication systems are already known. However, some of these have not been implemented on the technical side, and some important questions of communications still lack psychological answers.

Problem Area 1. Improvement of Voice Transmission. Studies should be made of several special listening and speaking problems. Ways of improving the production of voice signals through the control of side tone should be investigated. The efficiency of listening with one ear should be investigated under a variety of masking and distracting conditions. Studies employing both acoustical and psychological methods, should be made to discover the effect of a small enclosure on the human voice

Illustrative research questions. When using an oxygen mask or a noise shield, why is the loss of intelligibility greater than would be expected on the basis of physical measurements of the enclosures alone? Can one of two competing conversations be heard more or less effectively when both ears hear both, or when each ear hears only one?

Problem Area 2. Improvement of Message Formulation. Studies should be made to determine optimum ways of formulating or encoding messages for transmission by voice or other means. The requirements of both the speaker and the listener should be considered. This topic, and the related one of encoding information in relation to the action to be taken, call first for the kind of basic research on human information-handling capacity recommended under Research Objective II.

When methods have been developed for measuring the information-handling capacity of the human operator, tests should be made in a wide variety of situations to establish more clearly the optimum design of presentations using visual and auditory inputs.

Illustrative research problems. An international language is needed for air traffic control. Should this be a spoken language, a printed language, or a set of arbitrary symbols?

Problem Area 3. Optimum Use of Visual and Auditory Means of Communication. Studies should be made of the relative advantages of auditory and visual messages, including comparisons of auditory-sequential-periodic and visual-simultaneous-continuous presen-

tations. Studies should also be made of the advantages achieved by simultaneous auditory and visual presentation of the same information, and the relative advantages of uni-sensory and multi-sensory data displays.

Illustrative research problem. Tests should be made of the following hypothesis: If it is necessary to give an operator an important message, it is much better to give it to both the eyes and ears than to one sense alone.

Research Objective VIII. Optimum Man-Machine Systems Engineering.

The term "system" as used here includes the entire assemblage of men and machines engaged in air navigation and traffic control. The contribution of human engineering to the efficient overall design of this man-machine system should include the following:

a. *Systems evaluation-comparison of the new and the old.*
b. *Systems analysis- the identification of sources of variability or errors.*
c. *Systems research- the discovery of principles governing efficient man-machine combinations.*

All three kinds of studies should receive major emphasis. In achieving this research objective, cooperative research participated in by men trained in different scientific disciplines is usually necessary.

Problem Area 1. Human-Engineering Analysis of Existing Systems. Systematic studies should be made of existing air-navigation and traffic-control systems in order to discover sources of variability, delay, and error. These studies should have the following objectives:

a. *To provide facts needed in planning better systems for the future.*
b. *To solve some of the problems of present systems.*

Our study of present air traffic control procedures, summarized in Appendix I, is an example of the kind of work that is needed, although it is not nearly as thorough a job as we should like to see.

Illustrative research problem. There is need for an analysis of the relative importance of different factors now causing variability in the estimated arrival time of aircraft, including factors attributable to pilots, controllers, communication lags, weather, and instrument errors.

Problem Area 2. Human Engineering Research Studies, Analyses, and Evaluations of New System Components. Studies should be made of all new systems, and of new component parts of systems, at the earliest possible stage in their development, so that features that are desirable from a psychological viewpoint can be embodied in the final production item and undesirable features eliminated. As far as possible these systems studies should be planned jointly by research teams, including pilots, controllers, engineers, applied mathematicians, and engineering psychologists.

Illustrative research problem. Integrated studies evaluating distance-measuring equipment should be planned by a research team to determine how well this new equipment meets the needs of ground controllers and pilots and how well it functions as part of a total navigation and traffic-control system. Such studies would supplement those conducted to determine the engineering and electronic acceptability of the equipment.

Problem Area 3. Human-Engineering Research on Proposed Systems. Insofar as possible, scientific studies should be made of proposed new systems and system components, in order to discover basic principles of systems design, and to determine, before the characteristics of a new system are frozen, what features should be embodied in its design.

Such man-machine systems studies require special research facilities that are not now available. It will be necessary to manipulate entire systems including human operators.

The load on the system, the communication and display of information, and the tasks to be performed by the various humans in the system must be under the control of the experimenter, and must be subject to exact repetition. Many of these elements must be simulated.

Exploratory studies are needed to determine how the equipment needs for research in this problem area can be met, what kinds of facilities are needed, and how an integrated approach to systems research can best be accomplished.

Illustrative research project. A study should be made to determine what the simulator requirements are for human-engineering research on air-navigation and traffic-control systems. This study might well include work on the criterion problem. As another illustration, a research team including scientists from several specialized fields, equipment designers, and operating personnel should be organized to study ways and means of providing more efficient methods and techniques for carrying out human-engineering systems research.

Research Objective IX. Maximum Application of Existing Human-Engineering Information.

The final step in an applied research program is the application of research findings to practical problems. In fact, this is both the justification for the research, and the test of its worth.

The first question that should be asked in planning research on an applied problem is: **Are there any existing data that will answer the question?** It is our belief that there are now many areas of engineering design where existing data are not being applied, and where valid answers do already exist to critical questions.

The second question that should be asked is: **Does the problem call for research, or for consultation by experts?** Several considerations enter here. It obviously is not feasible, however desirable it may be, to settle all design questions by recourse to research. Time and cost prevent this. Most design questions involve a weighing of many different engineering, human, and economic factors. Thus single research studies seldom provide a complete answer to complex practical problems. The aims, therefore, should be the following:

a. *To anticipate the most general and most important questions and to support research on these questions.*

b. *To settle the more specific and the less important questions, or those questions that require an immediate decision, by using the best scientific information and advice already available.*

Through the continued support of long-range research over a period of years more and more immediate practical problems can be settled on a factual, scientific basis; but in the meantime the best possible use should be made of existing information.

Problem Area 1. Utilizing Human-Engineering Data in Systems Planning. Extensive use should be made of human-engineering data, and of consultants who have expert knowledge of the data available in the various areas of psychology, in overall systems planning.

Illustrative project. The help of experts in human-engineering and in personnel and industrial psychology should be sought in making decisions about how best to utilize human abilities in an air-navigation and traffic-control system, i.e. decisions about what men should do and what machines should do.

Problem Area 2. Utilizing Human-Engineering Data in Designing Specific Items of Equipment. Emphasis should be given to writing equipment specifications so that human-engineering requirements are met. Relevant data about human performance should be applied throughout the various stages in the design and development of new equipment.

One of the best ways to insure that this is done is for engineering psychologists to work closely and continuously with design engineers. In a few instances this is now being done, but the practice should be greatly increased.

Illustrative projects. Agencies that undertake to develop new flight instruments should insure that they have the assistance of aviation psychologists who have studied pilot display problems. Similarly, agencies that undertake to develop new radar equipment for air traffic control should arrange for continuing help from engineering psychologists who have studied radar display problems.

Problem Area 3. Providing Human-Engineering Handbooks, Engineers Guides, and Summary Reports on Special Problems. Existing information of topics of importance for the development of air-navigation and traffic-control equipment should be summarized in handbooks and special reports. In some cases the preparation of such summaries should be specified as part of the work to be done under a research contract; in other cases, this work should be included as part of a survey of problems in a given area or made the subject of a separate contract.

The Navy, through its contract with Tufts College for a Human-Engineering Handbook, has been supporting work in this problem area for several years. However, this Handbook alone does not cover all of the needs for human engineering data in the air traffic control field.

Illustrative project. There is a need for a technical guide to the methods of systems research. Such a guide might be developed, for example, by taking Chapter VIII of this report, greatly amplifying it, and publishing it as a special report.

CHAPTER I

OBJECTIVES

This report outlines a long-range program of human-engineering research on air-navigation and traffic-control equipment. In preparing it we have tried to achieve the following objectives:

1. **To summarize our knowledge about human engineering as it relates to air navigation and traffic control, and to describe techniques available for acquiring new knowledge in this area.**
2. **To indentify the major human-engineering problems of importance to the program of the Air Navigation Development Board.**
3. **To point out the practical outcomes to be anticipated from a research program directed toward the solution of these problems.**
4. **To list suggestions as to the specific kinds of psychological research which must be done in order to satisfy the immediate and ultimate needs of ANDB in the development of air-navigation and traffic-control equipment.**

A. The Information Used in Preparing This Report

Facts About the Present System. We began our work by learning what we could about the air-traffic-control system as it is today. This information came from interviews with operating personnel in various control centers in the first, second, third, and fourth regions. The results of this study form Appendix I to this report. Because this appendix describes present air traffic control procedures, we recommend that any reader not familiar with these procedures refer to it immediately for orientation.

We also surveyed the opinions of certain air-traffic-control personnel regarding the system which they are at present operating. This survey, summarized in Appendix II, was designated to orient us in our thinking about research problems.

Plans for the Future System. Finally we studied various plans and proposals that have been put forward for future air-traffic-control systems. This information was gathered through conferences with the staff of the Air Navigation Development Board (*ANDB*), through conferences with planning, operational, and engineering groups in the Civil Aeronautics Administration (*CAA*), and the United States Air Force (*USAF*), and the United State Navy (*USN*), and through conferences with persons in industry and in airline companies. We asked questions of many key people in aviation, including pilots and operating personnel, as well as men in technical and management positions. We also analyzed a great many published reports relating to traffic control. Although this background information has been invaluable to us in preparing the research program outlined here, we have made no attempt to include all of it in the present report.

The Role of the Human Operator. Throughout our exploratory studies, visits, and interviews our focus was on the human operator and his role as an individual and as a member of a team in the traffic control picture. We asked such questions as: **What specific things does a human operator do in a traffic-control system? What information inputs does he act on? What kind of decisions does he make? How many decisions does he make?**

We were, in fact, making in necessarily cursory style the kind of job analysis which always precedes direct experimentation in human engineering. And as we gathered facts that gave us a general understanding of the traffic-control problem, we tried to formulate the corresponding research questions: **How much is known about what a human operator should do in a traffic-control system? How much is known about what information inputs the human operator is best able to act upon under various conditions? What do we know about how traffic-control decisions are made?** Our research recommendations follow from the answers that we could give to such questions in the light of our present state of knowledge.

Organization of the Report. This report begins with a broad and general outline of the air-traffic-control problem, against which are set some basic questions of system organization and philosophy. It then proceeds to cover a series of major research areas within which the human operator's problems appear to lie. It concludes with discussions of research techniques and applications.

B. Readers for Whom This Report is Written

This report is written primarily for three kinds of readers: (1) members of the ANDB and its technical staff, (2) professional psychologists, and (3) engineers and other professional men in industry, air transport companies, the CAA, and the military services.

First of all, the report is intended as a guide to the ANDB and to other high-level Government agencies in planning and budgeting for human-engineering research. Second, it is intended to acquaint psychologists with the practical and theoretical psychological problems encountered in developing equipment for an air-navigation and traffic-control system. Third, it is intended to provide engineers and other professional men with an overall view of the scope, methods, and applications of research dealing with the human factor in engineering design.

C. The Nature of Human Engineering Research

Although human engineering research methods are discussed at various points throughout the report, it is appropriate at the outset to remark generally about the nature of human engineering studies.

Human engineering is a special branch of applied psychology that deals with the relations between men and machines. It attempts to find out what the capabilities and limitations of human beings are in using various kinds of equipment. One of its practical objectives is to provide the basic data that will permit engineers to design equipment which is adapted for efficient human use. Another, perhaps even more important, objective is to help engineers decide what equipment needs to be developed in the first place. Psychologists have something to contribute on this score because, in the final analysis, the decision to build a piece of equipment depends on an answer to the question: "**What should men do and what should machines do?**"

Steps in Human-Engineering Research. In general, an experiment in human engineering begins with a careful and systematic study of the job or task under consideration. The primary concern is for a detailed analysis of what the job proposes to accomplish, and what the operators presumably need to know and do in order to achieve that end. **This process is sometimes referred to as the study of system requirements or task requirements.**

Usually this analysis leads to the formulation of specific hypotheses. The researcher then tackles the problem of devising situations in which he can test these hypotheses and evaluate alternative equipment designs or equipment arrangements to find the most satisfactory way of meeting the job objectives. These studies take the form of controlled tests, carried out in accordance with appropriate experimental procedures and providing quantitative data which can be subjected to statistical scrutiny.

One of the most important aspects of this routine is the development or selection of an acceptable and valid performance measure or criterion. In case of simple, more or less unitary tasks, the criterion may itself be simple, but as the task becomes more complex or assumes the proportion of systems operation with groups of participating operators, the formulation of suitable criterion measures often itself becomes a major undertaking. Because the adequacy of the criterion is central to all human engineering, this is discussed as a special problem in several later chapters dealing with human-engineering research.

Human Factors and the Scientific Method. Human engineering is characterized not only as an area of study dealing with a special class of problems, but also by the fact that in dealing with the behavior of men, and of man-machine systems, it applies the methods of modern scientific analysis - methods that have led to so many techological achievements in the realm of the physical sciences. Throughout this report we shall try to convey something of the scope and variety of the human-engineering problems to which rigorous available methods can be applied.

CHAPTER II

THE AIR-TRAFFIC-CONTROL PROBLEM

It is easy, when talking about any man-machine system, to become concerned with the characteristics, procedures and equipment of a particular system and to confuse these with the problems they have been designed to solve. This is why it is hard to look beyond specific equipments and to see the basic functions they are intended to serve and the problems that brought them into being in the first place. **Yet such a viewpoint is essential if we are to think intelligently about the basic human problems in air-traffic control and not be distracted by subsidiary problems that are unique to a particular system.** Therefore, even at the risk of oversimplification, we shall attempt to summarize here some of the basic concepts of air-traffic control.

A. Air-Traffic-Control Principles

Two requirements are basic to the concept of air-traffic control. The first of these is safety; the second is efficiency.

Safety

The reasons why we are concerned about safety are obvious. The geography of air transportation is such that the density of traffic, and hence the possibility of collision, is great in certain areas. Many people, starting from widely-separated origins, often want to fly to the same place at about the same time. Not only that, but sooner or later they all have to land on the same runway. If the movements of the aircraft involved were independent of each other, the likelihood of collision would be great. Thus it becomes necessary to make the movements of each aircraft depend upon the movements of other aircraft. We must exercise control over their separate flight paths.

Efficiency and the Flow of Traffic

Collisions may be avoided by making one of the impending participants go some place other than where he wants to go. This detour may be a large one or a small one, but in any event it delays the progress of the aircraft for a certain time. If this happens often enough to enough aircraft, then we can say that there is a traffic problem.

In air transportation the bottleneck is the landing runway and the air space immediately around to it. It is the smallest space that all aircraft must occupy in common at one time or another. This is another way of saying that it is subject to the greatest traffic density. To see whether a traffic-control system is doing a good job, therefore, we can obtain an index of runway utilization. But more important than this, runway utilization sets the keynote for the design of a traffic-control system. Second only to the principle of safety we can say that all parts of a system should exist mainly for the purpose of achieving maximum runway utilization. And we should keep efficient runway utilization in mind at all times when thinking about traffic-control systems.

Additional air-traffic-control principles, such as reliability and flexibility, have been listed in other papers on air-traffic control *(cf. the RTCA Special committee 31 report)* but safety and efficiency appear to be of primary importance.

B. Evaluation of Opportunities for Exercising Control

If the object of control is to deliver aircraft to the landing runway at a maximum rate, without conflict, and with minimum delay, what opportunities are available for bringing this about? Since aircraft, once air-borne, always must keep on flying and therefore going somewhere, the opportunity for control must lie in programming their flight paths. Control can be exercised at many different places in the system and the problem is to decide where it will do the most good.

Terminal Area Control

Control in the terminal area, an area of 30- to 50-mile radius around the airport, will be essential in any system. We can assume that aircraft will arrive at this terminal area, either in a random sequence, in an irregular sequence such as would result from the use of take-off control without enroute control, or in a relatively regular sequence resulting from enroute control. The task is to transform the arrival sequence, whatever it may be, into a regular landing sequence with a rate of landing which approaches maximum runway utilization.

To achieve this transformation it is possible to vary the speeds of aircraft, to vary the length of their flight paths through the terminal area, and to vary vertical spacing. The kind of control that exists today depends primarily on variation in flight path. In heavy traffic, the present system is inadequate. For safety reasons, changes in flight paths involve large increments, such as a complete turn or flight to a new fix. The present system involves the use of holding areas and stacks, and usually only one aircraft at a time is moved from one altitude layer to another. The consequent delays can amount occasionally to several hours.

Shorter flight paths have generally not been assigned up to the present because of the lack of precision in determining the exact position and movement of aircraft, the lack of a commonly-available method for computing the shortest safe flight path for each aircraft according to its speed and position, and the absence of a method for displaying to the pilot the information necessary for high-precision flight.

The more extensive use of radar and other new technical developments, including those concerned with the human factors that are part of the system, should remedy many of the present deficiencies. For example, the use of surveillance radar provides the possibility of vectoring (giving heading instructions) to aircraft in lieu of complete turns or flights to new fixes. The use of such procedures on the Berlin Airlift and in Chicago has been highly encouraging.

Enroute Control

A schedule for an entire flight could be drawn up which would jibe with the schedules of all other flights so as to insure an efficient landing sequence. The schedule could start with a time for take-off and could contain times for reaching various fixes; or it could start with an undetermined take-off time and could impose more and more rigid control as the terminal area was approached. Obviously such a schedule would have to be well within the speed capabilities of the aircraft. With an unexpected tail wind the plane would have to loaf along. With an unexpected head wind it would have to speed up. Navigation would have to be accurate and the precision of navigation would have to increase as the terminal area was approached. There is no doubt that a more precise enroute control system than that now in use can be devised.

Scheduling Take-offs

It is theoretically possible to cause aircraft to touch down at a desired instant by scheduling the time of take-off. However, there is so much uncertainty in predicting the time enroute for any given flight that the most exact scheduling of take-offs could not, by itself, guarantee an orderly arrival of aircraft spaced one to two minutes apart. This was one of the lessons learned on the Berlin Airlift. Fitts and Long (1948), for example, after observing operations and interviewing many of the pilots, ground controllers, and operations personnel of the Airlift Task Force, concluded that the chief factor that limited traffic density was the inability of pilots to maintain their 3- or 4-minute take-off spacing while flying along the air corridors to Berlin.

Airlift personnel were almost universal in agreeing that this factor rather than Terminal area control (the approach radar and GCA equipment) was the chief "bottleneck" in the operation. Take-off control, of course, reduces the probability that a large number of aircraft will arrive simultaneously at the terminal area.

Recent studies of Airport Time Utilization Equipment (ATUE) by the Cornell Aeronautical Laboratory indicate that some degree of take-off control will be necessary in the future system.

Needless to say, it is also the business of a traffic-control system to permit loaded aircraft to take off and clear the area with a minimum of delay. Fortunately an airplane waiting to take off presents a simpler problem than an airplane ready to land. Nevertheless, adequate opportunities for take-off and a clear path out of the area must be provided and integrated with the landing part of the system.

Degree of Control

It is safe to state that the control system of the future must involve the minimum control necessary for handling traffic safely and efficiently. Terminal area control will obviously be essential. In many areas enroute control may depend primarily upon accurate navigation on the part of the individual pilot. Assuming that modern navigational aids will make this possible, more planes may still arrive in the terminal area than can be handled at one time. Delays caused by this event can only be avoided by a combination of take-off and enroute control. This would seem to be entirely feasible while at the same time maintaining fundamental dependance on navigational aids outside of the terminal areas.

Taking all factors into consideration, it is our conclusion that the greatest gains in safety and efficiency will be achieved in the next decade by solving the problems, human engineering among them, of terminal area control.

Our discussion of research problems, therefore, emphasizes the terminal control problem.

CHAPTER III

SOME BASIC QUESTIONS IN DESIGNING AN AIR-NAVIGATION AND TRAFFIC-CONTROL SYSTEM

In planning a long-range research program on human factors in air-navigation and traffic control, it is necessary to make some *predications* about the role human beings will play in the system of the future. This is obviously a very difficult kind of forecasting to do, but the things that psychologists know about human capabilities and limitations enable us to make some general statements on this point. Consideration of this very basic question will also point up some important problems for future research.

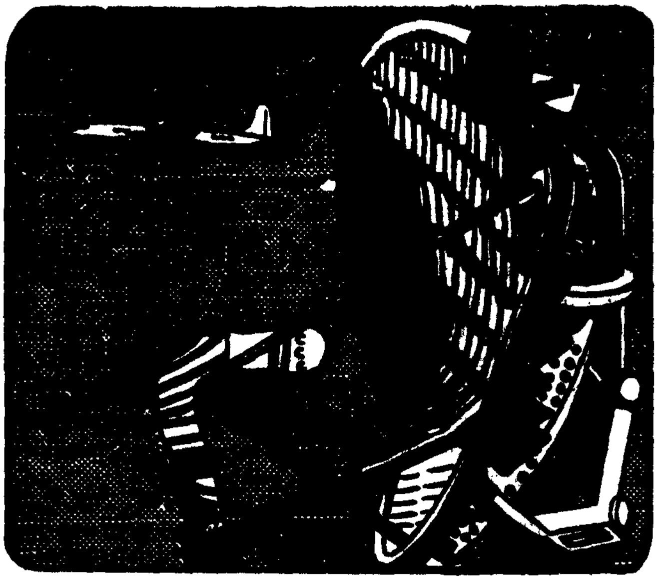
A. Possible Rolls of the Human Operator in Future Air-Traffic-Control and Navigation Systems

One way of approaching this problem of forecasting the directions of future developments is to ask: **What roles can the human be assigned in future systems?** Four possible kinds of control systems, distinguished in terms of the degree of human participation in the control process, can be postulated. We list these only in order to illustrate the range of possibilities. We do not wish to imply that they all are equally feasible or desirable.

1. *Fully Automatic Control.* To some people automatic flight and automatic traffic control appears to be the direction that future developments will take. Our society is continually becoming more highly mechanized. Automatic machinery opens doors for us; enables us to communicate with each other in a matter of seconds though we may be separated by miles; provides signals for our rail and highway traffic; and solves mathematical and logical problems of such speed that the layman's imagination is overwhelmed. If this is the ultimate direction in which air navigation and traffic control developments will go, then there will be no human operators in the control system of the future, and human-engineering will be concerned with problems of production and maintenance, rather operational problems.

2. *Automatic Control with Human Monitoring.* Another possibility is that human operators will always have to be around to take over in an emergency even though the equipment be fully automatic. Machines are not infallible. Dial telephone systems, for example, sometimes break down--tubes burn out, relays need replacing, wires deteriorate. Even if the primary task of the human becomes that of monitoring, maintaining, and calibrating automatic machines, some men will need to be capable of making intelligent decisions and taking quick action in cases of machine breakdown or in unforeseen emergencies.

The human-engineering research problems relating to such a control system would center about the capabilities of the human as a monitor, as a trouble-detector, and as an emergency controller, both on the ground and in the air.



3. *Semi-Automatic Control Supplemented by Human Performance of Critical Functions.* Another possibility is that the human may routinely perform certain critical functions, leaving the major work of the system to semi-automatic machinery. If this turns out to be the case, then long-range research on human functions would center about those higher-level mental functions we call reasoning, judgment, planning, and decision making. It would emphasize the problems of information display and communication.

4. *Primary Control by Human Operators who Would be Assisted by Effective Data-Analysis, Data-Transmission, and Data-Display Equipment.* Still another possibility that we must consider is that the role of the human in the future traffic-control system will resemble the role he performs at present. Human operators may do most of the critical tasks--sizing up display information, receiving and issuing communications, making decisions, and issuing directions--aided by much better data-displays, communication links, computers, and other equipment, than present-day controllers have.

B. Division of Responsibility Between Men and Machines

Some general answers to the problem of deciding the proper role of human operators in a control system can be made on the basis of what psychologists know at the present time about the limiting characteristics of human capacity and performance.

In some cases, our information on these points is fairly complete; in others, we must characterize the statements as being little better than informed opinions. In discussing these broad questions we have attempted to indicate what answers are based on well-established experimental evidence, and what on informed opinion.

Some General Characteristics of Human Performance That Help Define the Role of the Human

Alertness. In considering the possible role of the human in an air-navigation and traffic-control system we know that certain allocations of responsibility would not be desirable because of human limitations. The second alternative listed above, automatic control with human monitoring, often might not work well because there is evidence that in certain kinds of tasks humans are poor monitors. In tasks that call for long periods of relative inactivity, humans tend to become inattentive, and bored, and sometimes fall asleep (*see Mackworth, 1949, 1950*). Even if the system were arranged to force the attention of the human monitor at the time of equipment failure, his immediate reactions might be far from adequate.

One premise we have assumed in considering this kind of system is that the human should be prepared to take over critical functions of air-traffic control in case of emergency. But a man cannot make intelligent decisions in an emergency unless he has an adequate understanding of the traffic picture at the moment of the emergency and for a short time preceding it.

Thus, we are forced to conclude that the monitor must keep alert and thoroughly informed of the traffic situation at all times in order that he can take over in emergencies. We must also conclude that a monitoring system is one of the worst kinds of work situations when we want the human to stay alert.

The railroads long ago separated the functions of expediting traffic and of monitoring for possible collisions, giving responsibility for the former to men and for the latter primarily to automatic machines.

It is true, of course, that men do perform many monitoring tasks in modern industry. Electrical substations, for example, are monitored by men. Also, even though men may be inherently poor monitors it is possible that in certain special cases they might be more dependable monitors than machines.

Considerations such as these lead us to the following two conclusions which we believe to be well supported by present knowledge: *(1) Human tasks should provide activity.* The roles of the human operators in the future air navigation and traffic control system should be active rather than passive ones. Activity in any task is conducive to alertness, and helps to insure that the human will keep abreast of the situation. Activity also is conducive to learning and maintenance of proficiency. *(2) Human tasks should be intrinsically interesting.* The role of the human in any system should be intrinsically interesting in order for human efficiency to remain at a high level. Although there is no simple set of rules for making human jobs interesting, a great deal that we already know can be applied to this problem.

Overloading. A second consideration relating to the role of the human operator is the question of whether humans or machines should be assigned to tasks in which they may be "ganged up on" or overloaded. Our information here is very sketchy indeed. We do know that humans are notoriously variable in their behavior under conditions of extreme stress. Some break down completely; others turn out a creditable performance even under exceedingly adverse conditions. However, complex machines may also break down under such conditions.

There is some evidence to suggest that under overload conditions a human, in some ways, performs better than does a machine. Under disaster conditions, as an illustration, automatic dial telephone systems are known to have broken down completely under overload conditions when, according to informed opinions, human switchboard operators would have been able to get at least some calls through. Whether this is a universal generalization we can make about comparative man-machine performance is highly problematical, but we should at least not discard completely the idea that in some ways humans may function better than machines under stress conditions.

Fallability. The final consideration which needs mention is the relative fallibility of a man to a machine. Machines are by no means infallible, but in general they can be made to carry out specific functions with fewer errors than would be made by humans. This raises the question of whether *safety* should depend on human alertness and decision making or on automatic machines. Our answer to this is an unqualified assertion that the primary responsibility for safety in air traffic control should not rest primarily on humans. This leads to another important working principle.

It is our conclusion, based on what we know about human abilities, that as a rule machines should monitor men. We suggest as an important working principle that checking, verifying, and monitoring equipment be devised that will make it impossible for any human in an aircraft or on the ground to violate basic safety rules, such as assigning two aircraft to the same block of space. This is the reverse of the commonly-expressed idea that men should monitor machines. We are suggesting that in general machines should monitor humans.

What Can Men Do Better Than Machines?

In our search for a general answer to the problem of dividing responsibility between men and machines, it would help us considerably if we could find some general answers to the problem of what people can do better than machines, and vice versa. A listing of those respects in which human capabilities surpass those of machines must, of course, be hedged with the statement that we cannot foresee what machines can be built to do in the future.

1. Sensory functions. One respect in which human capacities often surpass those of instruments is in the sensory functions. This is especially true of absolute sensory thresholds, i.e. the minimum absolute energy necessary for sensory detection. The human eye, for example, is capable of detecting the flare of a match 15 miles away on a dark night. It can detect the presence of a black wire, 1/16th inch in diameter, viewed against the clear sky a quarter of a mile away. The human ear is so sensitive that it can almost detect the random collisions of molecules of air. It is far more efficient at low energy levels than any existing microphone. On the other hand, machines can be designed to respond to energy outside the wavelength bands to which our eyes and ears are sensitive. We shall not dwell on this problem any longer except to point out that psychologists, physiologists, and physicists have accumulated a vast amount of basic information about human sensory capacities. It is one of the areas in which many facts are known. Design engineers who have particular problems in this area can easily secure the information they need by consulting industrial or engineering psychologists. *(See, for example, the Tufts College Handbook of Human Engineering Data.)*

2. Perceptual abilities. Closely related to the above is the superiority of the human in perceptual abilities, particularly with regard to what psychologists call *stimulus generalization.* As an illustration, nearly every time you see your car you see it under varying conditions of illuminations, with varying amounts of dust on it, and from different angles. Yet you ordinarily have no difficulty at all in distinguishing it from other cars. In other words, you generalize your memory of your own car and recognize it even though the energy pattern acting on your eyes is always different. Abstract conceptual qualities like squareness, roundness, triangularity, are easily grasped and used by the normal person even though triangles, for example, come in an infiniture of shapes. We should note that engineers have not succeeded in producing instruments which have the versatility of the human in these capacities. *The conclusion here is that a human is very good at sizing up complex situations quickly, especially if data are encoded and displayed in such a way that he can use perceptual capacity to the maximum (i.e. if adequate "pictorial" or familiar "patterned" displays are used.)*

3. Flexibility. Another special capacity of the human is his extraordinary flexibility and ability to improvise. These abilities are still incompletely understood by psychologists, but they represent important respects in which humans surpass machines. The amount of flexibility a machine has is fixed by the amount that was built into it. The machine will attempt as many different kinds of solutions as its designer planned for and no more. Experiments on complex problem-solving in humans, on the other hand, show that humans may attempt many different solutions for the same problem-- just think of the number of ways in which this paragraph could have been written to convey essentially the same point. Flexibility is especially important in a changing and evolving system, such as one in which new techniques are constantly coming into use. It also provides insurance against complete breakdown in emergencies. *The conclusion here is that if flexibility in a system is important, it probably is a good plan to let human beings play an important role in the system.*

4. Judgement and Selective Recall. The nebulous ability we call judgment also appears to be unique in the human. In large part, judgment is due to the superior ability of the human to store large amounts of information and to pull appropriate information out of long-term storage at the appropriate time. This is what we ordinarily call memory. People do not remember everything they see, hear, or learn; but the things that are remembered are somehow integrated with the mass of material already there and are available for recall years later.

Good judgment is a crystallization based on experiences which resemble, but are not quite the same as, the situation facing a person now. An experienced controller may have an emergency situation which is not exactly like any other emergency he has ever seen. But if he has been properly selected and trained, he is capable of drawing upon similar experiences he has seen, or merely heard about, and of exercising good judgment in facing the present emergency. This kind of ability has not yet been built into a machine.

Machines can be constructed with memories, it is true, but the machines so far devised are not very efficient at the kind of selective, long-term storage needed in handling unique problems. *The conclusion here is that to the degree that we fail to reduce all operations to logical, pre-set procedures, we need people around who can make judgments.*

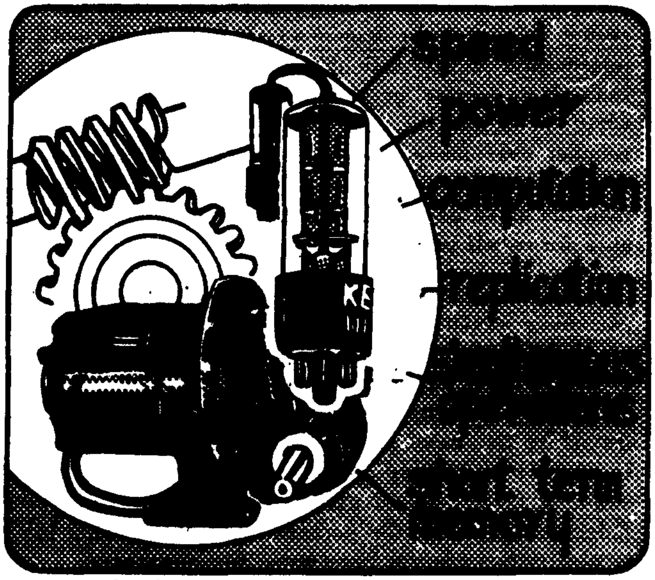
5. *Reasoning.* As we shall see later, automatic computers are superior in speed and accuracy to human brains in **deductive reasoning,** but no success has been attained in constructing a machine which can perform **inductive reasoning.** Inductive reasoning is that peculiar ability which mathematicians and scientists use when they formulate new principles on the basis of masses of empirical data. The original idea that formed the basis for Einstein's theory is an example of inductive reasoning although many of the later refinements of the theory probably have resulted from the process of deduction.

In summary then, we can see that the human carries within him some remarkable powers that cannot yet be duplicated by machines, especially abilities needed to deal with changing situations and unforeseen problems.

What Can Machines Do Better Than Men?

Humans, however, do have many faults as well as good points and it behooves us to list these as well. In general, machines excel humans in the kinds of things we have already turned over to them in our society--especially tasks requiring great strength, and tasks of a very routine nature.

1. *Speed and Power.* Although machines do not have many of the sensory and perceptual capacities that humans do, they far excel people in the ability to respond quickly and powerfully. Even under ideal conditions a man requires over 0.1 second before he can start to move a control in response to a signal, while in most normal work situations his lag time is even longer. Milton and others (1947), for example, measured pilot reaction time in the air and found an average lag of 1.55 seconds before they initiated a movement in instrument recovery problems. The time was 1.35 seconds for contact recoveries. In these experiments pilots were blindfolded and disoriented, then shown either their instrument panel or the ground and asked to re-orient and level the aircraft. An automatic pilot would, of course, respond much more quickly. **Machines can be devised to make movements smoother, faster, and with greater power than humans.**



2. *Routine Work.* Machines excel humans in **repetitive, routine tasks.** Machines can be counted on to make fewer errors in routine tasks, and to turn out responses that not only are quicker, but are far more uniform than a person can make. They also do not become bored and inattentive.

3. *Computation.* Machines are more efficient computers than humans--no matter whether the computations are simple or complex. In the latter case, a machine can examine all the possible deductions from sets of postulates, reject those which are invalid, and act upon those which are valid. It is important to remember, however, that the rules of operation, the postualtes, must be built into the machine.

4. *Short-term Storage.* Machines appear to excel humans in short-term memory. There are many jobs in our present society that call for short-term storage of information, followed by complete erasure of the data in preparation for another task. Machines can be built with this kind of memory. Humans, on the other hand, are not so good at it. They especially have difficulty in completely erasing information in short-term storage. Also, it is sometimes difficult to be sure that a man has noticed and remembered a particular fact--this is why controllers often ask pilots to verify that they have understood certain critical information.

5. *Simultaneous Activities.* Finally, a complex machine is capable of carrying on more different activities simultaneously than is a single human being. We are talking here about decisions and activities requiring some degree of attention--not reflex or automatic processes like breathing. There is much information to indicate that when he has to employ his highest intellectual abilities man is essentially a one-channel computer--he can only work effectively at solving one problem or attending to one thing at a time. Only when activities have been greatly overlearned can he do several things at once very effectively and even then he may actually have to shift back and forth rapidly between the two activities. The only way to get around this human limitation is by adding more men to do the job.

These are some of the things we can say with confidence about the relative abilities of men and machines. They provide a starting point. However, it is obvious that we need much more information of this sort--more specific information about human capabilities and limitations in performing different tasks--before we can determine the optimum division of labor between men and machines.

We turn next to the question of division of responsibility between different human beings in the air-navigation and traffic-control system.

C. Division of Primary Responsibility Between Human Operators

In any efficient air-navigation and traffic-control system there must be a clear division of primary responsibilities between the different human beings in the system. The exact nature of their responsibilities cannot be determined without knowledge of the equipments in the system; nor can the nature of the equipment that will give optimum system performance be determined without some consideration of what the responsibilities of various human beings will be. Very little research data are available as a guide to decisions of this sort. However, some general principles can be suggested on the basis of what we know about human characteristics.

How to divide responsibility between all of the people working on the ground versus all of those working in the air is a very important matter. It is also a very difficult problem to answer. The techniques of systems research, which are discussed in a later section, can be applied to this kind of problem.

This particular problem is so broad, however, that it will be very difficult even by these techniques to secure conclusive answers. Among the difficulties confronting the research worker are those of changing operational conditions, or even of simulating different conditions, in order to try out different allocations of responsibility. It will also be very difficult to insure that each condition is tried out impartially and the results measured objectively. It is our conclusion that extensive use should be made of expert consultants, including Industrial Psychologists and Engineering Psychologists, in arriving at decisions about the allocation of major responsibilities of this sort. Research on certain aspects of the general problem is also indicated.

The problems of allocating responsibilities within a group of different human operators doing closely related tasks are similar to those just considered. These problems include the division of work load between a pilot and co-pilot, or between two ground controllers. In this case, it will be easier to conduct systems research. The systems to be studied are smaller and this makes simulation, systematic variation, and measurement easier. Problems at this level, whether they involve operational procedures, human-engineering improvements, or requirements for future equipments, can usually be studied by the technique outlined in the later section on systems research.

Fortunately, we already know a good deal about some of the factors that determine how many and what kinds of things one individual can do, and there are a few general rules for dividing responsibilities between different men, and between men and machines. Here are two useful principles.

1. Who should make decisions. Other things being equal, the person who is best informed obviously is the best person to make decisions. A related principle is that decisions should be made near the point where basic information is derived--thus minimizing extensive communication links. Pilots have direct access to local air-derived information, such as data about the aircraft's altitude, about operating conditions, about icing conditions, and about the amount of gasoline remaining. They are the logical people to make on-the-spot flight and navigation decisions. Ground controllers have direct access to ground-derived and ground-stored information. They are informed about meteorological conditions, traffic loads, and schedules over a wide area. They are the logical people to plan, coordinate, and expedite the flow of traffic. In both cases, however, they should have all possible aid in analysis and computation, whether this is accomplished by other men or by machines. Data-gathering and decision-making should be carefully coordinated.

2. Equalizing work loads. Usually the most effective division of responsibility is one in which the work load is equitably shared by associated workers. The future traffic-control system must not overload the single pilot of a jet fighter, but at the same time it should permit efficient use of several persons on large transports. Often problems of work assignment can be clarified by determining the number of different tasks performed by a particular person and the relative importance of each task. The pilot who is making an instrument approach, for example, is a very busy man.

Two methods have been developed recently for reducing the work load of the pilot in this particular situation. One method is for a radar *(GCA)* operator on the ground to monitor the plane's position in azimuth and in elevation during its approach and periodically to give the pilot headings and rates of descent to fly. This relieves the pilot of one series of activities, that of cross-checking course-deviation and heading and deciding which heading to fly.

The other method is to provide the pilot with an airborne computer of the "Zero Reader" type that will tell him what bank and pitch changes to make from moment to moment in order to stay on the correct approach path. Other ways of simplifying the pilot's task during an instrument approach are undoubtedly possible. The point here is that we cannot expect a system to work if we overload one man.

D. Some Important Issues not Directly Dealt With in this Report

This is a good place to mention several issues that are of importance for human engineering, but are not directly dealt with in this report.

Technical Feasibility

Research in human engineering should keep abreast of new engineering techniques, and new equipment developments if it is to foresee human operator problems and provide information in time to influence the design of new items. Although this kind of background information has been considered in preparing the present report, it is not discussed explicitly.

Economic Issues

Decisions about what human operators will do and what machines will do in any particular system involve balancing the increases in safety and efficiency against monetary costs. For any fixed amount of money that can be invested in a man-machine system there is probably a unique combination of human and machine elements that will maximize efficiency. Human-engineering research can furnish part of the data needed to determine this optimum combination, but again, we have avoided any discussion of these economic problems.

Manpower and other Personnel Problems

Many different human activities are involved in designing, producing, and maintaining a man-machine system as well as in operating it.

Training. Manpower costs include those of training. Training costs may be high or low, depending on the design characteristics of the equipment that men must learn to operate. As an illustration, our analysis of present air-route-traffic-control centers revealed wide dissatisfaction with the new flight progress boards. In most centers these boards are arranged in such a way that the assistant cannot see what the controller is doing. For this reason he cannot assist the controller in many important aspects of his work, and receives little on-the-job training as a controller. Because of this, the CAA may soon have to establish special schools for training controllers, whereas the older type of boards were well suited for in-service training. Similar problems arise whenever pilots or ground personnel are trained on the job. Training time is an important criterion for the design of many items of equipment.

Maintenance of Skills. Tasks can be set up so that human operators eventually become deficient in certain important skills which are infrequently used. As an illustration, a pilot who relies too much on the auto-pilot may lose some of his skill in manual control, or one who routinely uses automatic landing equipment may lose his skill in making manual landings. This in turn creates special training problems, particularly training for emergency operations. We have not considered this problem directly, but it is another criterion for judging the goodness of equipment design.

Job Life. Still another aspect of the manpower problem is the effect that equipment design may have on the number of years during which a man can hold a particular job or series of related jobs. Most traffic controllers today believe that their jobs can be done only by fairly young men. Many controllers told us that fifteen years is considered a long time to work as a traffic controller. Also there are few opportunities for advancement. It is obviously a waste of manpower if workers become unable to hold their jobs after such a short work life, unless these workers can move on to other jobs where they can utilize their experience.

Equipment Maintenance and Calibration. All equipment, especially complex automatic equipment, requires human maintenance, calibration, and checking. It is obviously important to design equipment so that maintenance time is minimized, and few human errors are made in adjusting machines. In this connection we want to point out the similarity in consequence of calibration and maintenance errors on the one hand, and errors made by human beings using nonautomatic equipment, on the other hand. All sources of human error will not be eliminated by going over to automatic equipment.

Although this report does not deal in detail with these problems, all of the manpower and personnel factors mentioned above--initial training, maintenance of proficiency, life span of operators, and equipment maintenance--must be considered in planning for an efficient man-machine system. In this regard the research programs on personnel and training problems in aviation will contribute to the engineering development program.

E. Summary

Men versus Machines. In this section we have considered the roles men and machines should have in the future air navigation and traffic control system. We have surveyed the kinds of things men can do better than present-day machines, and vice versa. Humans appear to surpass present-day machines in respect to the following:

1. **Ability to detect small amount of visual or acoustic energy.**
2. **Ability to perceive patterns of light or sound.**
3. **Ability to improvise and use flexible procedures.**
4. **Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time.**
5. **Ability to reason inductively.**
6. **Ability to exercise judgment.**

Present-day machines appear to surpass humans in respect to the following:

1. **Ability to respond quickly to control signals, and to apply great force smoothly and precisely.**
2. **Ability to perform repetitive, routine tasks.**
3. **Ability to store information briefly and then to erase it completely.**
4. **Ability to reason deductively, including computational ability.**
5. **Ability to handle highly complex operations, i.e. to do many different things at once.**

Monitoring. We believe that men, on the whole, are poor monitors. We suggest that great caution be exercised in assuming that men can successfully monitor complex automatic machines and "take over" if the machine breaks down. We believe that engineers should seriously consider systems in which machines would monitor men, especially in respect to matters of safety, and prevent them from making serious mistakes.

Overloading. Both men and machines are likely to break down or become unstable if overloaded. Men are subject to emotional stress caused by personal problems and other off-the-job influences. However, it is possible that in some ways humans can do a a better job than machines under overload, or stress, conditions arising on the job--at least they may supplement machines in this regard, especially in situations where flexibility is an asset.

Flexibility. One of the greatest benefits to be gained from including human elements in a system is increased flexibility in adapting to changing demands. A proficient and well-trained human operator usually can adapt readily to the introduction of new equipment, to the sudden failure of equipment, or to the occurence of a unique and unforeseen problem. This particular human capacity can be utilized to the fullest only if the overall system is properly human-engineered.

Research Implications. Most of the general research objectives that we consider in the following sections are not tied to any particular assumption as to what the role of the human operator in the future air-navigation and traffic-control system will be.

In some cases this has prevented us from formulating research recommendations in as specific terms as we could have had we been concerned, for example, only with the present system.

Instead of trying to be unduly specific, we have tried to think in terms of functions that may be performed by human controllers in any system, In most cases, suggestions for research are slanted towards general human behavior in broad contexts. Information derived from such research programs will not only be applicable to equipment of a certain kind and date, but will anticipate problems and solutions in connection with future equipment.

F. Recommendation

It appears likely, that for a good many years to come, human beings will have intensive duties in relation to air navigation and traffic control. It is extremely important that sound decisions be made regarding what these duties should be. As we have indicated in the present chapter, many of the facts that we know about human beings are pertinent to decisions about the division of labor between men and machines. We suggest later (see Research Objective IX, Problem Area 1) that human engineering consultants can be of great assistance when plans for new systems are being made. Even though the problems are exceedingly broad, we believe that very worthwhile progress can be made by research in this area, especially by the systematic analysis of various kinds of data that are already available in aviation and in industry. Therefore, we recommend the following research objective:

Research Objective I. Determination of the Relative Abilities of Men and Machines to Perform Critical Functions in Air-Navigation and Traffic-Control Systems.

Basic research should be supported to provide the principles on which decisions about the most effective roles of men and machines can be based. The decision to develop a machine that will perform a certain operation usually implies a prior decision that a machine can do the job better, faster, or more reliably than a man. At the present time there are few rules that can be followed in reaching such decisions. Information is needed about such general topics as these:

a. What standards or norms of human performance can be expected when men are assigned certain air-navigation and traffic-control tasks and how much variability will there be between individuals in the performance of these tasks?

b. To what extent will the various human tasks require unusual human capacities, and long training programs?

c. How can human performance be measured in terms that will permit the meaningful comparision of the effectiveness of men and of particular machines when carrying out certain tasks?

Collection and synthesis of known facts about human abilities will help to establish some of the needed principles. Some of the information necessary for answering additional questions can be obtained from existing records or can be collected during routine operations. In other instances, it may be necessary to conduct extensive experiments to establish some of the principles that are needed in this area.

Illustrative Research Problems. In this report we have advanced arguments in support of the hypothesis that men cannot efficiently monitor automatic equipment. This hypothesis needs to be tested in various work situations, and it may be that the answer can be found by careful surveys of typical industrial situations, such as power plants or military lookout posts, where men are now employed as monitors. *As another example,* in this report we propose the hypothesis that under certain circumstances men may function better than machines under conditions of overload and stress. This hypothesis needs to be validated, and again the answers may be forthcoming from a careful analysis of records from the operation of automatic machinery, such as dial telephone systems, during wartime conditions, floods, partial power failures, etc.

CHAPTER IV

A GENERAL APPROACH TO THE HUMAN OPERATOR AS PART OF A COMMUNICATION SYSTEM

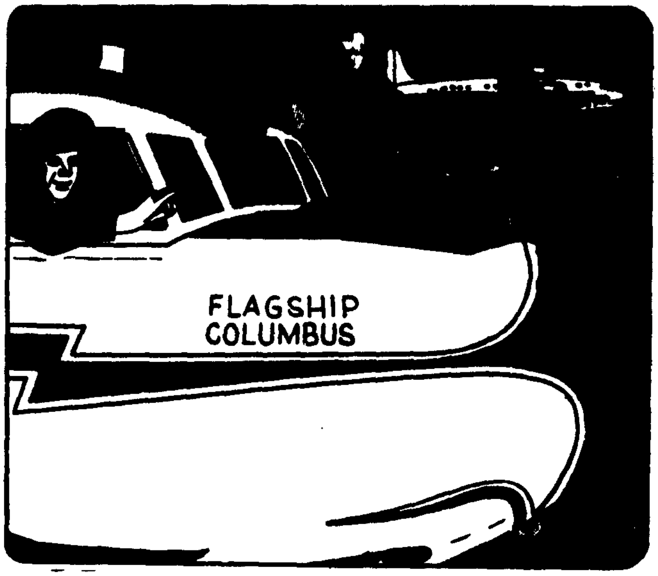
The problem of control is, at its heart, a problem of information. The decision to fly requires that some person have enough information about people and planes, and weather and places, so that he is willing to initiate some action. His decision must be communicated, as an essential item of information, to others. The decision to permit a take-off, the decision to fly a given course, the decision to land just these planes in just this order, each of these decisions involves the same basic process. Someone must assemble in one place, at one time, all of the indispensable information, commit himself and the people working with him to a given course of action, and communicate his decisions to others.

In the preceding chapter we have considered some of the more general features of this particular control situation. The most general control, it was found, can be exercised before take-off. Thus the control of the total traffic load in a terminal area requires first of all that only a certain number of planes take-off and fly toward that area. Once they have arrived, both safety and efficiency require that a coordinated effort be made to get them down on the ground. And in between take-off and touch-down the pilot must navigate his plane as effectively as possible. In accomplishing these ends, a highly complex system of men and machines is constantly engaged. It is the task of human engineers to examine the human links in the total chain, and to insure that the man-machine team is a harmonious and effective one.

A few words should be said at this point about one particular problem which is going to be given only a small amount of space in this report. This is the question of the manipulative skills needed to fly an airplane. We are very well aware that this is an important problem, and there are places in the control of air traffic where it seems to be almost all-important, as in manually-executed instrument landing systems. But an account of the how and why of flying skills is not our primary mission. We shall simply assume that we are dealing with pilots who possess normal aptitude and skill, and, incidentally, with ground controllers who are alert, intelligent, and adequately trained.

A. Decision-Making

As we have outlined the problem, the basic human action involved in an air-navigation and traffic-control system is the choice by a pilot or controller of a particular course of action from among the various alternatives open to him at the moment. Decision-making, choosing a course of action, we contend, lies at the root of the whole problem. Let us see what this involves, borrowing for purposes of analysis from modern communication theory (*see Shannon and Weaver, 1949*).



A control system requires of an operator a series of choices. He must select a particular route from a set of alternative routes, a particular approach path from a set of possible paths. If a controller on the ground makes such a choice, he must communicate this fact to the pilot, who is, in a sense, faced with the same decision. In both cases, the selection of the right course of action depends on the information available, including that contained in incoming messages, and also that recalled from past experience and training. Some decisions involve very specific actions; others such as the granting of a flight clearance, involve long sequences of actions.

Traffic control is possible only when the ground controller is able to assemble and take in enough information to make his choices, when he is able to transmit to the pilot sufficient information to determine completely the course the pilot will attempt to fly, and when the pilot is able to take in this information, plus the other flight data needed to determine how to manipulate his controls. The flow of information to and from the human operators in the system is one of the basic determinants of the performance of the system.

B. The Nature of Information

Information, in this context, is being used in the strict sense defined by modern communication theory.

People respond to slight energy changes in their environment, which are called signals or stimuli. These energy changes are not important as such but only as they carry information. The amount of information a stimulus carries does not depend at all on what the stimulus *is*; it depends on what the stimulus is in comparison with what the stimulus *might have been.* Suppose that a recipient knows in advance that a signal can only be either present or absent. For example, a pilot is waiting for a signal indicating that he is cleared to take off. Its arrival is enough to determine his choice. It divides the possible courses of action by two, or, said in other words, it reduces his ignorance to zero. Had the recipient been faced with a more complex decision, involving perhaps twenty alternatives, the simple signal would not have been enough. Either a more complex signal would have been required or it would have been necessary to repeat at least five times to determine the choice among the twenty alternatives. In short, the amount of information provided by a particular stimulus pattern depends on the number of alternative patterns in the set from which the pattern is chosen. [1]

Messages and Information.

A distinction is made here between a message and information. A message may consist of a given sequence of words, a pattern on a cathode-ray tube, a series of light flashes, or a complex encoded signal. The same message may contain a great deal of information, or little information, or none at all. How much it contains depends on the **degree to which it reduces the possible courses of action open to the receiver.** In the case of the human, this depends on the total context in which the message occurs, and particularly upon his past experience in similar situations, i.e. upon his stored information.

As an illustration of this distinction between a message and information, consider the more or less continuous chatter from the loud-speakers in an airport traffic-control tower. This is a flow of **messages** from planes taking off or approaching.

To the novice, these messages are about 99 percent unintelligible; yet the tower operator receives them and acts on them with little apparent difficulty. His ability to act on most of them is largely dependent upon the fact that, despite the length of the messages, they convey relatively little information.

Recent studies by the Air Force Human Resources Research Laboratory at Bolling Air Force Base indicate that air-to-tower messages are between 75 and 90 percent redundant. Through experience, the tower operator has learned what to expect—he knows pretty well what planes are in the air and when they may be expected to arrive, what information they will require and at what point in their approach they will ask for it.

In other words, he does not need much of the message, because he is acting to a great extent on the basis of "stored" information. In order for the casual listener, who does not possess this wealth of stored information, to comprehend and act on the message it would need to convey much more information than the untrained person could perceive on one hearing.

What Information the Operator Wants.

The amount of information conveyed to the operator also depends on the nature of the device that gives him the message and what questions he asks of it.

Take as a second example, meter or dial readings. A given pointer on a dial may have any one of the of the following three functions: **(1) it may serve as a check instrument, (2) it may give a qualitative indication, or (3) it may give precise quantitative data.**

The first indication contains a minimum of information, just an OK or not-OK. The second permits the choice among a number of alternatives. The third indicates a choice among a greater number of alternatives, and also permits the observer to resort to a large amount of his stored information about metric scales.

Which of these functions a given pointer serves depends both on the nature of the instrument and upon the kind of question the observer asks of it.

C. The Form Which Information Takes: Encoding

While the form that a message takes may not determine the amount of information that it contains, it may have a good deal to do with the efficiency with which it is transferred. This choice of message form, or the transformation of information from one message form to another, we shall call the problem of **encoding.** A familiar example is the use of binary as opposed to decimal digits. We may write either 111011 or 59. Another example would be the comparison of our modern alphabet with Chinese characters. The same amount of information can be represented by a series of choices, each from a smaller set of alternatives, or by a single choice from a large number of alternatives. Within certain practical limits, we can substitute length of message for complexity of symbols, and vice versa.

Complexity vs. Length.

From the above examples it may be seen that there are important psychological differences among various forms of messages. In general, a binary sys-

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[1] In communication theory the commonly used measure of information is the Bit. The number of Bits in a message equals $\log_2 N$, where N is the number of alternatives; the number of Bits also is the number of binary digits necessary to specify a particular one of the N alternatives.

tem is inefficient for use by humans; for example, a long learning period is required in order to achieve reasonable speed with Morse code. At the other end of the useful range is a system which employs thousands of characters, such as Chinese pictographs. These also can be used only after many years have been spent in their mastery.

The optimum range lies between these extremes, and it most probably involves a smaller number of symbols if the learning must be rapid; more symbols if highly-trained personnel can be employed.

The Total Information Available.

Within this broad optimum range, there are circumstances in which the total available information, rather than message form, appears to be important. The following test was made on a voice communication channel by psychologists at the Harvard Psycho-Acoustic Laboratory. At a given ignal-to-noise ratio, all the "words" of a small vocabulary--four monosyllables--were intelligible. When the "words" were chosen from a larger vocabulary of 1,000 monosyllables, and were heard at the same signal-to-noise ratio, it was necessary to repeat each sound about five times, on the average, before it was correctly identified.

From the point of view of communication theory, if we assume that each monosyllable is an independent signal, then one "word" from the larger vocabulary carries as much information (10 bits) as do five "words" from the smaller vocabulary (5 x 2 bits), and a single "word" from the larger vocabulary would seem on theoretical grounds to be more efficient. Under the limiting conditions of noise, however, it was found that the message from the larger vocabulary had to be highly redundant, with the result that approximately equal information was transmitted by a monosyllable of either vocabulary.

Optimum Balance.

The optimum balance between the number of symbols used and the length of message will depend on several factors, such as (1) the source of the information, the means of transmission, and the method of display, (2) the sensory channel (c.f. visual or auditory) through which it is perceived, (3) the rate at which it can be handled by the receiver, (4) limiting conditions such as noise and irrelevant information, and (5) the degree of training or instruction that can be given to the operator beforehand. Many of the particular problems that affect the optimum form of messages will be discussed in later chapters of this report. *(see especially chapters V, VI, and VII).*

D. Rate of Flow of Information

In a physical system, the maximum possible rate of flow of information is intimately related to the bandwidth of the system. Extremely high rates of flow are theoretically possible providing an unlimited frequency spectrum is available. Such considerations have almost no bearing at all on the **psychological problems** with which we are dealing.

The rates at which a man can handle information depend chiefly upon what he does with the information, how it is stored, analyzed, collated, transformed, and finally acted upon. There is some evidence to suggest that the maximum rate at which a man can take in new information is rather low. Much more direct evidence is needed on this point, but let us consider two common examples.

The Practical Upper Limit of Information Input. The upper limit of information input is a function of particular man-machine systems. But there is an upper limit for any practical situation. As an illustration suppose that a pilot is making an approach along an instrument landing approach system *(ILAS)* glide path using the cross-pointers that tell him about position deviation from the correct path and other flight instruments that report the attitude, speed, etc. of the aircraft. He suddenly breaks out of the overcast and elects to complete his landing by use of direct vision of the runway. The rate at which he must take in new information is now very high. A correct initial estimation of glide path requires that he first estimate his altitude, distance from the end of the runway, rate of descent, and drift.

Several seconds are required to assimilate this information from the new source and to make a new determination about the correctness of his approach path. If a substantial correction is required, the time may be too short.

As another illustration, consider the Air Route Traffic Controller when an unexpected, itinerant aircraft suddenly enters his sector at a time when traffic is already near the saturation point. It will require quite a few seconds to decide what to do in this case. It is our best guess that both these situations tax the upper limit at which information can be assimilated by the human operator.

Potential vs. Actual Information. In trying to discover what is the upper limit at which information can flow to a human operator, it is of the greatest importance that the distinction between ***potential*** information--the message--and the ***actual*** information taken in at a given time be kept in mind.

A pilot who is making a visual-flight-regulations *(VFR)* approach to a familiar airport needs to take in very little ***new*** information per glance, even though there is a great deal of potential information available to his eyes. As we should like to emphasize later, there may be terrific redundancy in a sequence of familiar visual inputs whether they be from a television screen or from a direct view of an airport. On the other hand, a single glance at a new visual pattern may make available a very large amount of information.

Central Processes, Not Sensory Ones, Limit Input. A little reflection suggests that the limit in these cases is not a sensory one. Either the eyes or the ears alone can take in more information than the brain can handle.

The results of recent researches *(Taubman, 1950)* illustrate this point very well. The ear is easily able to hear bursts of sound as distinct pulses when they occur at frequencies of 20 per second. Yet human observers cannot count 5 pulses of sound accurately unless they are separated by an interval of about an eighth of a second.

Similarly, the eye can easily see distinct flashes of light if they occur at a rate of 20 flashes per second. But a human observer cannot be relied on to count 5 flashes of light accurately unless the flashes are separated by about a half second.

Errors occur almost uniformly because humans underestimate the number of pulses or flashes, and this undoubtedly accounts for the results of other studies which show numerous errors among Morse-code operators in reading 5's (.....) as H's (....), H's (....) as S's (...), 6's (-....) as B's (-...), and so on.

Many other similar examples could be given of the brain's limited ability to comprehend new information rapidly. A more important factor than the sensory channel used often is the manner in which the message is organized. This is again the problem of formulation or encoding.

Organization of Messages and Rate of Flow of Information. It is reasonable to expect from what we know about human perceptual and thought processes, that the rate at which information can be assimilated will be a function of the way the message is organized, that is, the particular way in which the information is encoded.

Humans have an unquenchable desire to organize, construct, pattern, and arrange things in ways which "make sense". This, in turn, helps them to assimilate information. The combination of letters "tnoirzgaaoin" may contain as much information as the combination "organization" but the latter can be recognized and grasped in a fraction of the time required to assimilate the former.

Kaufman et al., (1949) found that the maximum number of randomly arranged dots which can be perceived at a glance is about six, but from other studies it seems reasonable to expect that 16 or even 25 dots can easily be perceived simultaneously if they are arranged in a square. In another study by Vince, (1949) subjects were required to respond to visual signals by tapping. When the visual signals were presented singly, the maximum rate of tapping was about 2 per second. When the visual signals were patterned in time, however, the rate of tapping increased to about 7 per second. In short, ***patterning*** the visual signals enabled subjects to assimilate and respond to more information. Research on patterning of dials *(see Chapanis, Garner, and Morgan, 1949, and Warrick and Grether, 1948)* is also relevant in this connection.

Although psychologists often can make some pretty shrewd estimates about the way patterning will affect the rate of information input, we still need much research on efficient ways of patterning or constructing all sorts of messages so as to make them easier for humans to grasp.

The Lower Limit of Information Input. If there is an upper limit to the rate at which a man can take in information, there is also a kind of lower limit, particularly in terms of the efficient use of the operator. If a pilot wants to know the rate at which he is deviating from his correct localizer position, he cannot get this from a quick glance at the ILAS localizer needle. It may be necessary to check the ILAS indicator several times, while cross-checking with other instruments, and remembering the previous readings, just to get a few bits of information.

Similarly, the present practice of relaying information to traffic controllers via company radio or an intermediate CAA facility slows up the informational input well beyond the limit of maximum human efficiency. The trouble is that a human operator is not a passive recording device. He is engaged in manifold other activities that seriously perturb the system in question.

The slower the input beyond a critical value, the greater is the chance of error. An important problem for research is the determination of limiting conditions, upper and lower rates, for different kinds of inputs to the human in different kinds of activities.

E. Storage of Information

If the human operator has a restricted range of inputs so far as rate is concerned, he does not possess the same limitation in another dimension, namely, long-term information storage. As a matter of fact, theoretical considerations suggest that the long-term storage capacity of a single human brain probably far exceeds that of all the computing machinery that has ever been built. However that may be, it is certainly very large.

For the present purpose we can distinguish three kinds of information storage-*transient, short-term, and long term.*

Transient Retention. First of all, it is evident that this human organism possesses a moderately good capacity for the transient storage required to deal with events that occur very nearly together in time, say within a 0.5-second interval. Successive musical notes or the group of dots and dashes making up a single Morse code character are perceived as being present "now". Some recent theorists *(see Hebb, 1949)* have speculated that this may be a kind of *circulating memory.*

We are not concerned in this report with the shortest transient storage that covers the psychological present, except to mention in passing that people often make errors in judgments of simultaneity, especially when their attention is centered on one of the events, or when the second event is more intense.

Transient storage operates principally as a smoothing or equalizing mechanism that adjusts the rate of assimilation of information into the human system. Over a matter of seconds, for example, a person can "play back" something he has just heard in order to analyze or think about it. He may take an appreciable time to get the point. There is the same storage capacity for things seen--although in neither case are limits well known in informational terms.

Short-term Storage. Storage beyond the transient level involves what is conventionally called memory and learning, a field too complex for more than passing mention. For the purposes of this report we believe that two types of learning can be distinguished. Let us call them simply **short-term** storage and **long-term** storage. By **short-term storage** is meant the ability of the operator to retain the information that is relevant to the particular problem with which he is faced at the moment.

There are real limits to such memory, and poorly planned procedures in an aircraft or control tower tax them. The basic phenomenon is retroactive inhibition, which occurs whenever a person tries to remember a large number of highly similar items. The conflict between these similar items results in partial forgetting and confusion during recall.

Confusion of this kind may be lessened (1) by **encoding** information in such a way that there is not too much similarity among the items to be remembered, (2) by **simplifying** the task to be accomplished by a single operator so that he needs to consider less information in making decisions, (3) by providing **messages that are already patterned** for grasping as larger units, and (4) by the use wherever possible, of **symbolic substitutions** so that an operator relies less on short-term (although probably more on long-term) information.

It must be noted in passing that confusion is often due to similarity in meaning - but a discussion of this aspect of the problem would take us too far afield.

Long-term Storage. By **long-term storage** we shall mean all of the effects of training and experience of the individual that provide the framework within which a given decision is made, such as the individual's knowledge of language and his knowledge of spatial relations. It would be possible to consider this information on a par with new and current information. But this presents us with an almost insoluble problem--the number of possible courses of action in this case is very, very large and, correspondingly, the amount of stored information is, to say the least, difficult to compute.

It seems desirable to take an alternative view, namely, that it is the function of **long-term storage** to limit and define the possible courses of action with which we are concerned at any one time. Thus, we can limit ourselves to the choices open to an experienced pilot who speaks English and who is about to land at an airport with which he thoroughly familiar. It becomes, of course, an empirical matter how large are these subsets, but this problem would appear at least to be of workable proportions.

The principal problems of long-term storage have to do with what are the various subgroups of alternative responses with which a given individual is provided at a given moment. These subsets include, besides his language, his knowledge of spatial relation, and other kinds of numerical or symbolic shortcuts; and the more-or-less permanent "sets" or attitudes, such as an attitude of caution with which he approaches a particular problem. A number of these problems present very promising areas for basic research.

F. Perturbation.

Up to this point the flow of information has been treated as if it were a process of almost mathematical precision. In reality, of course, any real system is subject to disturbances of many kinds--let us say that there is always **perturbation**, just to give the process a very general name. We now face an interesting point. So far as the recipient of information is concerned, the result of perturbation is no different from any other information as long as he is dealing with the single channel.

To take an extremely simple example, if a pilot has no other information, a flashing light actuated by a fan marker is no different from the flash caused by the chatter of a relay or by spurious transmission. The point is simply this - error in any system cannot be defined unless there is some independent, extra-system criterion against which an event can be compared.

The Criteria of Perturbation. There are many ways in which an external criterion of error or perturbation may be set up, but let us note that some criterion is always necessary. The following are a few examples:

1. A person has independent knowledge by another channel or at a later time of what information was **transmitted**. A comparison of transmitted and received information reveals "errors". Thus we monitor a communication circuit by feedback of received information. A similar, but less reliable, determination of information **transferred** is obtained by monitoring the actions of the recipient.

2. Through instruction or previous knowledge, it is agreed that hisses or crackles in a voice channel, or "grass" and "clutter" in a video display are "noise". They are put into a null class and provide only irrelevant information.

3. A person already knows what decision is to be made and consequently what information he needs. Other information is considered "irrelevant" to the problem.

The Effect of Different Kinds of Perturbation. In many ways these three types of perturbation are strictly equivalent. The result can be put in probability terms--on the basis of a given amount of information which is received, the greater the perturbation, the less is the probability that the course of action chosen will be the desired one. Or, if there is set up some standard of excellance that must be achieved, then the greater the perturbation, the more redundant must be the message in order to achieve that standard.

To emphasize for the moment a general point that will be repeated later in connection with particular forms of display, let us note that irrelevant information is at least as bad as "noise" in a system. Actually it may be much worse because it may take longer to identify and discard than strictly random perturbation. While there may be important differences among noise and irrelevant information, just now we would like to emphasize the likeness.

A further point should be made. There is nothing about the information itself, or the perturbation, that is inherently good or bad. It is only when the system, or the individual, is limited in some way that a problem arises. Thus if a person can assimilate information only at a rather limited rate, the inclusion of irrelevant information reduces the rate at which he can make decisions and lessens the efficiency of the system of which he is a part.

G. Redundancy

Information is transmitted to the extent that any of several possible events might have occurred. In order for information to be a maximum the probability of each event in a sequence must be independent of other events in the sequence.

Very often this is not the case. The next letter or the next word in speech is actually chosen from a very limited set and tells the listener little that he did not know before. Thus we see that the efficiency of a system may be reduced by redundancy. Shannon (1948) has extimated that the redundancy in terms of letters in English text is somethings over 50 per cent.

Redundancy and Noise. Let us point out that redundancy is in some ways just the opposite of noise. A highly redundant flow of information is a highly determined sequence. Thus a sequence **left left left left left** is structured and redundant. In contrast, a perturbed sequence might be **l h o i e s v k n e**, which is nearly random. In practice, the one is often used to offset the other because a highly redundant message seems to be received with fewer apparent errors through a given amount of noise. Actually, as was suggested by the experiment described earlier on syllables chosen from the two vocabularies, the gain is more apparent than real. The amount of information transmitted is about the same.

The important practical question always is one of encoding, whether to reduce error by exact repetition of a message having high informational content, or by the use of a single longer and more redundant message. These two are equivalent mathematically but they may have quite different effects on a human recipient.

Redundancy and Intelligibility. In some cases increasing the redundancy of a message may increase only slightly the probability of getting the information through. Thus if a pilot hears "Heading 145" as "Heading 45" he may continue to hear it that way even if the message is repeated several times. Here it may be better to encode the information differently if it is to be repeated. For example, the tower operator could say "Come in over the lake". Another interesting possibility is to give the same information to the eyes and to the ears instead of just repeating it through one sensory channel.

Finally, let us point out that both perturbation and redundancy decrease the amount of correct or relevant information communicated through a clear channel.

H. Research Problems

It should be clear from the discussion above that the measurement of human informational capacities constitutes a research area of basic interest to the development of air-traffic-control systems. The basic problem is the rate at which a human can assimilate information, and the conditions that permit a maximum rate.

Informational Capacities of Different Sensory Channels. There is some evidence at present that the amount of information that can be assimilated in a brief period of time approaches a constant as a limit. We need more evidence on this point and, in particular, we need data on the informational capacities of the various sensory channels.

It is commonly believed that visual presentation is more efficient than auditory. Research supporting this view, however, has not taken into account the redundancy in both visual and auditory messages, nor the adaptability of the two sensory channels to different ways of encoding information. Techniques for handling this problem have, to some extent, been worked out, and it would seem possible to determine the capacity function in terms of information rather than reproduction or action on the message.

Informational Capacity Over a Period of Time. The amount of information absorbed over a period of time is not a simple integration of the instantaneous capacity. The exact form of this function can and should be determined. Given such measures it will be possible to determine the optimum spacing of messages in time.

Information Assimilated in Relation to Amount Available. Another important parameter involves the amount of information assimilated as a function of the amount of information available. There is considerable evidence that a man can be swamped by too much information. Too much may well be as disastrous as too little. On the other hand, men have important sources on which they can draw in circumstances like this. Given time enough, they usually simplify their problems by making a symbolic transformation, substituting a single symbol for a pattern of underlying items. Or they simply learn to disregard some of the available information. The general problem, then, has the following two parts:

1. What is the effect of irrelevant information on the rate of utilizing relevant information? Is the effect of redundancy the same?

2. What happens in the case where all of the information is relevant, and where a large amount of information is needed? If the informational need exceeds the person's capacity, what protective devices are available? This part of the problem involves both encoding and storage. When pressed, the human tends to encode the available information into the most efficient form, to store it, and to put off the decision until sufficient information is on hand.

Breakdown occurs when there is not time for this encoding process.

Research is needed to determine the conditions under which such a process goes on and in particular, to determine if there are optimum means of presenting information for storage--either short or long-term--as opposed to presenting information for immediate action. Such research is closely related to some of the display problems discussed in other sections, such as the problem of combination instruments or the problem of how much information to put on a pictorial display.

Determining the Amount of Information Needed. In one sense, the efficiency of a control system can be given in terms of the ratio of information transferred to information needed. The research problem involved here is essentially methodological. What are the best means of determining the amount of uncertainty--and thus, the amount of information needed in any given situation or system? How does this need change with time?

Asking pilots what decisions they have to make represents one approach to this problem in the air-traffic-control situation. This, however, is not sufficient. We must have a more detailed analysis of the sequence of action and a reasonably reliable estimate of the probabilities to be assigned to alternative possible actions.

Techniques have been worked out for obtaining such data and assigning uncertainty values in simple situations. Research is needed on practical ways of extending these techniques to complex systems. The interest in information-analysis here is related to that in other chapters (see research objective III).

Recommendations

Research Objective II. Determination of the Capacities of Human Operators for Handling Information in a Communication System.

To insure the effective integration of men and machines, it is necessary to establish some general principles governing the nature of the operator as a link in a control or communication system. Decision-making, choosing a course of action, lies at the root of the whole control problem. The selection of the correct course of action, in turn, depends on the information available. As one aspect of the research program, therefore, we recommend the study of human capacities for handling information and suggest that this study be approached from the viewpoint of communication theory.

Problem Area 1. Factors Influencing the Rate of Flow of Information. Studies are needed to determine the information-handling capacity of human operators. This capacity should be measured with reference to such factors as the way in which the information is encoded, the sensory channel used, the regularity or spacing of messages in time, the effect of mixing relevant with irrelevant information, and the effect of increasing the total amount of information required for a decision.

Illustrative research problem. Test the following hypothesis: The presence of irrelevant information retards the rate with which a pilot or ground controller can handle relevant information.

Problem Area 2. Redundancy. Studies are needed to determine the optimum amount and form of redundancy that will insure the fewest errors by a human receiver of information.

Illustrative research problem. Tests of the following hypothesis are needed: The literal repetition of a visual or auditory message is one of the least satisfactory ways of insuring its correct reception - redundancy should be introduced by repeating a message in a different way.

Problem Area 3. Methods for Measuring Human Information-Handling Capacities. Since this is a relatively new research field, support will have to be given to the development of improved methods of measurement in the areas mentioned. We have so little experience to go on that our statement of this problem area is of necessity general in nature.

Illustrative problems. Messages used in current traffic-control operations should be analyzed in an effort to define basic message units. Units of measurement should be developed that will facilitate quantitative comparisons between such widely different means of communication as verbal language, printed language, abstract visual symbols, and scale-and-pointer patterns.

CHAPTER V

VISUAL INFORMATION DISPLAYS

The term **visual display** designates any device used to provide information for the eye of the human observer. The characteristics of such devices that concern us here are not the methods used to transform electrical, mechanical, or other signals into visual sitmuli, but the characteristics of the visual stimuli provided by the device, such as apparent brightness, color, spatial pattern and temporal pattern. In other words human engineering is interested in the manner in which the information is formulated or encoded for presentation to the eye.

The need for further research on visual displays is suggested at every stage of operation in the air-traffic-control system. It is fortunate, however, that the display problems of air control are very similar to those encountered in the display of data in many military information systems.

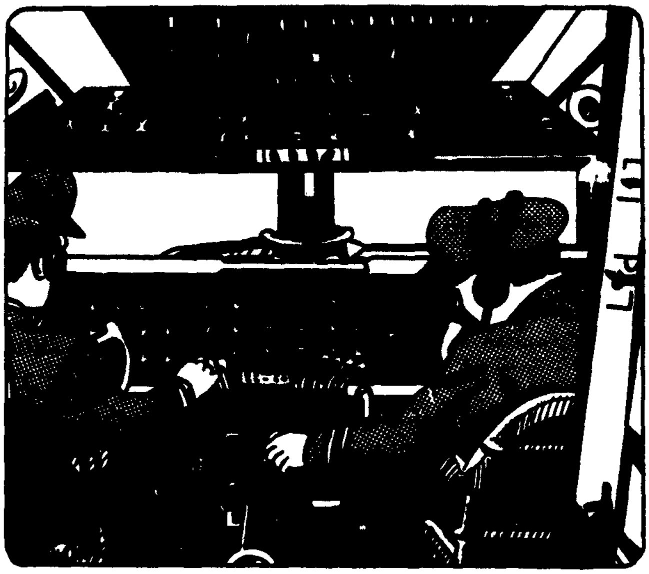
Display research that is now foremost in the efforts of engineers and psychologists working on many military contracts will, for the most part, be directly applicable to systems of air-traffic control. The present research effort, however, is insufficient to solve all the problems in the foreseeable future, and there are certain important problems that no one has yet gotten around to studying at all.

The following, in summary form, is a catalogue of the most important research that yet needs to be done. Although it is oriented primarily about the air-navigation and traffic-control display problem, this discussion is sufficiently general to apply equally well to displays for many other purposes.

A. Determining What Information Should Be Displayed

As we have emphasized before, the first step must be to find out how much and **what kind** of information a man needs to perform his particular task. For the practical problem of designing displays, we need to have an informational job analysis of the operator's task, both ground and air, as it will be in the future. It is impossible to design a good display without knowing what critical information it must provide, and it is certainly a mistake to put more information on a display than is necessary just to avoid doing the job analysis.

Such an analysis gives the framework within which the real problems are set. These problems have to do with what a man does in getting an answer out of the information presented. Sometimes he has to make only a simple comparison. At other times the readings of his instruments must be transformed, the complex situation analyzed so that relevant items are selected, and new combinations of information made.



The nature and timing of these tasks of analysis, comparison, transformation, and recombination have much to do with the best way of displaying the data with which the man has to work.

B. The Kinds of Displays That Are Available

There is no completely satisfactory way of classifying visual displays in terms of the requirement they place on the human operator who uses them. However, several papers on the subject are available (*see especially Chapanis, Garner, and Morgan, 1949; Fitts, 1949; Grether, 1948; and Kappauf, 1949a*). One of the most discussed problems in the field revolves around a distinction between pictorial and symbolic displays. The point at issue here is chiefly one of realism, the extent to which the encoded information resembles the kind of information one gets when using unaided vision to observe things in nature. Because of the importance of this distinction we shall consider it first and then take up some other special problems in the design of displays.

Much complex data can be shown either pictorially or symbolically. The basic problem to be decided is which method is best for what kinds of information and for what uses of the information. The following is an attempt to define precisely pictorial and symbolic displays, assess their general advantages and disadvantages, and consider the factors that affect their use. Much of this discussion is based on an earlier report by Grether (1947).

Pictorial Displays

A pictorial display exhibits relevant information

(1) by means of the same continua along which the information itself is normally measured, and (2) without distortion of critical relations.

Realism. The great advantage of this type of display is that it is easy to interpret. Length is shown as length, angle as angle, color as color, and distance as distance. If one aircraft is twice as far away from the observer as another, it appears twice as far away on the display. If one object is one-half as large as another, it appears as such.

The most obvious examples of pictorial displays are scale models and distortionless pictures. A less evident type of pictorial display is the polar-coordinate plotting board. Also included are televised pictures and photographs. Many radar displays employing cathode-ray tubes, such as the plan position indicator (PPI), A-scan, C-scan, and E-scan, fulfill this definition.

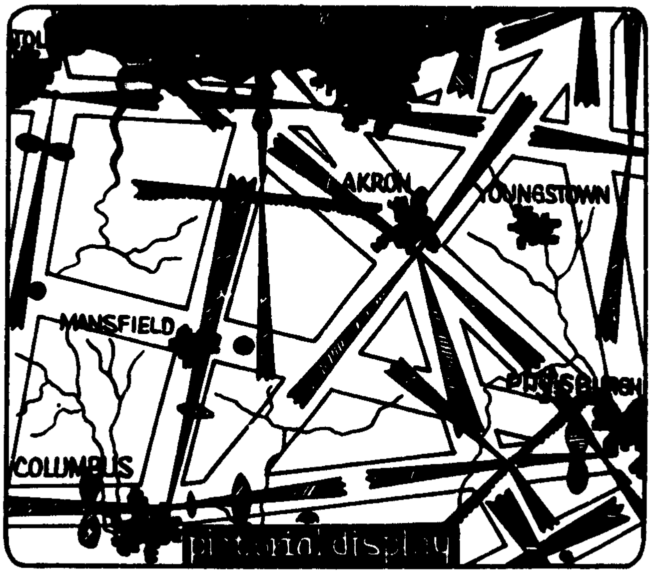
In practice, of course, very few aviation displays are completely pictorial in the sense that they represent all aspects of possible information in a manner true to nature. There are many types of useful displays, however, that depict relevant information pictorially.

A PPI indicator, for example, is not pictorial in relation to the height of objects or their identities, but it is completely pictorial in the portrayal of two-dimensional information - all geometric relations between the objects portrayed are essentially the same on the display as they are in reality. Being less subject to visual perspective and size constancy effects, the PPI indicator may even be more "accurate" than a direct view of the scene.

Semi-Pictorial Displays. To have a pictorial display, it is not necessary to have accurate registry of all sizes, shapes, colors, and brightnesses. The important factor is whether the critical relations are shown in an undistorted manner. If true size is a necessary datum for the transmission of essential information, it should be displayed accurately. If shape provides required information, it should be displayed with precision.

In practice, complete realism in a display is seldom desirable. In the first place, it is probably advantageous to strip away much of the irrelevant information normally making for realism and to show only the critical relations. In the second place, a somewhat modified display sometimes looks more real than an exact copy of nature. As an illustration, a display for airport surface control might want to show only the runways, taxiways, and parking areas, and objects in these areas, and to omit all detail in the remaining parts of the airport.

Probably much of the discussion concerning the relative merits of pictorial and symbolic displays stems from a lack of recognition of the fact that a display does not have to be, and rarely can be, completely pictorial to have the advantages of realism. There are as many kinds of pictorial displays as there are symbolic displays, and the decision is not ended when we say we will use a pictorial or realistic display. Rather, the decisions have just begun.



Consider the three-dimensional map, for example. Mountains would be completely invisible on a model of the United States, if all three coordinates were to the same scale. And yet a very satisfactory scale model can be made if the elevation coordinate is a different scale than the surface coordinates. However, when the three coordinates are all different scales, then geometrical relations are in fact seriously distorted. Thus, we have to decide which aspects of the display will be pictorial, whether all aspects of the display will be to the same scale, whether the aspect being scaled is distance, area, brightness, or whatever.

Symbolic Displays

A symbolic display portrays information in terms of intermediate or transformed scales. In symbolic displays the information usually is not displayed in the same way it is observed in nature, or if it is, a distortion of the information continuum is introduced.

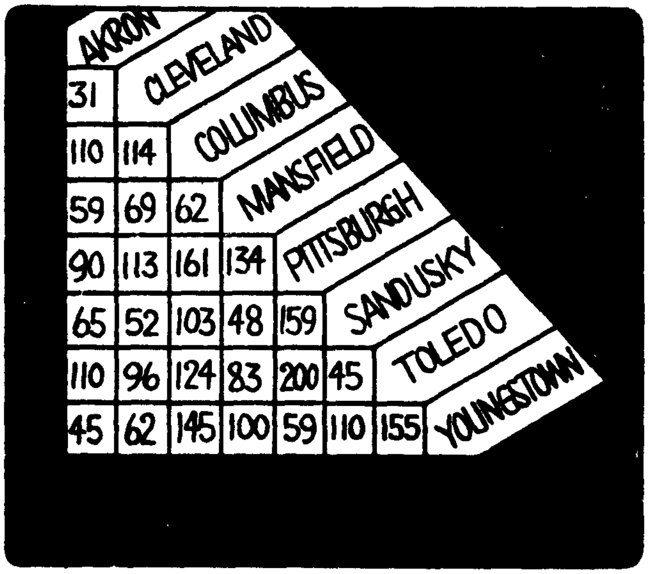
For example, distance, a scale of extent, may symbolically portrayed as a number. Numbers, of course, can very accurately indicate distance, but the number scale is not the same thing as the scale of perceived distance. Distance may also be shown by the position of a pointer on the circular scale of a meter. Here distance is represented on a scale of extent, to be sure, but it is a curvilinear scale of distance and is thus distorted with respect to the scale of perceived distance, which is linear.

One great advantage of a symbolic display is that it makes possible almost any degree of precision along a given dimension. It is usually possible to provide as many steps along the transformed scale as are justified by the intrinsic reliability of the data.

Scales of Extent. Any scale that represents certain classes of information by a continuum of extent constitutes a symbolic display. Time, for example, might be shown as the length of a line. The size of a radar pip can be used to symbolize the speed of an aircraft.

Scales having nongeometric relations also fall in the class of symbolic displays. These include scales of brightness, color, flicker, frequency, and shape. Scales constructed from these properties may be used to portray a limited amount of information symbolically. As an illustration, altitude layers in a holding area might be portrayed by different colors or shapes.

Numerals and Letters. By far the most important symbolic representation for display purposes is the use of numbers and letters. A vast amount of complex information wholly unsuitable for pictorial display can be shown by this means. Good examples of this are such quantities as time, temperature, and weight, which cannot be sensed directly by vision. Through long experience man thinks easily and effectively in symbolic terms when dealing with this kind of information.



	AKRON	CLEVELAND	COLUMBUS	MANSFIELD	PITTSBURGH	SANDUSKY	TOLEDO
CLEVELAND	31						
COLUMBUS	110	114					
MANSFIELD	59	69	62				
PITTSBURGH	90	113	161	134			
SANDUSKY	65	52	103	48	159		
TOLEDO	110	96	124	83	200	45	
YOUNGSTOWN	45	62	145	100	59	110	155

Combined Pictorial and Symbolic Displays.

Many conventional displays combine dimensions of information in pictorial and symbolic form. As an illustration, no radar displays are completely symbolic. All have at least one pictorial dimension. The B-scan, for example, distorts bearing information, but presents range as a linear extent in which true relations are preserved. The G-scan shows azimuth and elevation angle without distortion, but indicates range by the length of "wings" projecting from the pip. Displays of three-dimensional information are usually partially symbolic except for those that depend upon stereoscopic vision or devices that create the impression of depth.

There is, of course, no reason why combinations of displays may not be advantageously exploited for specific purposes. For example, a PPI display of radar bearings and range, with altitude and identity added symbolically as color and shape coding of echoes, might be more useful to an air-traffic controller than a conventional PPI. The "Navascreen" is an example of an effort in this direction.

Factors Influencing the Selection of Pictorial or Symbolic Displays.

The decision to use a pictorial or symbolic display depends chiefly upon two things. The first is whether it is mechanically or physically possible to display a given kind of information by the particular display method. This is in part a technological problem, but there are also certain classes of information that cannot be represented directly. Temperature is an example. Assuming, however, that the information can be displayed by both methods, the second consideration is the use to which the display is put. The first problem, how to get data into a display, is largely a matter for engineers. The second problem is a human-engineering one because it relates directly to the efficiency with which the display can be used. There are several considerations that determine the selection of the kind of display.

1. *What Kind of Information is being Displayed?* The choice between symbolic or pictorial display depends first of all on the kind of information to be displayed. In general, we can say that a pictorial display is usually superior whenever **relational information** is being displayed, but that a symbolic display is usually better for portraying **spot or discrete** information. For example, if we want to display the position of a particular aircraft, a symbolic display showing the range and bearing of the aircraft can be read quickly and accurately (and these are the main criteria of a good display). If, however, the position of the aircraft relative to that of another is required, then the user needs to do a great deal of mental translation before he can see the relative positions of the two aircraft from, let us say, a set of six numbers. The information portrayed in the pictorial display requires much less transformation before it is acted on than does the information in the symbolic display.

In general, the greater the number of items about which relational information must be shown, the greater the advantage of the pictorial over the symbolic display. But the advantage is only in showing the relational information, not the specific item information.

Thus, the relative positions of 100 cities are easy to see on a map, but would be very difficult to infer from a symbolic display. If, however, we need to know the distances between any two selected cities, then the entire map is not as good as a two-way numerical table listing these distances. Particular cities could be located much more quickly, and there would be no interference from the extraneous information presented on the map. A correspondingly good display might be achieved, of course, by **selective display** of the pertinent part of the map.

A symbolic display is ideally suited to the discrete and single-item type of information. If discrete information about many different items is necessary, however, then the symbolic display loses its advantage, and the pictorial display can become more efficient even when relational information is not required.

2. *What is the Information Used For?* Another major consideration, even more important than the kind of information to be portrayed, is the question of what the user of the information intends to do with it.

As a general rule, we can say that the information should be presented in the form in which it will be used.

Thus, if a ground controller is simply going to report a range and bearing to an aircraft pilot, the best way to give the controller that information is in the symbolic form in which he later transmits it (i.e. as numbers).

However, if the ground controller wants to know where to look for an aircraft, then the display he sees should, figuratively speaking, "point to" the approaching aircraft. The crux of the matter is that information should be displayed so as to **minimize** the transformations that must be made before decisions are reached and action is initiated.

An Illustrative Experiment. Investigations by Williams and his associates at the University of Illinois will illustrate the kind of experiments that can be conducted in this area (see *Williams and Roscoe, 1949; Roscoe, et al. 1950*). Their experiments involved comparison of several pictorial and symbolic methods of displaying distance and bearing from an omni-directional radio range station.

Subjects in these experiments were pilots. They solved various orientation problems using static mockups of the displays as well as operational displays in a Link instrument trainer. The pilots used the information presented in the displays to decide on a course of action, e.g. a direction to fly, in order to approach or depart from the Very High Frequency Omnidirection Range (VOR) station either directly or along some designated track over the ground. The results show that the pictorial displays were uniformly superior to the symbolic displays for this kind of task and that the best of the pictorial displays was one that was azimuth stabilized with the VOR station represented in the center of the display.

These experiments need to be supplemented by much more work comparing pictorial and symbolic displays. Other uses for pictorial displays should be investigated--such as making an instrument approach and landing--and other kinds of symbolic and pictorial displays should be tested.

Summary Statement. Although the issues are now fairly clear, we must conclude that at the present time we do not have a firm scientific basis for answering many of the important questions about the kind of display to use for various purposes. It is true that experiments have been done to answer some specific questions, and that a few very general principles seem to have rather wide application. But there is a lack of clearly-established principles to guide our choice of the type of display for specific functions. Instrument companies still have to rely chiefly on past experience with older-model instruments and on the subjective opinions of their engineering staffs when they decide what kind of display to use with a new instrument.

C. General Problems in the Display of Transitory Information

There are a variety of problems that need to be solved before visual displays of maximum effectiveness can be designed. Many of these problems are associated with the fact that a large number of displays must be designed to present ever changing, transitory information. Displays that present flight information to the pilot or displays for ground controllers that depict the continually changing position of aircraft in the traffic system are of this type.

The very fact that the information presented is transitory creates a number of problems not found in displays designed to present more or less permanent status information such as is found in maps, charts, and printed messages. In this section we shall present some of the more important considerations that arise in the design of displays for presenting transitory information. Not all of these problems are unique to the changing character of the information but all are associated with displays of this type. In the next section we shall discuss the problems that arise in connection with displays for presenting status information.

Several Simple Displays, or One Complex Display?

Frequently, one has the option of displaying a small amount of information on a single instrument and of using several such "simple" instruments, or of displaying a larger amount of information on a more complex instrument.

Pictorial displays usually require more space, but make relational information more readily available than do symbolic displays such as pointer-scale instruments. This is one of the considerations in choosing between these two types of displays.

Combined symbolic displays also usually occupy less space than several simple displays, and may require shorter and fewer eye movements; but the complexity may create confusion.

The question is largely one of optimum patterning of visual stimuli. **What kind of patterned arrangements of scales and pointers and other kinds of displays permit most rapid reading, and the easiest relating of correlated information?** Unfortunately, not enough research has been done on this problem to provide any general answers.

Two commonsense principles have been followed by workers in this area. One is that related things should go together wherever possible. The other is that there is a limit beyond which we should not go in crowding information into a single display. Much more research on this problem is needed.

How Should Position in Three-Dimensional Space be Displayed?

We have mentioned how important it is at times to show relations in a "natural" or easy-to-interpret way, and we have considered some of the problems of complex displays.

A special problem of great importance in aviation is the display of the position and inter-relations of objects in three-dimensional space. The pilot wants to know his attitude with respect to the air steam and the ground. He wants to know where other aircraft are in relation to himself and how these relations are changing. The ground controller also wants to know the location of aircraft in relation to each other and to the control point. (See Hermans and Loucks (1947) for a review of the psychology of orientation).

"Three-Dimensional" Displays. A satisfactory pictorial method of displaying bearing, range, and height is still being sought. Various methods that crowd three-coordinate data into one display have been tried out, some experimentally. Methods that employ two separate displays to give three-coordinate data have been studied and several have seen operational use. At least three distinct ways of displaying three-coordinate information to a GCA final approach controller have actually been used - two symbolic displays (meters); a combined symbolic-pictorial display (an elevation meter plus an azimuth sector scan); and two pictorial displays (an elevation sector scan plus an azimuth sector scan). However, because the results produced by these variations in display have been confounded with technical improvements and the elimination of intermediate human operations, it is not possible to make direct comparisons between these three kinds of displays.

Recent research at Johns Hopkins has included systematic investigations of various symbolic systems for adding a third dimension to blips on a cathode-ray tube by varing the size, brightness, or color of the blips. Research at Ohio State has included the analysis of various projection systems for showing three spatial coordinates on two-dimensional surfaces. Preliminary unpublished results indicate that polar sector coordinates are superior to rectangular coordinates for this purpose. For example, two polar sector scans were found to be superior to a B- plus a C-scan.

Flight Instruments. The aircraft pilot is interested in his location in space, his attitude, and his rates of change of location and attitude. Up to now, cockpit displays have been very different from ground displays, although for some segments of a flight, such as an instrument approach, some of the information being displayed to a pilot and to a ground controller is the same. With the growing interest in the use of a cathode-ray tube type of display in the cockpit, the problems of air and ground displays of space relations are becoming more alike.

Human-engineering research on the problems of displaying flight data has been centered chiefly at the USAF Aero Medical Laboratory and at the University of Illinois. Dr. Roger Loucks, under Air Force contract, continued some of his war-time research on flight instruments after returning to the University of Washington. Experiments at the University of Illinois have included studies of DME and VOR displays and special kinds of landing displays. *(see, for example, the experiment described on page* 22.*)*

Work at the Aero Medical Laboratory, as an illustration, has included laboratory studies of speed and errors in interpreting attitude displays, studies utilizing specially designed equipment for simulating and recording instrument flight, and experiments in which aircraft performance, control movements, and pilot eye movements were all recorded during actual flights using different kinds of instruments and instrument arrangements. Experiments at the Aero Medical Laboratory have included studies of displays for altitude, attitude, heading, speed, and glide path-localizer deviations.

An Analysis of Instrument-Reading Errors. Fitts and Jones (1947) at the Aero Medical Laboratory, made an analysis of the kinds of difficulties experienced by Air Force pilots in reading instruments. The "critical incident" technique was used and emphasis was placed on near accidents or close calls. The following were the major types of errors or difficulties involved in reports of 270 such experiences:

	Percent
1. Misinterpreting Long-Range Scales.	18
2. Misinterpreting Direction of Indicator Movement (Reversal Errors).	17
3. Misinterpreting Visual and Auditory Signals.	14
4. Errors Involving Poor Legibility and Visibility.	14
5. Mistaking One Instrument for Another.	13
6. Using an Inoperative Instrument.	9
7. Misinterpreting Scale Values.	6
8. Errors Associated with Illusions.	5
9. Omitting the Reading of an Instrument.	4

The results of this analysis help to define many of the more serious problems in designing flight instruments.

A Study of Pilots' Eye Movements. Fitts, Jones, and Milton (1949), in another series of studies for the Air Force, measured the eye movement patterns of pilots as they flew various maneuvers. One of the things they found was that it requires much longer, in flight, for the average pilot to check certain instruments than it does others.

The ILAS cross pointers, for example, were fixated for about 0.9 second each time they were checked, as compared with about 0.4 second for the air speed indicator. This emphasizes the importance of designing instruments that can be read quickly.

Eye movement records provide one kind of criterion measure for evaluating differences in different designs or arrangements of instruments.

Relative Motion Problems

If you were a pilot and heard someone say "Right wing down", what would you think he meant? A moments consideration will make it clear, of course, that the statement is ambiguous. It could mean either (1) put your right wing down, or (2) your right wing is down, put it up.

This illustrates the kind of relative motion problem encountered in aviation. Perplexing direction-of-motion problems arise chiefly in connection with the design of qualitative displays. A qualitative display is defined as one which provides relational information, usually in regard to spatial relations (up-down, right-left) or magnitudes (more-less).

In What Direction Should Indicators Move? In designing most displays one must decide what reference point(s) should be fixed and what point(s) should move. In scale-and pointer-type instruments there is a choice of whether the entire scale or the pointer should move. In either case, there is the further problem of which way the moving element should go, relative to the fixed reference point and relative to the direction in which related controls are moved.

This direction-of-motion problem is a very frequent and troublesome one with air-borne displays, and also arises with some ground displays. In fact, it is the center of several lively controversies. For example, should heading information be displayed by means of a moving scale or a moving pointer, and which way should the scale or pointer move in a right turn? Should the Cross Pointers, or Zero Reader, give a "fly to" or a "fly from" indication? Which way should the attitude instrument (artificial horizon) rotate, relative to the pilot's eye, in a right turn? Should the GCA controller's display be set up as if he were facing the on-coming aircraft, or as if he were in the aircraft facing the runway? Should the Landing Signal Officer on a carrier hold his signal flags *up* to tell a Navy pilot "You are too high", or hold them *down* to indicate "Go Down"?

These relations are critical when there is a sudden transition from contact to instrument flight and vice versa. There also is a problem with respect to the realism of "naturalness" of each type of movement and the attendant possibility of committing reversal errors in times of stress. Fitts and Jone (1947) for example, found that even experienced pilots reported many reversal errors in interpreting instruments and using controls. In fact, this was the second most common type of instrument-reading error revealed by their study.

An Illustrative Experiment. A recent report by Gardner (1950) from the Aero Medical Laboratory illustrates experimental work dealing with motion relations in a flight instrument. A simulated cockpit was arranged so that a joy stick controlled the movements of a Zero-Reader-type instrument having a vertical and horizontal needle. The task was to keep the needles centered in spite of "rough air" simulation. The relations between control stick motion and resulting motion of the display were varied systematically in all four ways possible.

Objective scores for pre-flight Air Force trainees showed that the best performance was obtained when a movement of the stick to the right (right bank) caused the vertical indicator to move to the right. The movement relation for the horizontal needle was not as critical as it was for the vertical one. The investigator points out that the superiority of this "fly from" indication, (one in which the direction of movement applied to the control opposes the movement of the display), while clear cut, was based on data from beginners, and that further research is needed on pilots who have had a great deal of practice in using an instrument designed in accordance with the opposite principle.

Representative summaries of the principles that are supported by available facts on the direction-of motion problem can be found in publications by Chapanis, Garner, and Morgan (1949); Fitts (1949); and Gardner (1950). This is another problem on which more research is needed. It is an area in which there is still a great deal of controversy and lack of uniformity.

As far as ease of learning is concerned, the data on novices uniformly favor the "fly from" type of indication, but many present-day instruments violate the principles that are known to hold for the beginner. Worst of all, most large instrument panels contain a mixture of instruments - some designed according to one direction-of-motion principle; others according to exactly the reverse principle.

Scale-Design Problems

Scales of Extent. Most symbolic instruments use some kind of scale in which values are represented by position on a linear or circular scale of extent. Here one usually is concerned with *quantitative reading,* i.e. the ability to derive a number from a display.

Considerable work has already been done on the problems of designing scales for speed and accuracy of quantitative reading, and the factors affecting scale reading are fairly well understood. At Princeton University, for example, Dr. W. E. Kappauf and his associates have been studying the legibility problem for the Air Force for several years. Their studies have dealt with scale length (dial size), the spacing of scale marks, and dial illumination. In a typical experiment, subjects are asked to read panels of instruments that have varying numbers of scale-division marks, and time and error scores are recorded.

Much work still needs to be done to fill gaps in the legibility picture, but a well-designed scale for many uses is now possible. For a summary of facts on scale design see Kappauf, 1949.

Long-Range Scales. It was mentioned earlier that one advantage of symbolic scales is their ability to provide exact quantitative information. When we include many steps on a scale of extent, however, the scale gets excessively long.

The typical engineering solution to the problem of long scales is to use multi-revolution dials - dials with two or more pointers, each of which represents a different value. Clocks and altimeters, for example, have multi-revolution dials. However, satisfactory these may be from an engineering standpoint, they are difficult for people to use.

The seriousness of this problem was first pointed out by the results of Fitts and Jones (1947) "pilot error" study, and was later verified by Grether's (1949) experiments on altimeter reading errors. Grether, for example, tried out nine designs for an altimeter. Four of these gave approximately one-tenth as many large errors, and at the same time were read several times more rapidly than the conventional altimeter. This was true for 97 experienced Air Force pilots as well as for novices.

The results of Grether's experiments, and of several related studies, fortunately point to what may be a very satisfactory solution to this problem of designing long-range scales. It consists of the use of a single sensitive pointer on a circular dial, plus a veeder-counter type indicator that shows the number of revolutions of the sensitive pointer. This combination of a pointer and a counter, first recommended as an altimeter display, has recently been proposed for various other long-scale instruments such as the DME indicator. Its suitability for these various uses needs to be determined experimentally.

When to Use Numbers. When precise quantitative information is needed, a direct (symbolic) display of numbers generally has been found to be excellent. Chapanis (1949) for example, found that range and bearing could be read quantitatively more quickly and accurately from counters than from a bearing cursor, azimuth scale, and range rings. The time required to read range and bearing for one target, on the average, dropped from 3.5 seconds to 1.8 seconds, while errors were less than half those occuring when a direct numerical display was used. Also, it has been found *(see Carter, 1947)* that tables usually are read more than twice as quickly and accurately as graphs showing the same functions, providing interpolation is not required.

Multi-Purpose Displays. As we have pointed out, the most perplexing problems often arise when a designer sets out to make a multi-purpose display. In the experiment referred to above, for example, Chapanis found that in setting information into the equipment it was harder to use a direct-reading counter than it was to use the conventional bearing cursor and range rings. Which of the alternative designs, then, is the best compromise if the display is to be used in several ways? This illustrates the kind of decision that instrument designers often have to make.

What we must look for in such cases is the best compromise in terms of the multiple uses for which a display is intended. The combination pointer-counter design recommended for the altimeter is an example of such a compromise.

Geometric Scales. Another problem concerns geometric scales, i.e. scales in which changes in magnitude are indicated by variations in length or area. Values of size or length may be used to code information in various displays. As an example, size might be used to indicate altitude on a display. This could be done in two ways. In both, the targets would vary in size according to altitude. In one application there would be a numbered scale of standard sizes visible at the side of the display, to which the observer would refer. This involves matching stimuli and is a relative discrimination situation of a somewhat specialized sort. Some data on how accurately this can be done have been collected by Dr. Samuel Renshaw at Ohio State University for reference sizes varying from 1/8 inch to 2 inches viewed at 15 feet (about the distance for viewing plotting boards.)

In the other application there would be only targets of various sizes visible. This involves an absolute judgment of size. The question, for example, is how many steps of size can a man make use of on an absolute basis?

Special Scales. Still another problem concerns the same questions of relative and absolute perception, as they apply to displays in which information is carried by nongeometrical relations. These include color, brightness, and flicker. Some exploratory work has been done on these problems as well as on the problem of absolute size discrimination. But at present we can get only a first approximation of the usefulness of these kinds of scales.

Psychological Problems in Using Numbers. In operational situations where numbers are read, interpreted, transmitted, and heard, the particular numbers involved are of special psychological importance. Because engineers and scientists deal with numbers on such familiar terms, they frequently do not realize that the average person reacts to numbers in peculiar ways.

One group of problems centers around the fact that certain kinds of number scales can be used much more easily than others. Chapanis and Leyzorek (1950), for example, found that the ranges of targets on radar displays could be located with greater relative precision if the scales were in 1,000, 10,000, 2,000, or 5,000-yard units rather than in 6,000, 7,000, 3,000, or 8,000-yard units. Although, in naval work, a 5,000-yard scale is equivalent to a 2.5-mile scale, the latter resulted in errors which were about 50% greater than the former. This study is a good start, but we need more information on still other possible kinds of numerical scales.

Another group of problems centers around the fact that people exhibit marked number preferences when they are given complete freedom in the selection of numbers for purposes of interpolation. Some work is in progress on this problem at The Johns Hopkins University, but we are still far from understanding all the intricacies of this behavior or what can be done to combat it.

Problems of Visibility and Speed of Detection

Visibility and *detectability* have not been exhaustively studied in the case of transitory information displays. A research program on detection of radar returns has been under way for several years at Johns Hopkins University, but a good deal of work remains to be done. (See, for example, Williams, 1949).

The form and spacing of display numbering, the coloring, shape and size of symbols for use on radar scopes, and the effects of contrast relations, are all subjects for needed experiments. So are the relations between training level, fatigue, and other personal variables and performance on detection tasks. Experiments to determine and improve the visibility of radar scope signals under daylight illumination conditions are still to be carried out. In part, this is a technical engineering problem. Perhaps our television manufacturers will oblige us with a solution to the latter problem, urged on as they are by a demanding public.

Problems of visibility also occur in relation to scales, especially when instruments have to be read at night in the aircraft cockpit or in dimly illuminated rooms. Present systems of instrument lighting are far from adequate. On the whole, however, visibility and detectability problems can more nearly be solved by careful engineering based on the application of existing information than can most of the other problems facing the designers of air-navigation and traffic-control equipment.

The Size and Sensitivity of Displays

Over and above the requirements of visibility and legibility, the *movements, sensitivity* and *damping* of *indices* within displays is sometimes a problem. This is especially true where the display is used as a guide to the manipulation of controls (see the last topic in this chapter). Optimum pilot performance, for example, may depend on the proper sensitivity and damping of indicator needles, just as gain and damping are important in adjusting an autopilot servo for maximum performance and stability.

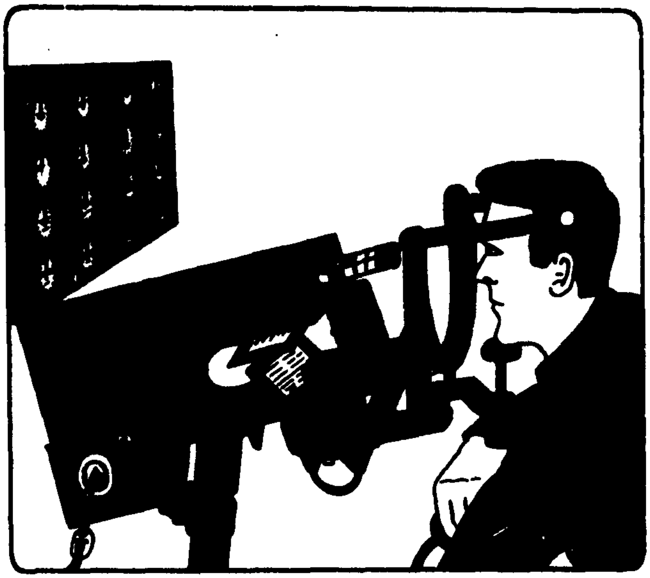
Controlling size is one way of controlling sensitivity. Size also influences the realism of some displays, and in some cases may determine the proper direction-of-motion relations.

The problems in this area are somewhat specialized and perhaps should be considered in relation to certain special design problems rather than as a general problem of display.

Displays for Monitoring and Check Reading

We have taken the position that the human operators are poor monitors when all they have to do is to watch the performance of automatic equipment. However, there are many tasks in which some monitoring is involved. A pilot whose primary task is to watch his flight instruments also has to monitor or intermittently check his power-plant instruments. Ground controllers must be alert to "take over" functions normally performed for them by semi-automatic devices.

Here we shall be considering check reading. *Check reading* is defined as inspecting an instrument, or group of instruments, for the purpose of detecting



deviations from a null or normal condition.

Panels with Many Dials. A moderate amount of work has been done on check-reading problems. The Psychology Branch of the Air Force Aero Medical Laboratory, for example, has found that a properly arranged bank of 16 single-needle instruments, with all pointers aligned in a similar way, can be checked for deviations in less than a second, with an average of less than three eye fixations *(Warrick and Grether, 1948; White, 1949).* In these experiments the panels of instruments were exposed by a shutter mechanism and the time to reach a decision and respond appropriately was measured for each of a number of subjects. The best pointer alignment positions were found to be at 9 o'clock and 12 o'clock. Patterns of lights have also been used successfully when a check-reading indication is desired. Lights cannot be used to give more than an on-off indication, however, whereas pointer-type instruments can be read in finer steps as well as check-read, if they sometimes must be used for quantitative reading.

Emergencies. Very little has been done on the special problem of warning signals. And very little indeed has been done on questions of displays for use in emergencies or in case of the failure of automatic equipment. When he first assumes control in an emergency the human operator may be faced with much more than he can actually handle. Should the controller have special displays for monitoring purposes only, or should he monitor the actual displays he will use should he take over? Should there be some semi-automatic programming of operations that the operator can put in action during the transition as a buffer to keep himself from being overloaded? These are some of the questions to which good answers must be found if the problem of monitoring is to be solved.

Problems of Transfer of Attention

Changing from One Display to Another. Everyone knows how difficult it is to unravel a radar PPI picture when one first looks at it. The amount of information one must take in is great. Yet the operator who has been watching the scope may be well oriented. The only new information he is taking in concerns the parts of the display that are changing. If an operator in a control tower is to transfer his attention from one display to an occasional check of aircraft position on another display, means should be provided to enable him to see what he needs to see without undue groping.

Similarly, if a pilot suddenly has to shift from visual to instrument flight, he needs to make the transition as quickly as possible. On a smaller scale the same need arises when a pilot shifts his eyes from one set of instruments to another.

There should be no inhibiting or interacting effects when men change jobs or change displays. This brings up the problem of coding information on one kind of display so that it corresponds as far as possible to the same information on another display. Displays to be used together must have a common informational denominator. How this may be done is a problem in minimizing transformations of information.

Need for Uniform Principles. The considerations of transfer of attention emphasize the danger of studying one particular instrument, or of planning in terms of part of a man's job, without at the same time considering what other things he will be doing concurrently. Above all it emphasizes the need for uniformity and over-all planning throughout a man-machine system. For example, studies are needed in which an entire pilot's flight panel, having all instruments designed in accordance with a uniform principles, would be compared with a panel designed uniformly in accordance with a different principle.

D. General Problems in the Display of Status Information

Unlike the rapidly-changing situations and transitory data previously discussed in this section, information concerning weather, radio and navigation facilities, air routes, airports, and terrain is relatively slow in developing and changing. Status information gives operating personnel reference data for planning and general decision-making. Operators may need to refer to the displayed material from time to time over a period of many hours. Status information is often presented on maps and charts. Plotting and flight progress boards are utilized for other types of information. Finally, printed or written material may be used to present information such as reminders written on slips of paper, instructions for emergency procedures, and tables of cruise-control data. Much of the information in these categories is displayed on the ground--to controllers or to pilots prior to take-off. However, maps and charts of terrain and radio facilities, and some weather data must be available in aircraft during flight and must be read in the cockpit. The ready availability of status information is obviously essential to the successful operation of air-navigation and traffic-control systems. The communication and display of weather information offers special difficulties, and will be considered first.

Present Practices in the Display of Weather Data

Under present practices Air Route Traffic Controllers are regularly briefed individually by Flight Advisory Weather Service (*FAWS*) personnel just before going on duty, although there is considerable variation in the thoroughness of the presentation of this information. Windsaloft charts and weather maps are available at the *FAWS* desk in the working area, and the hourly weather sequences are distributed to all controllers during the duty period. The method of this distribution varies widely in different centers. A single copy of the sequence reports may be passed around, individual controllers taking such notes as they wish; a summary sheet of pertinent information may be prepared for each sector and posted near the appropriate controller; the controllers may have to walk to the *FAWS* desk and secure the desired information; or special reports on important changes in weather may be relayed by mouth.

In addition, controllers may receive weather reports from agencies outside the control center (control towers, airline dispatchers, pilots, etc.) and pass these along to the weather service personnel to be summarized and sent out by teletype. Some control centers use a large map of the area on which is presented coded weather data.

Pilots read the latest weather reports at the *FAWS* desk, or receive briefings from weather personnel before taking off from an airport. They may also request additional weather information from airport-control towers over which they fly enroute to their destination. This latter is a two-way procedure, since control-tower operators often request first-hand weather observations from pilots in radio contact with their stations.

Present Problems in Regard to Weather Displays

Weather Information Often is "Out of Date". Pilots and controllers frequently complain that the weather data displayed by present methods are often several hours old. This time lag may cause serious inconveniences or delay in directing the flow of air traffic. Changes of flight plans may be necessitated by pilots encountering unexpected weather conditions while enroute. The delay in weather reporting apparently stems from a variety of causes, many of which are not directly problems for human engineering.

Too Much Weather Information is Displayed. Operating personnel, especially pilots, often assert that too many weather data are given to them. It is difficult to sort out the desired information from irrelevant data, and both time errors and errors of interpretation may result. Conversely, information that is very much needed may sometimes be lacking in present reports.

Difficulty in Locating Weather Information When Needed. The central weather display board, if there is one, often is not visible to all controllers, and there may be no adequate substitutes for providing close at hand the latest information needed in planning the flow of traffic over a given area of operations. Many controllers report that they just keep a running mental picture of the weather as they get it from their contacts with pilots and tower personnel.

Forgetting Weather Data. Because of the necessity of applying information of this type over long periods of time (up to several hours), memory difficulties are encountered, especially by pilots. Partly because the original briefing may have been too long and detailed, partly because of the passage of time filled with attention-demanding activities, much essential weather information is forgotten by the time it is needed by the operator.

A better system is needed for making the original data available for ready reference over a period of time on duty or the period of a flight. Pilots have reported difficulty, due to forgetting, in interpreting the symbols in which standardized weather messages are coded, with consequent loss of information from an examination of such reports.

Long Messages. Tower controllers frequently complain of the amount of time on the air that they have to devote to answering pilot requests for weather information, or in relaying requests from pilots to weather personnel. It appears that some means other than voice communication may be desirable for transmitting weather data.

Future Weather-Display Problems

As traffic becomes denser and control more precise, the importance of up-to-date and efficient communication and display of weather information will increase. There will always be an element of uncertainty in weather forecasting. We can at least try to insure the rapid dissemination and efficient display of the reported and forecast data.

The Psychology Branch of the Aero Medical Laboratory has just completed the first systematic human-engineering work in this field. A series of studies attacked the problem of providing USAF pilots with more adequate, useful, up-to-date weather information. The aims of these studies were:

1. To determine any discrepancies in opinion between pilots and forecasters regarding the kinds of information needed in order to accomplish a particular mission.

2. To determine the technical information the forecasters believe they need in order to make adequate forecasts.
3. To determine how well pilots engaged in various types of flying in various kinds of aircraft (strategic, tactical, training) understand weather terms, symbols, teletype sequences, etc.
4. To determine the deficiencies in present station layouts and briefing techniques, and so get clues regarding the optimum layout of weather stations and optimum methods of conducting pilot briefings.
5. As a result of (4), to help set up an "ideal" weather station to be used for experimentation in data presentation techniques, station layout, visibility, noise control, and related problems.
6. To determine critical incidents which pilots believed were caused by lack of weather information, improper briefing, or other weather causes.

This constitutes a very broad attack on the problems, but preliminary analysis of the data has revealed many useful facts of immediate use and many clues for more intensive research on weather problems.

Maps and Charts

Maps and facility charts supply related information about the terrain, air lanes, and navigation facilities enroute, and about the procedures to be followed in approaching an airport. Although this information is relatively stable, it changes often enough so that a pilot or a ground controller cannot safely trust his memory for it.

Tradition. Maps have been in use for centuries, and many of their characteristics are the result of tradition. Elevation color-coding used on most maps, for example, is a throwback to the early days of color printing when the choice of hues and shadings was very limited. The symbols, and the terrain features, selected for representation on maps, often have little resemblance to the way things look from the air.

Problems for Research. What we have to say about research on maps will sound a lot like what we have said about other kinds of visual displays. We need first of all to know what information is needed—what critical things pilots need to have shown, and what things are not essential and only clutter up the display. We need next to study different ways of representing the terrain, radio facilities, air routes, etc., - to find out what symbols to use, how to encode the information, how to provide good legibility even when maps and charts are used in dim illumination, how to facilitate quick reading, etc. (See Crook, 1949).

At present the US Navy is supporting work in this area by human engineers on the staff of Dunlap and Associates, particularly on problems of status displays for use in the cockpit. This work is primarily at the operational level. The Air Force is supporting some laboratory work by the Tufts College Institute for Applied Experimental Psychology relating chiefly to the printing of maps for use under special kinds of low-level illumination. If continued support is given these two projects it is probable that significant improvements in the design of maps and charts can be expected.

E. Special Problems of Ground and Air Displays

It is our belief that research problems in the field of displays should be formulated in as general terms as possible in the hope of getting general answers. However, some specific problems are important enough to warrant special attention. One such question is the extent to which the display of information on the ground and in the air presents peculiar problems.

Problems Peculiar to Ground Displays

A few important problems peculiar to the task of the ground controller can be pointed out. The ground controller will likely make decisions about flight plans and take-off clearances, admission to the approach area, and assignments to the time sequence of landing. Numerous related data must be considered in reaching such decisions. One special problem is estimating future positions of aircraft. Another special problem is the integration of displays used by several men doing related tasks, and the provision of efficient transfer of information from one controller to another as the flight progresses from one stage of control to another.

Once critical decisions regarding a single flight are made, the progress of the flight must be checked repeatedly, in order to be sure that traffic is flowing along the designated routes with proper spacing. This task probably will call for replacement of the present flight progress boards with pictorial displays depicting the approximate locations of aircraft over a wide area, as well as the locations of airports and obstacles to flight. This type of pictorial display will have much increased usefulness if altitude, speed, and identity of aircraft can be coded into the presentation.

For certain tasks ground controllers will need second-to-second information - for example, when they use displays to direct or monitor the final approach to a landing or to direct taxiing aircraft. The problems of ground displays in this case resemble in many ways the problems of air display. Controllers will need to make rapid directional responses, verbal or manual, in accordance with the momentary situation. This calls for a special type of display whose design characteristics deserve most careful attention.

Problems Peculiar to Air Displays

The pilot's informational requirements vary with the amount of responsibility assigned to him throughout the various phases of the air-navigation and traffic-control system. If he is made responsible for deciding upon his entry into the system, for determining his flight path through the system, and for committing himself to a landing with subsequent departure from the system, then his informational requirements are at a maximum. If, on the other hand, these decisions are made for him, either by automatic ground equipment or by ground controllers, and his task is merely to execute the decisions, then his informational requirements are less.

Minimum Pilot Display Requirements. Regardless of the extent of ground control, or the amount of equipment available in the aircraft for automatic flight, it may well be desirable to provide the pilot with enough fundamental decision-making information so that he will not be completely "blind" in the event of a breakdown of the ground system.

We therefore have the problem of deciding what this fundamental information should be and of determining optimum characteristics for the "stand-by" instruments for emergency use. In some ways this problem is similar to that of any monitoring task; in some ways it has problems peculiar to the air.

Some unique problems arise because it is the pilot's responsibility to execute traffic-control decisions. Execution of these decisions may, in routine flight, be accomplished through automatic control of the aircraft. But the possibility of manual control must be open to the pilot; hence each individual pilot must be provided with the information necessary to undertake it.

Pilot Performance is a Critical Factor in Traffic Control. By way of introducing the problems of manual control, we must first point out that the pilot often will be expected to fly his aircraft according to a precise schedule defined in terms of track over the ground, altitude, and speed. Precision is especially desirable in the terminal area. The controls now at his disposal for doing this are poorly suited to the task. As a consequence, many hours of training are required before a pilot can become proficient at this task, and errors are made in its performance, occasionally by even the most skillful.

Under normal circumstances non-fatal errors usually result in little more than inconveniences. But in a tightly scheduled situation, such as is contemplated for traffic control, frequent errors of this sort can hardly be tolerated. Missed approaches, time delays, deviations from planned positions, errors in altitude control, would ruin the precision of any system and seriously affect the flow of traffic. *Errors of this sort are bound to occur because the average pilot cannot fly with the precision that will be required by the system using the conventional controls and flight instruments now found in the cockpit.* This was convincingly demonstrated during the Berlin airlfit, where inability of even skilled pilots to maintain separation enroute was the most serious bottleneck in the traffic-control system, *(Fitts and Long, 1949).*

The future traffic-control system, in addition to imposing requirements of precision flying now beyond the reach of the average pilot, will add to his job by placing in the cockpit new displays unique to the traffic situation. The pilot will have more to do than now, and this will not increase his ability to fly according to a strict track, altitude, and time schedule. It is evident, if the system is to work, that some way must be found to relieve the demands on the pilot and supply him with the proper information to allow him to fly with the necessary precision.

Simplifying the Pilot's Flight Task. The most promising and practical way to permit the gradual introduction of more and more automatic equipment and still permit the pilot to maintain his proficiency, apart from introducing extra-curricular practice sessions, seems to be to design the pilot's equipment in a way that will make the flight task an easier one. This would have a double-barreled effect. If the job can be simplified, the pilot could, by definition, improve his performance to the point where he could perform as the system demanded. At the same time, maintenance of proficiency would no longer be so critical because relearning would be more rapid after periods of non-practice. Furthermore, the pilot would have more time for planning and navigating.

In order to make the flight task an easier one, we must first determine what there is about it now that makes it difficult. The crux of the problem seems to lie in the relation between the movements of the aircraft's controls and the movements observed on the various displays that represent the performance of the aircraft.

Design Problems Relating to the Manipulation of Aircraft Controls

The Manipulative Side of the Pilot's Task. In order to execute his own or a ground controller's decision the pilot is obliged to move the aircraft controls in a way that will cause the aircraft to fly according to the desired directions, altitudes, and speeds. In order to do this the pilot must decide which controls to move, when to move them, at what rate to move them, and how much to move them. Since the information that the pilot needs is continually changing, it must be continually available *(see Williams, 1947).* The pilot cannot rely entirely upon his stored information (prior training) to guide his control movements any more than a motorist can drive down the street blindfolded.

The Pilot as a Closed-Loop Regulator. Flight information comes to the pilot for the most part either through direct vision of the outside world or through flight instruments. It is the latter with which we are mainly concerned. But in either case the information is presented in the form of two indices, one representing the desired performance of the aircraft, the other representing the actual performance of the aircraft. One or the other of these indices moves in correspondence to the response of the aircraft to appropriate movement of the cockpit controls. The task of the pilot is to align the various pairs of indices.

Thus the pilot is faced essentially with a tracking task. It is a complex task involving many kinds of tracking. In a single maneuver, for example, the pilot may be required to perform both compensatory-pursuit reactions and following-pursuit reactions. He may simultaneously be faced with a position tracking task, a rate tracking task, an acceleration-tracking task, and even the task of stabilizing a third derivative relationship between control position and index movement. (For a general treatment of the pilot as a regulator see Craik 1947, 1948; Ellson, 1949; Hick and Bates, 1950).

Stability Problems. Unfortunately, it is in the higher tracking tasks that the pilot is basically interested. He is interested, for example, in his position in space as might be represented by a localizer needle. Yet direct positioning of this needle by aileron and rudder without additional information about heading and bank is virtually an impossible task. Heading governs the rate of movement of the localizer needle, bank governs the rate of change of heading, and finally, aileron position governs the rate of change in bank. The pilot cannot tell by looking at the localizer needle what change in bank is called for, i.e. how to position the aileron. Control of other dimensions of flight (altitude and speed) is only slightly less complex. Finally, the entire tracking task is complicated by various time lags (with consequent overshooting) that are introduced as a result of the inertia of the aircraft and the lags of the instruments themselves.

Simplifying the Pilot's Task. If the pilot's task is to be simplified this is an area in which great gains can be achieved. Recent records taken during certain maneuvers of instrument flight at the University of Illinois (unpublished) suggest that the pilot works at his maximum capacity for accepting and processing new information when flying test maneuvers. The records showed that only a very small portion of the information actually presented by the flight instruments was being used. Had more of the available information been accepted the resulting performance could have been greatly improved. Presumably more information was not accepted because the pilot had already reached his maximum rate for handling information. The implication is that much of the information the pilot needed should have been "predigested" and presented to him in terms of the relatively few alternatives that really need to be considered in order to perform the task, rather than in terms of the estimated ten to twelve alternatives that are displayed to the pilot because of the way the information is encoded in conventional flight instruments. Eliminating unessential information in this manner allows the pilot to spend full time on information that is critical.

Research on the Problems of Aircraft Control Manipulation. Research on this problem should start with an investigation to determine the least number of alternatives that a pilot needs to be concerned with in performing his manipulation task. The number of alternatives is undoubtedly related to the characteristics of the control system itself. This approach opens up new possibilities for simplifying the pilot's task through redesign of the stability and control characteristics of the aircraft.

A great deal of research must be done to determine how to present the pilot with no more information than is necessary in his normal task and yet provide him with sufficient information to cover all possible tasks that he might be called on to perform. This is no small problem. The Zero Reader type of instrument, for example, has admirably simplified the task of control manipulation in a normal instrument approach. But it does not present basic position, heading, bank and pitch information that might be required for other maneuvers such as, for example, recovery from unusual attitudes and positions.

Still another area of research must be concerned with the size, sensitivity, and dampening of various instruments used for control manipulation. Since these problems are similar to problems mentioned elsewhere in this chapter they will not be expanded on here.

Summary. Finally, and in summary, we need to know a great deal more about the tracking behavior of human beings. This is especially true when the tracking task to be performed is complex and rapidly changing in character and when various time constants are introduced into the control-display linkage. We need to know what happens to complex tracking behavior under conditions of stress and fatigue. And we need to develop more complete criteria of tracking performance.

F. The Criterion Problem in Research on Visual Displays

This chapter has considered research leading to the improvement of visual displays for presenting visual information to pilots and ground controllers. As in all research the question of criterion measures, by reference to which results are evaluated, is a critical one. We have emphasized the importance of two considerations, (1) the nature of the information to be displayed, and (2) how the information is to be used. These two considerations serve in part to indicate valid experimental situations and measures. The final test, of course, is the relating of specific test results to efficiency in the operational situation. The criterion problem is considered in greater detail in Appendix III.

Laboratory Experiments. Most of the research problems outlined in this chapter will have to be investigated initially in the laboratory. In some cases the criteria of good design are fairly clear. Problems of *visibility,* for example, suggest that criterion measures be secured by standard procedures employed in studies of minimum stimulus conditions such as *low illumination.*

Problems of *check reading* require emphasis on *speed* of response rather than precision, while studies of *quantitative reading* require major emphasis on *accuracy.* Fortunately, in many human-engineering experiments speed and accuracy have been found to go hand in hand *(see, for example, Grether, 1949);* in other words the design giving greatest accuracy usually gives greatest speed.

Research on flight instruments and control manipulation introduces very important questions regarding the laboratory equipment employed and the degree of "realism" used in experimental situations. Here the checking of the results from the laboratory in operational situations becomes increasingly important. We would like to emphasize again the importance in many operational tasks of *division of attention,* discussed in a preceding section. This consideration emphasizes the importance of evaluating specific instruments in terms of how well they can be used on the job where the human operator has many tasks to perform.

Ease of Learning as a Criterion. Other things being equal, the design is best that facilitates most rapid learning of a particular task. This is one reason for using novices in laboratory experiments and in using learning time as a criterion of effectiveness. However, there are other important considerations, such as the ease with which highly trained operators can transition to the new design, and the *level* of performance reached at the end of an extensive learning period. In general, ease of learning is an indication of final performance, but it is not safe to assume that the relation is close. Performance during learning should not be the only criterion used to evaluate design principles.

G. Summary and Recommendations

This chapter has covered the most extensive, and probably the most important area of human engineering. It is an area in which great strides have been made in the last six to eight years, and in which some vigorous research is underway. It is also an area in which a great deal more remains to be done.

It is appropriate, in summarizing this chapter, to emphasize two general research areas that are equally important for the research recommended in the preceding chapter, and in those to follow. These are the related problems (a) of determining the information requirements of various tasks, and (b) of developing criterion measures of success in task performance.

We therefore recommend the following three broad research objectives:

Research Objective III. Determination of the Essential Information Required at every Stage in the Operation of an Air-Navigation and Traffic-Control System.

Systematic studies are needed to determine the essential information required for making the decisions and carrying out the various tasks involved in navigating and in controlling traffic. Such information analyses are needed in connection with most of the technical objectives that follow. These studies should include experimental investigations in the laboratory, job analyses, system analyses, operational analyses, and field studies of certain existing operations. They should cover both transient and status information and the information needed both by the ground controller and the pilot. They should be made for specific existing systems, and also, in so far as possible, for the basic functions common to all systems.

Illustrative research questions. What does a pilot need to know about weather? What information is essential in a pictorial display for airport taxi control? What information is essential in order for a pilot to orient by means of ground lights? What is the relative frequency of different types of air-to-ground messages such as "command-type" and "information-type" messages? What information should be included in a Human Engineering Handbook?

In specifying information needs research should answer such specific questions as the following:

a. What information is needed?

b. With what accuracy is it needed?

c. How much time is available to use it?

d. What decisions will be made and what actions taken about it?

Research Objective IV. Establishment of Criteria and "Indices-of-Merit" for Human-Operator and Man-Machine Performance.

The criterion problem arises in connection with all of the research problems dealt with in this report *(see Appendix III)*. The answer to the problem begins with the determination of a theoretical ideal level or "model" of desired performance. This ideal model should define the ultimate criterion for the system. Unfortunately, it is not often that the research worker can relate his experimental data directly to such an ultimate criterion. Instead he must make use of proximate or intermediate criteria or "indices-of-merit."

The development of satisfactory intermediate criteria is an important problem. At this level we deal with parts of the system, sometimes even with single instruments and specific ways of using them. It is essential not only that we measure the effectiveness of these specific operations, but that we relate our measures to the higher order or ultimate criteria in terms of which the entire system is being designed.

Investigators in the field of human-engineering have made some progress in establishing criterion measures. However, many new criterion problems arise whenever research is undertaken on a new system.

It is our belief that the criterion problem cuts across every aspect of human-engineering research, and that almost every investigator must devote careful thought and expend some research time on the criterion aspects of his special problem. We believe accordingly that it may be misleading to break up this general topic into specific problem areas and so we list no specific problem areas here. The criterion problem should be studied as an important aspect of each of the other research objectives.

Illustrative Research Questions. Questions illustrating the criterion problem can be grouped under three headings:

a. Questions about ultimate criteria: How can the ultimate objectives of a system be form- more specifically and quantitatively? For example, is runway utilization the best single ultimate criterion of the efficiency of a traffic-control system?

b. Questions about intermediate criteria: What are the most satisfactory measures of the effectiveness of a communication system? A display system? An airport lighting system? How do the measures of the effectiveness of each of these systems relate to the ultimate criteria? For example, are pilot eye movements an index of the effectiveness of a proposed instrument-arrangement, and how do eye movement measures relate to the accuracy of instrument flight, to safety, etc.?

c. Questions about techniques of criterion development: What are the best methods of collecting data on what human operators do on the job? What are the best methods for determining the reliability of these measures? What are the best methods for determining the interrelations between intermediate criteria, and the relations between intermediate and ultimate criteria? For example, what is the most reliable method of obtaining and reporting information about accidents and near-accidents?

Research Objective V. Determination of Principles Governing the Efficient Visual Display of Information.

A good display is one that facilitates the flow of pertinent information to a human operator. The principles governing the design of such displays are still incompletely understood and much work is needed in this area.

Problem Area 1. Simplicity versus Complexity of Visual Displays. Studies are needed to determine the relative advantages of displaying a given amount of information (a) by means of a number of relatively simple instruments, and (b) by means of a single complex instrument. We propose a general hypothesis that there is a limit to the amount of information that should be crowded into a single display. Research is also needed to determine the maximum number of different ways in which related information can be encoded and presented simultaneously.

Illustrative research problem. If one wanted to depict, by means of a symbol on a cathode ray tube, four things about an aircraft, it would be possible to do this by using the color of the symbol to depict one thing, its size another, its brightness another, and its shape still another - (its position, of course, would provide information along two additional dimensions). Studies should be made to determine whether a controller can respond effectively to symbols which are categorized simultaneously in as many different ways as these.

Problem Area 2. The Display of Spatial Relations. Studies should be made to determine principles governing the effective display of information about the relative position of aircraft and ground objects in tri-dimensional space. Numerous questions of great practical importance must be solved in this problem area. These include the following:

a. *What coordinate systems and what type of projections should be used in showing spatial relations on bi-dimensional pictorial displays?*

b. *How should information about spatial relations be encoded on symbolic displays?*

c. *What combinations of symbolic and pictorial displays are most effective?*

Illustrative research problem. Test the following hypothesis: In a semi-pictorial airborne approach and landing display it is better to show azimuth and elevation pictorially, with range presented symbolically, than to show azimuth and range pictorially with elevation presented symbolically.

Problem Area 3. Coordination of Displays and Controls. Studies are needed to determine the display characteristics that are necessary when the action taken in response to displayed information is a manipulation of controls, and when this movement in turn results in a modification of the display.

This problem area is particularly critical for the pilot. The pilot sees the movement of displays relative to his own eye and the rest of the cockpit; yet he must interpret this information in terms of the movements of his aircraft relative to the earth.

Problems which arise here involve direction-of-motion relations between displays and controls, the question of what is responded to - displacement, acceleration, or some higher order, and the optimum sensitivity of displays. Such problems have been receiving some research attention, but as yet few general design principles have been established.

Illustrative research questions. Should flight instruments be designed in accordance with the "fly-to" or "fly-from" principle? In a pictorial display of the aircraft's track over the ground should the aircraft appear to move and the ground appear to remain stationary, or should the aircraft's location appear fixed and the ground appear to move? When should azimuth stabilization and when should heading stabilization be used? How accurately can controls be positioned in response to derivative information? What is the optimum sensitivity for a heading or back indicator? Principles that will settle questions of this sort must be established to achieve the level of pilot performance required for precise navigation and traffic control.

Problem Area 4. Displays for Quantitative Reading. Studies are needed to determine principles for designing displays so as to increase precision, and reduce the incidence of gross errors, in reading scales. Considerable research has been completed on scale reading precision, and on the nature and magnitude of interpolation errors, but relatively few studies are available on the origin of gross errors such as "reversal" errors, and on ways of minimizing such errors.

Sources of possible confusion in shifting from one instrument to another, or in interpreting different kinds of scales, should be investigated thoroughly. The potential value of studies planned to eliminate the causes of gross errors is indicated by the results of recent experiments which showed that by changing the face of the conventional altimeter the frequency of 1,000-foot errors could be reduced by a factor of more than 10.

Illustrative research problem: Determine whether the principle of combining a single sensitive pointer and a counter to provide a "long scale" instrument can be applied generally in the design of many different kinds of instruments.

Problem Area 5. Displays for Check-Reading and Monitoring. Studies are needed to determine principles governing the display of simple yes-no information so that the eye can quickly detect deviations from a null or desired condition, picking out a deviating instrument from among a large number of normally-reading instruments. We have expressed doubts about the suitability of a human operator for most monitoring tasks. However, there will continue to be many jobs in which pilots and ground controllers will devote part of their time to check reading, which is an aspect of monitoring. It is essential that they have properly designed displays for this purpose.

Illustrative research problem. Conduct tests of the following hypothesis: There is an optimum visual angle for viewing any monitoring display, and speed and accuracy of check reading will be impaired if display size is too large or too small.

Problem Area 6. Display of Status Information. Studies are needed on methods of encoding and displaying weather information, on ways of representing landmarks and terrain features on maps, and on ways of summarizing information on charts and display boards. Much improvement can and should be effected in this problem area. A few projects are being supported by the military services, but these should be supplemented by studies relating especially to the traffic-controller and civilian pilot.

Illustrative research problem. How should the changing weather picture be displayed so that it is readily available to the pilot in the form in which it is needed?

CHAPTER VI

PROBLEMS OF DIRECT VISION FROM AIRCRAFT

Under daylight conditions with good visibility a pilot relies on vision from the cockpit for general orientation, flight control, the avoidance of other aircraft, and the successful landing of his own craft. At night and/or when visibility is reduced, instrument displays and more elaborate traffic-control procedures offer substitutes for certain of the visual cues of contact flight. The questions which develop out of this situation and which are to be considered here are two in number. *First* there is the problem, How much information do pilots want from visual cues from outside the cockpit under different conditions of visibility and with different kinds of instrumentation? *Second*, How can this visual information be provided most effectively as visibility becomes limited? The obvious general way to meet a need for better vision from the cockpit under conditions of poor visibility is through the use of marking lights and flood lights, but the most effective form for such marking and lighting remains unsettled.

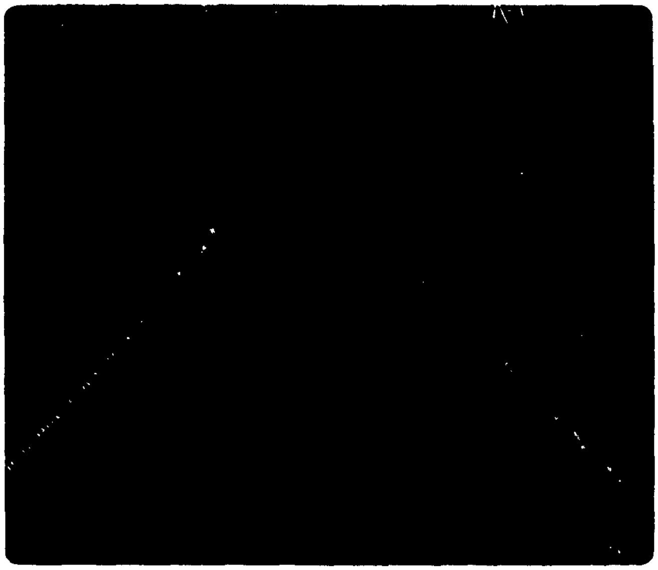
In part, decisions on marking and lighting procedures must await research results, but in very important ways these decisions as well as the research which is carried out in regard to them will be determined by the instrumentation and blind landing aids available to the pilot and his expected needs for vision beyond the windscreen.

A. Airport Lighting and Marking

General. The airport lighting and marking problem is in a sense all one problem, but it is convenient to distinguish between the approach lighting problem and the lighting of runways and taxiways. The task of handling the approach lighting problem would appear to require more analysis of requirements, more basic psychological data, and more research know-how, while the runway and taxiway problem would appear to be within the scope of simpler trial-and-error procedures. The following discussion thus deals separately with these two areas. Both have been the subject of recent review studies sponsored by the Committee on Aviation Psychology of the National Research Council.

The Approach Lighting Problem.

Lighting needs. The needs for airport lighting along the approachway can be set at a variety of levels, depending upon the kind of instrument guidance available to the pilot, the accuracy of that guidance, and his confidence in it. At least three levels of need may be delineated. The *first* is the need of the pilot who would make a contact landing on a clear night when, without lighting of some sort, the terrain or ground plane would not be visible.



The *second* level of need is that of the pilot who would shift to a contact landing procedure as soon as his aircraft drops below an overcast. This is the pilot whose aircraft is equipped with electronic aids which permit him to make the early approach through the overcast in reasonable approximation to a designated glide path, but who wants contact landing cues before he commits himself to a landing. The *third* level of need for ground lighting in the approachway is that of the pilot who has even better equipment and who would use ground cues as check or confirming data only. Such a pilot would use electronic aids almost to the point of touchdown but would want enough information from outside the cockpit to confirm his instrument indications until the threshold of the runway itself finally comes into view.

The lighting arrangements which will best meet each of these several needs are conceivably quite different, as different, for example, as effective displays for quantitative and for check reading may be from each other. The approach system which provides the most useful contact guidance under certain visibility conditions may fail to provide the most easily obtained confirming information under poorer visibility conditions.

Hence, approachway lighting research must be formulated in terms of specific requirements. Which set of requirements one seeks to fulfill may well change his answers to such questions as the following: How many lights must be visible to the pilot at a time? Where should they be located in relation to the approach path? What lamp pattern is needed in the approachway? etc.

At present, many approach lighting systems are in use at different airports in this country. The fact that they are all used successfully above the current CAA weather minimums for "open" airports would suggest that at these visibility levels, the particular approach system one has doesn't make much difference. Thus, approachway lighting is a problem principally because we are interested in an ultimate reduction of weather minimums. The first need level cited above is quite easily satisfied, but need levels two and three pose problems, particularly as we consider conditions of progressively poorer visibility.

Tests of Approach Lighting Systems. Unfortunately there is very little good evidence, either experimental or observational, on the relative merits of different approach lighting systems under very restricted visibility, because too few pilots have had enough useful experience with different systems under restricted visibility to make qualified, unprejudiced judgments.

There are many arguments for and against specific solutions. Most studies of approach systems have been what we term in this report "systems evaluations", and they have been open to most of the criticism cited in Chapter IX as applying to systems evaluations carried out in the past. Needed are some adequate experiments which will determine the extent to which minimum visibility conditions for safe contact landings are dependent on the particular approach lighting system used, and determine the most useful light pattern for check guidance for highly developed instrument landings. Available procedures for conducting such tests include the running of field experiments, or the use of a flight simulator in a laboratory, or both.

Approach-Lighting for Contact Landing Following Break-Through. Most of the work on approach systems to date has been formulated in terms of the second need level suggested above--that of the pilot who wants good contact cues after break-through. The search for the "best" system to meet this need begins, as is appropriate, with a consideration of the specific information and task requirements of the pilot who is to land by last-minute contact cues.

The Airport Lighting Evaluation Panel *(see Breckenridge, 1949),* Kalberer (1950), and the Flight Technical Group of the International Air Transport Association (1950) have all made analyses of the approach and landing problem and have outlined the requirements of an approach system in terms of the pilot's tasks during contact landing after break-through. These requirements (somewhat paraphrased) run as follows:

1. **That the system should provide the following information:**
    - **(a) Orientation of the ground plane, or horizontal**
    - **(b) Direction to the threshold or touchdown point**
    - **(c) Distance to the threshold or touchdown**
    - **(d) Identification of the threshold**
    - **(e) Orientation of runway**
    - **(f) Rate of travel or closure**
    - **(g) Departures from the glide path**

2. **That the system should provide such visual reference that the need for looking back at instruments, once the system is in view, be no greater than the need for referring back to instruments during normal contact landings.**

3. **That the approach light display and the various instrument displays used in approach and landing be such that possible confusions during transitions from one to the other are reduced to a minimum. *(This is the problem of division of attention discussed earlier in this report on page 27, Chapter V.)***

4. **That the system be positively and immediately identifiable and distinguishable from other light systems, especially the runway.**

5. **That the luminous intensity of the system be coordinated with that of the runway lights so that glare and dazzle are minimized.**

Minimum Information Required for Orientation. Although much can be said for the reliability of such "logical" analyses of approach lighting requirements by experienced pilots and engineers, and certainly there is good agreement between the sources cited, they usually need "sharpening" through experimental test.

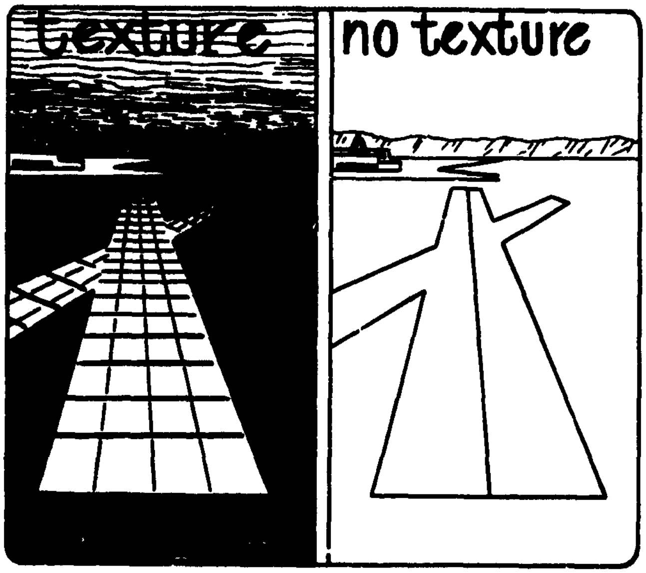
The fact is that we do not know exactly how much ground information is needed for successful landing after break-through. It is conceivable, for example, that a system providing only three items of information from the above list would be adequate. An experimental determination of these minimum information requirements is one of the jobs for which a simulator or a simplified laboratory setup would be well suited. In effect, we need to know what patterns and arrangements of light sources best define a surface and one's orientation to it when the observer is moving relative to it.

The work of Gibson (1950) and others would suggest (1) that a potentially ambiguous four-sided figure is perceived as a rectangle lying in an available well-defined plane whenever the projection in the plane is a rectangle, and (2) that ambiguous four-sided figures are normally perceived as rectangles whenever possible, even in the absence of well-defined planes, and that this very perception in each case defines the plane of the rectangle.

This is another way of saying that rectangles have strong shape constancy--a condition not true of triangles, to cite one exception. Reports that pilots were confused about ground plane orientation when viewing a "funnel" approach pattern support these propositions.

But available data do not tell us how much "rectangularity" is needed, or how much the use of right angles in an approach pattern can be reduced without producing disorientation, an unconvincing ground plane, and unsuccessful approaches. It might be found, for example, that a relatively few non-extended light sources (effectively point sources) would define a rectangle but not provide the basis for a convincing ground plane. Presumably one advantage of extended, bar-type or row sources would be that they can be used to define the horizontal as well as a series of right angles with the flight line.

The basic notion to be kept in mind is this: Since the pilot's task in contact landing requires adequate space perception, the obvious cues to give him through the medium of an approach lighting system are cues which will assist him in his space perception and orientation.



These presumably should be cues which he uses regularly in ground activities and in contact flight. Extended horizontal lines provide one cue to orientation. Texture or detail provides a basis for judging orientation and speed of travel.

A good hunch at the present time is that both of these cues should be used in approach lighting patterns (as indeed they are in many) in conjunction with the "readily perceived rectangle" discussed above, but the specific details of the system which will work best under low visibility need to be determined experimentally.

The program of research in this field must, of course, be preceded by agreement on the criteria of a good system, e.g. the kind of corrections that can be made after break through.

Approach Lighting When There is Electronic Guidance Almost to Touchdown. When electronic guidance is used right through to the vicinity of the threshold and when the only contact part of the landing is the final touchdown, the pilot ceases to be interested in obtaining ground plane data from his approach lights.

Pilots who have been testing various Sperry instrument landing aids suggest that the primary requirements for this type of landing are for information on direction to touchdown, and little more. The approach lights need only to confirm or correct the instrument indication that the plane is on course (see Sperry Gyroscope Co., 1950).

At least two follow-up studies are needed relative to this statement of the information requirement of approach systems for highly developed instrument lands: first to determine whether somewhat less skilled pilots concur in this requirement statement, and second to compare different light patterns for their effectiveness in providing the desired information.

The Question of Commitment in Landing. In relation to the landing problems just discussed, there arises the question of how far a pilot will proceed in an instrument approach without getting visual cues from outside the cockpit. Once a pilot goes below a certain altitude or proceeds to a certain point with his approach, he is committed to follow through and attempt a landing. The point below which he cannot pull out and go around, as determined by the type of aircraft being flown, puts one reasonably definite limit on this zone of "commitment".

The pilot's "emotional threshold" *(as used by Kalberer, 1950)*, and the accuracy of available instrument aids may set a somewhat higher limit as the point beyond which he would not commit himself to a landing without outside visual cues. Presumably as instrument-landing aids are developed to greater precision and as pilots develop greater confidence in them, the emotional threshold of the typical pilot will be lowered until it approximates the pull-out point.

Part of the problem of commitment is tied up with the adequacy of the pilot's information about ground level visibility. According to a recent report (1950), present Weather Bureau data are not very accurate indications of the altitude at which the pilot may expect to see ground lights in the approachway or along the runway. For the night runs summarized in that report, the Weather Bureau had implied poorer conditions than the visibility which was actually encountered. For the day runs, the Bureau data had a standard error of 100 feet. This problem is discussed further on page 41, this chapter.

Comments on Some Features of Existing Approach Lighting Systems. All approach lighting systems in use or in design propose to show the pilot "where to go". Lighted trails thus constitute a single common feature. But these trails have been single or multiple, straight or curved, parallel and and nonparallel. There are good logical reasons for having a single-trail, centerline pattern in the approachway *(see IATA report, 1950)* but the endorsement of any one system should await the completion of tests of the relative effectiveness of different trail patterns when marked with lamps of equivalent power and construction - tests which could well be carried out with a good sinulator.

Several systems have proposed to show the pilot "how far to go" to touchdown *(Calvert, Modified Slopeline)* but nothing is known about how useful such information is to the pilot.

The Slopeline approach lighting system is the one system specifically designed to provide three-dimensional cues in a direct manner--cues which indicate to the pilot where he is with reference to the glide path. The Arcata tests of 1948 (ANC-1948) indicated that this system might be effective to ceiling and visibility conditions of 25 feet and 1/16 mile by day and 0 feet and 1/8 mile by night for planes with good cockpit visibility. However, it still needs to be shown that glide path cues will contribute anything useful over and above the cues offered by a satisfactory system of defining the ground plane.

Identification. The problem of identifying the approachway to distinguish it from the runway, lighted city streets, etc. has been handled variously through the use of differential lamp patterns (in some systems) between approachway and runway, differential color, light size, shape, and flicker. The use of some flickering lights, among the approach lights as against all steady lights on runways, and the use of extended bar lights in the approach system as against nonextended lamps on runways, seem perfectly straightforward from the point of view that the visual discriminations should be easy.

The usefulness of color unfortunately is limited by the diminished discriminability of different colors in heavy haze and by the fact that filters necessarily reduce lamp brightness, but to get the greatest return from color coding, laboratory research on color discrimination in haze is very much in order. How much use can be made of lamp pattern itself as a way of identifying the approachway depends, of course, on what lamp pattern is arrived at from other considerations, but clearly one assessment needed for every double-trail approach pattern is a measure of its confusion with the runway pattern.

Runway and Taxiway Lighting and Marking.

The most important operational requirements for runway lighting and marking appear to be that they provide the following information: (a) orientation of the runway, (b) distance traveled along the runway, and (c) location of turn-off points *(see IATA report, 1950)*.

Most pilots who have had experience with all-weather tests are agreed that runway marking is of great importance. In the absence of runway marking patterns which are specifically designed to facilitate the landing maneuver, pilots make as good use as they can of painted runway numbers, tar marks, and any other available texture or contrast cues.

Among the marking patterns that have been proposed or tried out are arrowlike or chevron markings *(Haber and Gerathewohl, 1948)*, sets of rectangular bars or stripes, and comb-like patterns. The Calvert pattern, which includes a bold runway centerline as well as edge stripes, is currently in trail use at certain airports in this country (LaGuardia, Newark, MacArthur) and has evoked favorable comment. The relative visibility of stripe or bar patterns as compared with arrowlike figures has not been determined, but one experiment on form perception *(Helson and Fehrer, 1932)* indicates that the brightness threshold for perceiving rectangles is lower than that for circular or certain angular figures. Of no small practical concern in the testing of different patterns will be the effect which patches of rain water on the runway may have on pattern recognition.

Distance traveled along the runway can be coded into the runway marking pattern *(as both Calvert and Kalberer propose)* or can be coded into the runway lights. General opinion holds that the present practice of marking only the last 2000 feet of runway (by changing to amber lights) is inadequate and that more detailed distance data should be provided. It is clear that this problem is not a difficult one to deal with experimentally and that an early change to some standardized distance marking scheme would be highly desirable.

The problem of identifying turn-off points should not be difficult in itself, but the solution to both this and the preceding problem within the same display system raises again a question which was discussed earlier in this report, that of how much separate information can be presented effectively in a single display.

Evaluation of Alternative Procedures in Airport Lighting Research.

The best available test data on the use of different lighting systems under actual low visibility conditions are the Arcata results. The fact is, however, that the Arcata tests are generally appraised as having been inconclusive--as having answered some minor questions, but left unanswered the most important ones. This raises the question as to how research on problems of airport lighting and marking might best proceed in the future.

An alternative to field trials, as remarked earlier in this section, is found in the development and use of a good flight simulator. Such a testing device in which different lighting systems could be cheaply and easily "installed", may reasonably be expected to provide data on the adequacy of pilot orientation during approaches with different systems, on the adequacy with which he can recognize parts of any given system and respond to them correctly, and on the utility of particular features of different systems. It should speed the collection of these needed data since it would permit the running of many trails under carefully controlled visibility conditions. Calvert (1948a), Breckenridge, and Bakan, among others, have all maintained that simulators which can be used in the laboratory provide the most effective way of comparing alternative lighting systems.

The Use of Airport Lighting Simulators. Once ready for use in testing lighting systems, these simulators will in fact be suitable for certain basic research as well. Little is known about visual thresholds for moving sources, for lights which appear in unexpected locations, etc. and simulators will provide one way of collecting such basic data. Although plans were made within the last two years by the Committee on Aviation Psychology of the National Research Council to support the completion and use of simulators for testing purposes of all sorts, this work has not been undertaken.

One thing a simulator would fail to do would be to put the pilot in any danger. This would be both an advantage and a disadvantage--the latter being that test results obtained with a simulator may not necessarily give evidence of the confidence the pilot would have in the system in actual flight. The simulator, like the instrument training flight with a safety pilot, does not put the pilot completely on his own and may not measure validly the minimum visibility conditions under which a pilot would, in actual flight, be willing to commit himself to a landing. The simulator should assist, however, in answering many minor design questions and in the development of perhaps two, three, or four systems which could then be given appropriate field trials. The latter would in turn establish the validity of the simulator for handling comparable problems in the future.

In view of the cost, difficulty, and hazards of field trials, as well as the uncertainties of getting equally adequate data in all portions of a field experiment, the recommended course of action in this area is to defer further field trials until adequate basic experiments in visual orientation and adequate simulator tests have been completed and final evaluations are in order.

When field trials are set up, provision should be made for measurements of vertical visibility on every run, for an approximate equality of light output of single units in all the systems under study, for detailed recording of the plane's position throughout each approach, for photo-recording of instruments and pilot eye movements throughout approach, recording of communications, and for the administration of the tests by a research team impartial in its attitude toward the several systems and interested only in collecting reliable evaluation data.

Validity of Simulators. Although we advocate the extensive use of simulators in studying airport lighting problems we want to stress the importance of reproducing in the simulator the essential kinds of visual clues of pattern and movement that are available to a pilot in the air. This in itself is a research problem. Some early flight tests may be necessary in order to check on the validity of results secured with specific simulators.

B. Aircraft Lighting

The exterior lighting of aircraft to avoid collisions is not an important problem for all-weather flying, but rather a problem for night flying under conditions of satisfactory visibility. While considerable thought has been given to this lighting problem, essentially no research has been conducted on the advantages of different marking systems. Lamp intensity, flash rate, and color have been varied in different installations. Seemingly little thought has been given to light configuration, the use of short rows or bars of lights, and the like. Power considerations always impose limitations on such lighting systems, but the distinguishability of different lamps and lamp arrangements gives indication of being a profitable area of study.

C. Adequacy of Vision Through the Windscreen

Problems associated with the adequacy of vision from the cockpit fall into two separate categories which, most simply, may be called problems of quantity and problems of quality. Problems of quantity are concerned with providing enough windows in the aircraft so that the pilot can see enough of the outside world to fly his plane safely and efficiently. Problems of quality, on the other hand, are those of optical distortion, haze, scratching, and other defects in the windows, which seriously distort or veil what the pilot can see. The two groups of problems are sufficiently different for us to deal with them separately. Although some research was done in both areas during the war, there are still many questions to be answered and we have attempted below to summarize briefly the important issues.

Field of View from the Aircraft

Providing the pilot with an adequate field of view from the aircraft runs into a serious conflict of interests which must ultimately be resolved. Most pilots would like to be able to see much more space than they can from almost all present aircraft. Aircraft designers, on the other hand, would like, for structural and other engineering reasons, to keep the number of windows as small as possible. Further, the trend toward higher speeds in aircraft is almost universally associated with more streamlining and smaller windows. This basic conflict between the interests of the pilot and those of the designer poses a very knotty problem, indeed.

Deficiencies in Present Aircraft. That pilots do have valid complaints is borne out by the Arcata results. Certain kinds of runway lighting systems were not feasible with some aircraft simply because pilots couldn't see all the lights on the ground. Other data collected by Romejko (1945) during the war showed a correlation between the percentages of taxiing accidents and downward visibility over the nose for five types of fighter aircraft. P-38's, which had the best downward visibility, were involved in the fewest taxiing accidents; P-47's, with the poorest visibility over the nose, had the highest rate of taxiing accidents. However, the 1949 accident at the Washington National Airport in which a P-38 flew into an Eastern Airlines DC-4 on the final approach emphasizes in a tragic way the need for even better downward visibility in aircraft.

Status of Research. Research in this area during the war provided us with an instrument for measuring fields of view *(Leyzorek, 1945)*, a mathematical way of expressing the field of view in units of solid angles *(Chapanis, 1944)*, and some measurements of the field of view from military aircraft *(Leyzorek and Romejko, 1945)*. Since the war Edwards, working at the CAA Technical Development and Evaluation Center, has been conducting similar studies with the aim of determining windshield areas which should be provided in commercial aircraft.

The Aero Medical Laboratory has supported one study (which unfortunately is classified) on the possible uses of periscopes in the cockpit, and Roscoe, at the University of Illinois, has conducted several studies on the uses of an optical projection system in landing. The latter method of providing a view of the ground seems to warrant additional study.

Optical Quality of Windows and Transparent Panels

A pilot must not only be able to see out of his aircraft, he must also be able to see things undistorted and undimmed by poor quality glass or plastic. Here again, we encounter a basic conflict between pilot requirements and engineering requirements.

Aerodynamic Considerations. Aircraft designers would like to streamline aircraft as much as possible. This usually means setting windows in at large angles of incidence to the pilot's line of sight. And, unfortunately, large angles of incidence inevitably decrease light transmission, and increase the deviation and distortion of light rays through the panel. Aircraft designers also would much prefer to use curved panels rather than flat panels for aerodynamic reasons, even though it is much more difficult to manufacture curved glass or plastic with good optical qualities. Finally, there is a marked trend toward an increasing use of plastic, instead of glass, for transparent panels because plastics are cheaper, lighter, and easier to work. However this may be, plastics scratch, fog, and haze much more readily than glass and so raise another group of problems.

Status of Research. Unlike the field-of-view situation, we do not even have adequate methodologies for studying the optical quality of transparent sections. There is little agreement among manufacturers about how to measure distortion, haze, and other optical characteristics of transparent panels. This, then, is the first important step which needs to be taken.

There are a few studies, done during the war *(Pinson and Chapanis, 1946; and Chapanis, 1946)* which show marked impairment of depth perception resulting from poor quality glass. Some pilots reported difficulty in landing certain types of aircraft because of the distortion produced by windscreens, and there are documented case studies of air sickness produced by distortion in the windscreens of certain kinds of aircraft. The problems are real, but we shall need much more thorough data before we can formulate standards of optical quality for windscreens which will be acceptable to pilots without placing unreasonable demands on aircraft designers.

D. The Measurement of Visibility

The meteorologist regularly includes in his weather report information concerning what he calls visibility. Visibility data are employed in weather predictions and, more important in this connection, they are utilized by the pilot as an index of what he may expect to see during flight. The meteorological visibility is usually defined as the distance along an horizontal path at which an indefinitely large and dark object will just be seen by daylight.

Sources of Inaccuracy in Present Predictions. There are a number of bases for inaccuracy in predictions, from the recorded meteorological visibility, of how far a pilot may expect to see various objects during flight. In the first place, the measure of visibility made at the average weather station is a poor approximation of how far the standard large and dark object may just be seen along an horizontal path. Generally speaking, large and dark objects are not available, and they are almost never available at each of enough distances so that the distance at which they are just visible can be determined with accuracy. Furthermore, it is not possible to measure meteorological visibility at night since it is impossible to see a large dark object at any distance if the night is sufficiently dark.

It has been customary to employ as the measure of visibility at night the value measured during the day. Informed opinion considers it entirely unlikely that atmospheric clarity remains the same between day and night, since it has been shown that clarity depends upon temperature change, which usually occurs when the sun sets.

Physical Measurement of Atmospheric Clarity. Because of the unsatisfactory state of the conventional visibility measurements, there has been strong support for the substitution of a physical measurement of atmospheric clarity. Perhaps the best known of the instruments designed to measure atmospheric clarity is the transmissometer designed by C. A. Douglas of the National Bureau of Standards. Instruments constructed on different principles have been designed by W. E. K. Middleton of the National Research Council of Canada and S. Q. Duntley of Massachusetts Institute of Technology.

There is at present considerable disagreement as to which instrument will best measure the physical quantity which corresponds to how far objects will be seen. A further complication is introduced by the fact that atmospheric clarity along paths from aircraft to ground is not equivalent to clarity along an horizontal path. There has been considerable interest, in this country and abroad, in developing an instrument which will measure atmospheric clarity along slant paths. Research is at present being conducted by E. O. Hulburt and associates at the Naval Research Laboratory. The Armed Forces-NRC Vision Committee has recently established a working group to consider the research needs in this area.

Predicting What the Pilot Will See. Even if it were possible to obtain a satisfactory measurement of a physical correlate of meteorological visibility, this measurement would not predict how far objects of interest will be seen by the pilot. It is obvious that few objects of interest are indefinitely large and dark. There has been considerable research concerned with the relative capacity of the eye to see objects of different sizes and contrasts. Research has been particularly active during and since the last war.

One organization currently engaged in research of this type is the Vision Research Laboratory at the University of Michigan which has been supported by the Office of Naval Research. Data currently available would make it possible for approximate conversion factors to be applied to values of meteorological visibility in order to predict the distance at which objects of interest would be seen. Entirely satisfactory predictions await further research in which the objects of special interest to the pilot are experimentally investigated. British research on rockets whose flare is observed from the ground may lead to important results.

E. Recommendations

Research Objective VI. Determination of Optimum Conditions for the Use of Direct Vision.

Even with Extensive use of electronic aids and automatic equipment for all-weather flying, direct vision will continue to be an important factor in many flight conditions, especially for flights to small, marginally-equipped airports, and for light aircraft carrying minimum equipment. Therefore, some research should be continued on problems of direct vision.

Problem Area 1. Airport Lighting and Marking. Systematic studies should be made of such questions as the following.

a. **What cues are most important in permitting a pilot to orient with respect to the runway when he sees a pattern of lights from the air?**

b. **What is the best way of indicating position along the runway?**

c. **What factors influence ability to shift quickly from instruments to ground displays, and from ground displays to instruments?**

d. **What is the interaction between approach-light design and the design of cockpit instruments?**

We believe that work on these problems should be carried on chiefly in the laboratory, through use of simulators. However, this should be accompanied by some carefully planned flight test work to check on the validity of the criteria employed in the laboratory research (see Research Objective IV).

Problem Area 2. Vision from the Cockpit. Studies should be continued to determine by scientific means the required field of view from the cockpit, and the required quality and angle of transparent sections. The efforts of the CAA Technical Development and Evaluation center along these lines should be supported. Every effort should be made to see that manufacturers meet the vision requirements that are already known.

In addition to studies of requirements for direct vision through the windscreen, the possibility of providing supplemental views of the terrain and other aircraft through the use of reflective or refractive optical systems should be investigated. Such studies will be closely related to those on the use of pictorial displays of space relations (such as television displays).

Illustrative research question. How does the accuracy of manual landings in marginal weather vary as a function of the field of view through the windscreen?

Problem Area 3. Measurement of Atmospheric Transmission Characteristics. Studies should be continued to determine better ways of measuring and predicting the conditions of visibility that will exist during a landing approach, and of improving visibility through the choice of the type and spatial distribution of energy in airport light sources.

Illustrative research problem. What ways of measuring visibility from the ground agree most closely with actual visibility of airport lights from the cockpit of an approaching aircraft?

CHAPTER VII

VOICE COMMUNICATION

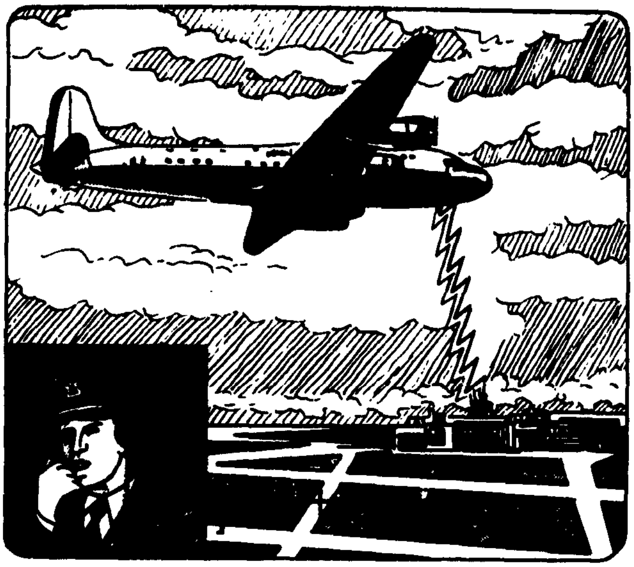
Voice communication has always been an essential element in air navigation and traffic control. It offers the quickest and simplest means of requesting and of providing many kinds of information. We pointed out earlier that both pictorial and symbolic visual displays enjoy peculiar advantages for communicating certain kinds of data. For example, information relating to terrain is far more adequately represented by maps or pictures than by a verbal description. However, there is reason for supposing that spoken language will continue to play a significant role in air-traffic-control in the future. Let us consider briefly, therefore, what may be done to put this part of the total traffic-control problem on a good footing.

There appear to be four ways of improving voice communication for purposes of air-traffic-control. These are: (1) **by improved technical equipment designed to minimize the harmful effects of noise; (2) by systems research aimed at identifying and eliminating some of the current "bottlenecks" in communication links; (3) by studies of the voice signal in relation to the talker with the view of exploiting his maximum capability as a transmitter; and (4) by psychological research to determine how to formulate and present verbal messages to human operators in such a way as to insure maximum accuracy in the shortest time.**

A. The Technical Improvement of Voice Communication

The actual state of voice communication in aviation today falls short of what is technologically possible. All that a person needs to convince himself of this is a good short-wave receiver and a few minutes to "listen in" on some of the standard channels. Almost certainly these deficiencies contribute to some failures in air navigation and traffic control. Both air route traffic controllers and tower controllers agree that lack of adequate communication facilities is the chief "bottleneck" in present air operations (see *Appendix II*).

In contrast with this, we know that the technical means are available for very good communication between any two points--witness the existence of broadcast facilities that put program material into every corner of the United States at the same time. From a purely technical point of view, the pilot could be provided with far better quality in his voice communication channel if we were to set out to accomplish this end.



Technical Requirements

First let us consider briefly, what the requirements are for satisfactory voice communications. Then some of the difficulties in meeting these requirements will be considered.

These requirements are adequately stated in any one of the several mathematical articles that have been published recently by French and Steinberg, (1947), Beranek, (1947), and Fletcher and Galt, (1950). In general, we may assume that the total spectrum of speech sounds may be divided somewhat arbitrarily into about twenty bands. In each of these separate bands the speech signal must be more intense than the noise in the same band by a satisfactory margin. Furthermore, in the interest of naturalness and to avoid interband masking, it is desirable to have uniform amplification in the various bands.

In specific terms, satisfactory speech communication requires that the speech sounds be picked up from the speaker and transmitted to the listener with uniform amplification between 300 cps and 6,000 cps, the signal reaching the listener's ears being at least 15 db more intense in each of twenty bands than the noise at the same point.

Noise Limits Adequate Communication

So much for the formal requirements. They are simple and clear enough and, more important, the technical means by which they can be achieved are pretty well known. What are the difficulties? In terms of the technical operation of such a system, the chief culprit is *noise*. Let us consider briefly the problem of noise and then look at two other important factors that limit the present efficiency of voice communication channels, namely, *inadequate engineering and economic limitations*. (It should be noted that we are dealing here only with the signal as it reaches the human ear, and not with the question of whether the listener interprets the signal correctly).

The sources of noise are three in number: **first, acoustic noise that gets into the microphone; second, electrical noise that enters the circuit in the equipment and radio transmission link; and third, acoustic noise entering the listener's ear directly.** The three sources of noise are summative, that is, noise once it enters the system must be added to the noise from other sources and cannot be eliminated later. The magnitude of the noise is measured with reference to the signal, that is, the important factor is to achieve a favorable over-all signal-to-noise ratio.

Electrical Noise is an Engineering Problem

Electrical noise arises from a wide variety of sources. It may consist of atmospheric static, or r-f radiation from ignition systems and other electrical equipment in the plane and on the ground, and finally of background noise in the transmitter and receiver.

Most kinds of electrical noise cannot be removed by simple measures. Atmospheric static, for instance, has a given intensity at any particular place and time. Its intensity cannot be altered. The degree to which it interfers with radio transmission will depend on the location and intensity of the disturbance, propagation conditions, the band-width of the receiver, etc. Within rather wide limits, the only way to beat atmospheric static is to put on the receiving antenna a signal which is stronger that the competing static. This means more powerful transmitters located at short distances, and, of course, wide geographic separation of stations on the same frequency. Likewise for receiver background noise, the solution is an increase in r-f signal strength. Ignition noise, and other forms of man-made static can, of course, be controlled. In this case, the problem is largely one of adequate maintenance. The method of modulation (f-m and a-m) is also important.

This is not the place to go into detail concerning the electrical and engineering problems involved in finding the most practical way to reduce electrical interference. Two comments are warranted concerning the psychological aspects of the problem, however.

First, proposals have sometimes been made for noise-reducing circuitry that reduces the audio-frequency range of the system. This may result in an apparent improvement of the signal-to-noise ratio without any real benefit so far as the listener is concerned. The ear is fundamentally a highly efficient frequency-selective system, and external restriction of the range almost never improves on the ear's achievement.

Second, some of the more elaborate noise-reduction circuits, such as "hole punchers", which filter out certain bands in the spectrum, may give rise to peculiar and unpredictable forms of distortion. It is not anticipated, however, that such devices will play any great role in air-traffic-control systems.

Noise Surrounding the Pilot

The noise that reaches the ears of the listener directly presents a number of somewhat unrelated problems. These had best be discussed separately for the pilot and the ground controller.

At the pilot's position, as is well known, listening conditions are often rather bad. The airplane noise can, and should, be reduced by proper acoustical treatment of the plane. But this will not always be effective, and pilots will open windows, which more than offsets the best work that the acoustical engineer can do.

Under these circumstances, resort must be had to two measures. First, the pilot's headset or helmet should exclude as much sound as possible. From 10 to 30 db of insulation can be provided readily by a comfortable cushion such as was used by the U. S. Navy during the recent war. Equally good insulation, although less comfortable, is provided by the standard Air Force sponge rubber cushion. It should be noted, however, that such cushions are not a matter of chance, that "any old cushion" will not give equal results. Recent work of Bekesy suggests that 30 to 35 db is the best that can be expected of any such device. What is now required is probably not new headset designs but rather some effort to make good headsets more generally available.

The second part of the solution is to provide an adequate signal at the pilot's ear. Wartime experience suggested that adequate audio power was one thing on which most manufacturers skimped. Any single figure is somewhat arbitrary, but something in the neighborhood of 500 milliwatts per headset is indicated. Furthermore, careful attention should be given to be sure that, as the power is pushed up, performance does not deteriorate when the receiver is overloaded.

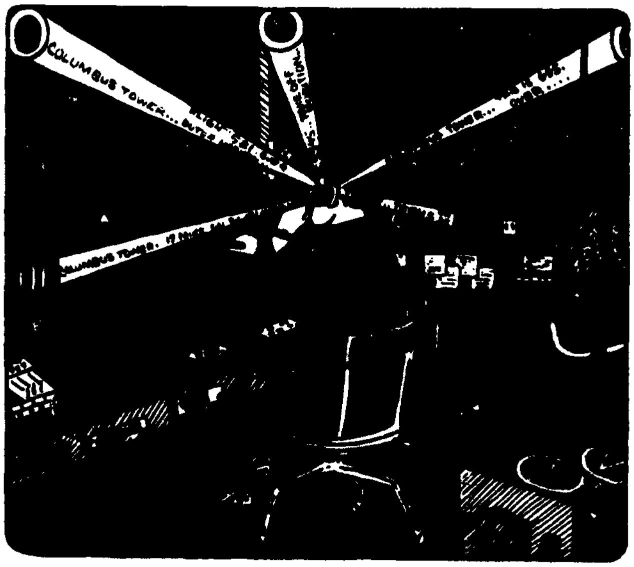
Babble in Control Centers

Let us turn to the ground operator.

The problem of reducing the babble in Control Towers and Air Traffic Control Centers would appear offhand to be more nearly a straight operational problem than anything else. It is clear that ten people connot converse effectively in a small, highly reverberant room; yet this is very nearly what is attempted in some cases.

The telephone company learned many years ago that central exchanges could not be operated by having an operator sit facing a bettery of separate telephones, each with its distinctive bell, trying to answer each in turn. The steps to be taken require programming of communications just as much as programming of air traffic.

The most serious offender in the present arrangements is the open radio circuit in a stand-by condition. Since most receivers have AVC, gain is automatically increased until background noise and static reach signal levels. It is inevitable that, with three or four such lines, there can never be favorable listening conditions. The first step would seem to be some kind of interchannel noise suppression; but if it is possible to achieve this, then some kind of annunciator or ring-down device could also be attached. There is really no reason why the tower operator should not have the same kind of communication facilities as does the agent at the ticket counter, line lamps, ring-down relays, etc. If it is concluded that all circuits must have a continuous aural monitor, then the least that could be done is to let one man serve this function and have him assign the channel to the appropriate controller until his traffic is cleared. The panoramic adaptor is another possibility here. It permits the operator to be in aural contact with one station, and at the same time get visual indications from all stations on neighboring frequencies.



The psychological factors underlying the tower operator's problem are fairly clear. Good communication requires a signal-to-noise ratio of roughly 4 to 1. This cannot be achieved when several equally loud signals feed into one man's ears with equal priority. Furthermore, unless there is some important overlap, it is probably more efficient for the operator to handle one message at a time. In general, the more important problems needing investigation here do not have to do with voice communications *per se* but the total informational input to the single operator.

Talking Over High Levels of Noise

The third source of noise is at the microphone of the talker. In some ways, this is the easiest problem to solve, at least up to a certain point. Beyond a given level of ambient noise, it is the most difficult. The limiting factor, of course, is the speaker's voice. The easy way to get a good ratio of signal to noise at this point is to bring a microphone up close to the speaker's lips. By careful use of a good microphone, quite satisfactory results can be obtained so long as the noise does not exceed about 105 db in over-all level. Thus, if movable microphones are used in control towers, there is little reason that this source of noise should be disturbing.

There are unfortunately a fair number of aircraft in which the 105 db level is exceeded, at least in the cockpit. For these planes the solution lies either in **(1) sound treatment of the plane, or (2) a microphone provided with a suitable noise shield or other noise-cancelling features.** Work remains to be done along the latter line although reasonably satisfactory instruments have been built.

There are also serious ambient noise problems in some of the newer GCA installations. These are produced by noise which gets into the radio channel and adds unnecessarily to the pilot's difficulties. There is no evident reason why attention to the needs of the users on the part of the equipment designers cannot cut down this source of noise to acceptable levels.

Why Not Improved Equipment?

From this brief survey it would appear that there are not any great hurdles in the path of getting satisfactory voice communication. The laws of physics impose limitations, it is true, but let us repeat what was said above, namely, that there appear to be on hand, or there can be developed, all of the technical devices that will give first-rate communication between pilot and ground, or between one ground station and another. *Why don't we have such facilities today?* Perhaps the answer lies beyond the mission of this report, but let us mention two important road blocks.

The first is *inadequate engineering.* By this is meant the failure to apply fully the information that is available today. It is fairly evident that the voice channels have been the step-child of the navigational and traffic-control systems.

Radio voice links have been taken for granted while engineering personnel have been busy with the more spectacular crop of war babies like DME, surveillance radar, and the like. Even less attention has been given to the audio-frequency characteristics of such systems than has been given to the radio-frequency problem. It is axiomatic that these problems will not solve themselves and improvement will come about only when airlines, manufacturers, and government administrative agencies give sustained attention to the problem.

On the other hand, when a determined effort is made to improve voice communications, there will appear a number of interrelated problems that may be called *economic.* As illustrations, there are limits to the weight of equipment that can be carried in a plane, to the cost of building radio equipment to very high standards of precision, to the number and power requirements of ground facilities that will give interference free transmission, and to the space available in crowded terminal facilities.

All of these have to do with what it will cost to bring voice communications up to acceptable standards. In some cases, these economic limitations are already quite real. In small private aircraft, for instance, the weight limitation is a very real one. So is probably the cost of building a larger number of more powerful ground stations.

B. The Improvement of Communication Systems

Consideration should be given to the numerous complaints that are lodged against the telephone and radio circuits by the people who are using them under present operating conditions. These are detailed in Appendix II of this report, and they seem to show that the ratio circuits are not only the step-child of development programs but also the undeserving scapegoat for a good many troubles.

Minimizing Delays. Delays in communication between centers, between controllers and pilots, and between tower and center, represent a breakdown in the very nerve-fibers of control. It is hard to understand how control can function at all if delays of from 5 to 10 minutes sometimes occur in getting through to a neighboring control center.

To outsiders, such as the writers of this report, these delays do not make sense. Suppose that each position in a control center were provided with the *ten* (or *twelve*) keys of a modern frequency signalling system, and that the centers, control towers, company radios, and auxiliary facilities were interconnected by modern crossbar switching. In less than two seconds any controller could be in touch with any other person in the system to whom he wanted to give information or from whom he wanted to receive it. If desirable, the connection could bridge the line being called so that direct information would be obtained about the busy condition at the other end. Direct interconnection with company radio would permit talking to the pilot without the intervention of a third person.

Systems Studies. Studies are already under way that will consider some of the traffic load and trunking problems of such a system. The Bell Telephone Laboratories, for example, are reviewing the entire problem of traffic-control-center communications for the CAA. It is to be sincerely hoped that these studies will not stop with the conventional facilities but that they will go ahead to outline what can be done with the equipment and facilities that need no development but can be taken down from the shelf to provide almost an Aladdin's lamp in comparison with some present communication circuits.

C. Improving the Voice Signal at Its Source

Here, as at many other points of this report, we might consider some of the personnel problems involved in selecting and training operators but it is beyond the scope of this report to deal with these problems. We would like to point out in passing that people can be tested for the intelligibility of their voice signals, and that speaking ability can be improved by drill and by policies that emphasize that on-the-job voice communication should aim at one-time transmissions.

Apart from the selection and training of speakers there are several ways in which the design of equipment and communication systems interacts with the speaker in such a way as to affect the voice signal. These interactions are important for communication engineering and are a legitimate topic for human engineering.

Control of the Side-tone.

Side-tone is the auditory experience of the talker as he hears his own voice. The signal may reach his hearing mechanism either through bone conduction or by an around-the-head route from the mouth to the ear. In circumstances in which the talker wears a headset he may hear from his earphones essentially the same level of signal that his other listeners receive. Harvey Fletcher found that a strong side-tone tends to reduce the vocal intensity of the speaker. Lightfoot and Morrill have confirmed these findings. Thus, equipment-wise, the level of the side-tone should be reduced in order to keep the talker's signal at a high level.

The time aspect of side-tone is especially interesting. Delayed side-tone is an auditory feedback that is out of time with talking event. Such delays may occur over lines of cascaded amplifying units. Noticeable delays are more common in circumstances in which the output of a communication system enters a room and then, together with echo, re-enters the electrical system.

The effect of noticeably delayed side-tone upon the speaker is to block temporarily his progress in talking, or with small delays, to stretch out or prolong the utterance of a message. Black (1951) reports that within the range of delay from .02 to .30 sec. maximum retardation of speech occurs with about .18 sec. The time of transmission of short messages is increased by more than 100% with this delay. Investigations are underway to try to determine the deleterious effect - if any - of the delay that occurs in normal speech because of the air link between the source of speech and the ear.

Two persons communicating with each other may also sometimes be caught up in an unstable feed back system. If the signal to one man is weak and the other loud, the first talker may speak louder and louder while the second talker may speak softer and softer, and thus each feeds signals to the other that tend toward even greater instability.

The Acoustic Environment

The acoustic environment of the speaker may be interpreted as having two major aspects, **(1) the sound that the speaker hears immediately before he transmits, and (2) the external sound that surrounds him as he speaks.**

The speaker is affected by at least two aspects of his acoustic environment in a manner to alter his effectiveness in communications. First, sound intensities, other than ones produced by side-tone, cause the speaker to raise the intensity level of his voice. Second, in two-way conversations the speaker tends to take on some of the characteristics of the voice to which he is responding. It, thus, becomes possible to control the responding speaker's voice advantageously by feeding him a moderately strong signal that is precisely articulated (see Black, 1950a, 1950b).

D. The Improvement of Message Reception

Aside from the improvements resulting from the application of research findings to equipment and operational procedure, there remains the additional possibility that the speed and accuracy of communications may be enhanced by the more efficient wording of messages and/or the more rapid presentation of auditory information to the listener.

Message Formulation For Listeners

The language of air-traffic-control in present use has evolved through years of usage, dating back to the "Ham" radio operators, and is not the product of linguistic research. Although considerable standardization of vocabulary (and of some messages) has been attained, it is by no means apparent that the standardized system in current usage is the most efficient one that could have been devised. Indeed, it is highly doubtful that such is the case.

Furthermore, much voice communication is not well standardized, and there are many variants even of the standardized vocabulary. It is striking to note the wide discrepancy between one control tower and another with respect to the phrasing of messages involved in identical operations. Also, as traffic density increases and controllers have more to do, they frequently use non-standard (abbreviated) phrasing. It seems probable that message intelligibility is reduced and transmission time increased by this lack of a uniform, scientifically-designed communication vocabulary. Added to noise, as a source of communication inefficiency, is a poorly formulated set of messages, transmitted in individual vocabularies.

Message analysis research is currently in progress, which has as its objective ultimate improvement in message wording. One of these studies (now being undertaken by the Medical Division of the CAA, and by the Human Resources Research Laboratories of the USAF) is designed to secure the necessary data to construct an international aviation vocabulary for use in air-traffic-control. Other message analysis studies, in progress at the University of Virginia, have sought to define the fundamental "message units" involved in military communication such as strategic long-range missions, and in such short-range operations as ground-controlled interception and close support of ground troops. The communication measurement program being conducted by the Franklin Institute for the ANDB should also contribute materially to the general problem of message formulation. Message formulation research seems highly relevant to the communication involved in air-traffic-control and air-navigation operations. The optimum redundancy of messages for listeners is an important problem (*see Chapter IV, Section G.*).

Relation of Message Formulation To Speaking

Although routinized messages are largely conceived in terms of accommodating the set of the listener, there is the corollary problem of accommodating the capacity of the sender. The sender is typically less intense at the end of a phrase than at the on-set of talking. Also the length of transmission per breath decreases with conditions of high altitude. Possibly the talker's efficiency at the end of a unit of normal speech approximates his condition at the beginning of a transmission at altitude, although this equivalence has not been established.

The ultimate system of routinized messages should be constructed to accommodate **(1) the business of the moment, (2) listener set, (3) speaker efficiency.** The Naval School of Aviation Medicine is exploring the possibility that message units of five syllables may represent a feasible compromise, satisfying listening, talking, and business.

Monitoring More Than One Channel

It is often desirable for a listener to be able to get information from more than one source. The headset, however, provides only one-channel monitoring at a single instant. The single-earphone headset is frequently employed commerically and in training to provide two-channel monitoring - one electrical and the other face-to-face communication. This situation occurs in the cockpit of commercial aircraft.

Whereas in military flights it is standard practice for the pilot and co-pilot to wear a helmet and often an oxygen mask, this is rare in commercial flying. Hence, in military situations, use of the interphone between the pilot and co-pilot is standard practice; in commercial flying the pilot usually talks to the co-pilot in open air.

The result is that a headset is rarely worn over both ears at the same time. A few tests suggest that this procedure does not seriously interfere with the efficiency of radio reception, provided the cant of the headset does not break the seal of the cushion (hence, the goodness of the insulation) on the ear being used. This question deserves investigation, with regard to the efficiency of the open ear, the ear with the headset, and the influence on the latter of noise entering the unprotected ear.

E. The Ear Versus the Eye as a Means of Communication

One of the most frequently asked, and least frequently answered, questions that is put to the psychologist is whether it is better to give information to a man by eye or by ear. Actually the problem is one that has received a great deal of attention, especially in the area of education since the invention of the motion picture. After all the work that has been done, the best thing that can be said is that there is no general answer.

It is pretty well agreed that the eyes and the ears are far ahead of any other sense organs that we can use for communication. But of these two, each has its special characteristics and only a careful and detailed statement of the particular problem can elicit a clear answer. Even then a practical test of the two alternatives may be the best recommendation that can be made. We offer here a few generalizations in the hope that they may point the guiding lines in such a particular analysis.

Basic Differences Between Vision and Hearing

The most important distinction between vision and hearing is that vision is organized with respect to space, and hearing with respect to time. There are, of course, temporal properties of things seen, and spatial localization of sounds heard. But these are secondary. Along with the difference between space and time goes a difference in what fills them in. The eyes see objects in space; the ears hear events that happen. With our eyes we orient ourselves, and see both objects and ourselves in relation to one another. Our ears furnish us with a sense of continuity and tell us when things start and stop. These differences are very fundamental, yet the two senses fit together and neither is sufficient without the other for normal activities.

Superimposed on the inborn differences between the two senses are the ways we are taught to use them. Through the eyes we build up knowledge about many complex geometrical properties of the world. With them, we are able to make directly quantitative judgments of high accuracy. Furthermore, as mentioned earlier the development of the so-called "constancies" permits us to judge the properties of objects abstracted from the accidental circumstances of their location, orientation, illumination, etc.

These complex perceptual skills often make a man's eyes more useful than elaborate instruments. In contrast, the ears of the most useful in direct face-to-face communication. Coupled with man's ability to speak, our ears provide us with spoken language. Written language is always a later and slowly learned substitute for speech.

Where the Ears are Better

At the risk of being somewhat superficial, we can list some of the more obvious situations in which the ears are probably superior to the eyes.

1. *As an alarm, where a signal must be given at an unexpected time in a long continuous watch.*
2. *As a signal where timing is important, such as a "Ready, Now!".*
3. *Where the process of communication is two-way, the efficiency of the conversation depending on the rapid give and take of messages.*
4. *Where the rate of informational input is very low but where it must be relatively continuous such as monitoring some process continuously.*

It will be noted that all of these examples have the one aspect in common, namely, that time is the important variable either in terms of the absolute time of occurence or in terms of rate of change.

Where the Eyes are Better

A corresponding list for the eyes might be as follows:

1. *When "relational" information, as defined elsewhere in this report, is to be presented. Broadly, this probably means information that can be presented meaningfully with respect to two orthogonal dimensions.*
2. *When complex information must be displayed briefly although it requires a longer period for its appreciation. The PPI screen is perhaps one example.*
3. *In the display situation, (or equally good, the trigonometric table) where a great deal of potential information can be stored and use made of the analytical ability of the eyes as they search through the total display for the relevant information. Cathode-ray storage tubes, facsimile, etc., are devices that take advantage of this ability of the eyes.*
4. *Where it is possible to make quantitative estimates directly, such as "half as much" when interpolating in scaled reading.*

The eye finds its usefulness, then, where it is judging spatial properties, or information that can be displayed in spatial terms. In addition, the eyes have the advantage that they can search through information and single out wanted items, and, from a practical point of view, it is much easier to store visual information. By the same process, the eyes are at a disadvantage in picking up and reading sudden signals.

Research comparing the eye and the ear as channels of communication is underway at the University of Virginia, under Air Force contract. (See, for example, Cheatham, 1950;) Day and Beach 1950). Among the recent (unpublished) findings at Virginia is that under conditions of divided attention auditory reception appears superior to visual for messages employing language.

The Eye and Ear Are Only Sensing Devices.

When we consider specific problems of air-traffic-control, we sometimes find that neither visual nor auditory methods of presentation possess any inherent advantages. We venture the assertion that for much of the information required, it makes no material difference whether eyes or ears are used.

Many of the decisions which will be made depend upon highly symbolic forms of information. It is often immaterial whether such symbolic material is presented to a man as words spoken or as numbers read from a dial. In either case, the important limitation is the ability of the recipient to handle just so many numbers at one time, just a certain complexity of the material presented. The sensory channel used makes rather little difference.

The critical questions are not eye versus ear, but rather such questions as: **Is the information encoded in the most useful form? Does it have to be transformed before it is used? Does the instrument store the information in useful form, and release it as soon as it has been utilized?** At times the eye and the ear may supplement and reinforce each other; at other times one or the other may be more effective; and, finally, the entire system must be planned to make sufficient use of both.

F. Recommendations

Research Objective VII. Determination of the Psychological Requirements for Communication Systems.

Communication is an essential element in air navigation and traffic control. Many of the psychological requirements for good communication systems are already known. However, some of these have not been implemented on the technical side, and some important questions of communications still lack psychological answers.

Problem Area 1. Improvement of Voice Transmission. Studies should be made of several special listening and speaking problems. Ways of improving the production of voice signals through the control of side tone should be investigated. The efficiency of listening with one ear should be investigated under a variety of masking and distracting conditions. Studies employing both acoustical and psychological methods should be made to discover the effect of a small enclosure on the human voice.

Illustrative research questions. When using an oxygen mask or a noise shield, why is the loss of intelligibility suffered greater than would be expected on the basis of physical measurements of the enclosures alone? Can one of two competing conversations be heard more or less effectively when both ears hear both, or when each ear hears only one?

Problem Area 2. Improvement of Message Formulation. Studies should be made to determine optimum ways of formulating or encoding messages for transmission by voice or other means. The requirements of both the speaker and the listener should be considered. This topic, and the related one of encoding information in relation to the action to be taken, call first for the kind of basic research on human information-handling capacity recommended under Research Objective II.

When successful methods have been developed for measuring the information-handling capacity of the human operator, comparisons should be made in a wide variety of situations using visual and auditory inputs to establish more clearly the optimum conditions for each type of presentation.

Illustrative research problems. An international language is needed for air traffic control. Should this be a spoken language, a printed language, or a set of arbitrary symbols?

Problem Area 3. Optimum Use of Visual and Auditory Means of Communications. Studies should be made of the relative advantages of auditory and visual messages including comparisons of auditory-sequential-periodic and visual-simultaneous-continuous presentation. Studies should also be made of the advantages achieved by simultaneous auditory and visual presentation of the same information, and the relative advantages of uni-sensory and multi-sensory data displays.

Illustrative research problem. Tests should be made of the following hypothesis: If it is necessary to give an operator an important message, it is much better to give it to both the eyes and ears than to one sense alone.

CHAPTER VIII

SYSTEMS RESEARCH , ANALYSIS, And EVALUATION

Long-range plans for research on air-traffic-control systems must include provisions for systems research, analysis, and evaluation. These operations are ordinarily associated closely in any practical research program, but they have somewhat different aims.

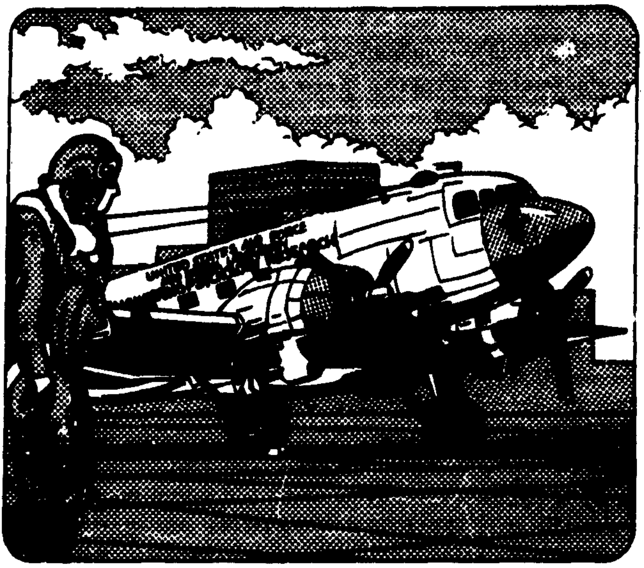
System research has as its aim the discovery of general principles that can be applied to the design and development of new systems. It is concerned with the question: *What kind of system is needed?*

System analysis has as its aim the discovery and identification of sources or error or variability in a system, the measurement of the relative magnitude of the errors contributed by the various subsystems, and the arrangement of the man-machine elements in a system in their most efficient combination. System analysis tells the design engineer about the weak links in the system--the components that need to be improved--and suggests directions in which further developments may profitably proceed.

System evaluations measure the efficiency and output of a total system so that it can be compared with other systems. The evaluation is, in a manner of speaking, a final examination. When the design engineer has done the best that he can with a new system, a system evaluation will tell him whether his new system is any improvement over the old system.

Definition of "Error" in a System. We can distinguish four kinds of errors in a system. These are (a) qualitative errors, (b) quantitative errors, (c) temporal errors, and (d) sequential errors. Qualitative errors refer to errors of kind; quantitative errors to variations in amount; temporal errors are delays in a system; and sequential errors are those that occur when an operation is performed out of its proper sequence, or, at least out of its most efficient order. In many contexts variability and error are synonymous. These sources of error are discussed more in detail later in this chapter.

Definition of a System. It is worth emphasizing that the word "system" includes the entire assemblage of men and machines which are concerned with air-traffic control. We particularly stress the words "entire assemblage" because experience has shown that isolated man-machine elements, even through they function well in the laboratory, may not perform efficiently when they are installed as links in a large system.



A. Some Criticism of Equipment Evaluations Carried Out in the Past

Subjectivity. In the past, evaluations of systems and new items of equipment have frequently been infused with highly subjective elements. Engineers who design gadgets and organizations that sponsor their development naturally have feelings of personal investment in their inventions and it is only human that they may fail to appreciate some of the shortcomings of their brain children.

Use of Overly Skilled Observers. In addition to this source of bias, most engineers are prooly qualified to evaluate equipments from a human-engineering standpoint. They are, in the first place, often more highly trained and more intelligent than the average person who will actually operate the equipment. Complex sequences of operations that an engineer takes in his stride may completely baffle a person without technical training. In the second place, the engineer's technical training frequently predisposes him to use it in a different way than would a person less familiar with its construction principles.

Another common procedure for evaluating new equipments in the past has consisted of turning the new item over to a group of pilots, or to some other group of consumers, and asking them for their opinions. This procedure is open to many objections. The pilots or consumers who are selected to test the item are frequently exceptional, the cream of the crop, and hence not qualified to judge the suitability of the item for average users. As a matter of fact, this use of very highly skilled pilots characterizes experimental flight test groups almost without exception.

Varying Criteria. Different evaluators may also use entirely different criteria for their judgments. Since the basis of their judgments may not be clearly stated, the evaluators also commonly render opinions on the basis of irrelevant considerations.

Resistance to Change. Finally, if a new system or équipment involves procedures or operations markedly different from those to which the evaluators may have been trained up to that time, they may give the new arrangement an unfavorable rating simply because it is unfamiliar and they do not have enough time to become thoroughly trained in the new procedure.

If a new, scientifically improved instrument panel were to be turned over to a group of pilots for evaluation, there would undoubtedly be many complaints that pilots could not use the new arrangement, even though careful tests might show it to be decidely superior when tested with men who had been trained on it. Much of the resistance to the adoption of new, more efficient typewriter keyboards, as an illustration, arises from secretaries and typists who are over-trained on present keyboards.

Of course the people who have to re-learn are inconvenienced temporarily by the change and may make more errors for a time. An ideal here is to discover improved designs that not only are better for novices, but to which highly trained operators can make the transition easily. This problem of relearning, however, is a factor that should be considered apart from the basic efficiency of the layout.

In this connection, the Bell Telephone Laboratories are studying the process by means of which an individual can arrive at a stable opinion about a new item of equipment. They find, for example, that the initial reaction often is quite unstable, and that it is necessary to shift back and forth between the old and the new equipment several times before a reliable judgment of the new can be made.

B. System Analyses and Evaluations Are Experiments

System analyses and evaluations overcome objections such as those discussed in the preceding section and substitute objectively verifiable results for subjective opinions. The systems analyses and evaluations we are concerned with are experiments in the true sense of the word. They are, to be sure, much more complicated than the traditional model of an experiment which holds all factors constant except one. System studies invariably involve the simultaneous manipulation of several independent variables, but the manipulation is a deliberate, controlled manipulation. The simultaneous involvement of several variables means that the analysis of the data must be done with special statistical techniques but the techniques are available for extracting meaningful results from multivariate problems. *(See, for example, Brownley, 1947; Cochran and Cox, 1950; and Edwards, 1950).*

Because system evaluations are experiments, they require the same careful planning, and are subject to the same requirements, as any laboratory experiment. Some of the special research methods employed in system studies, and the desirable qualifications for personnel who use these methods are considered in the following sections.

Sampling

The validity of the results obtained in any experiment is in a large measure determined by the adequacy of the sampling used in the experiment. All inferential statistics and tests of significance are valid only if the sample meets certain strict requirements. In human-engineering studies, two important kinds of sampling have to be considered. These we shall call *population* and *situation* sampling. Psychologists and statisticians have been generally aware of the former, but have often ignored the latter.

Population Sampling. The primary concern of the experimenter with respect to population sampling is to insure that the people, the subjects, used in the evaluation of a piece of equipment or a system are representative of the group that will ultimately use it. The subjects should be properly trained, but not overly trained. In some cases the experimenter may want to use novices in order to find out how easily they learn to use a new item of equipment. Subjects should be as intelligent as, but not more intelligent then, the ultimate users of the equipment. Finally, they should have roughly the same kinds of abilities and capacities as the people who will use the equipment. For example, if a certain radar in an air-traffic-control center will be used by enlisted men who have no more than a high school education, that radar should not be evaluated by using college students as experimental test operators.

It is beyond the scope of this report to discuss sampling procedures in detail. Suffice it is to say that statisticians have evolved several, and that the treatment of experimental results is dependent in part on the kind of sampling procedures used in an experiment. *(See Deming, 1950; McNemar, 1940; and Yates, 1949).*

Situation Sampling. Not only must equipment evaluations adequately sample the ultimate consumers of that equipment, they must also sample the kinds of situations that the equipment may be expected to meet. This is what we mean by situation sampling. The research must include the kinds of situations that will occur in the real job. For example, if we want to test the utility of an approach lighting system for a pilot who does not know where the runway is, then somehow or other we must get pilots disoriented before we make the measurements in our experimental flights.

The importance of situation sampling for systems studies is perhaps so obvious as to require no further comment. Nonetheless, it is frequently overlooked in the planning of system evaluations.

Control

The essence of experimentation is control over the variables under study and the situation in which the human operator works.

Systems studies require that the experimenter have aircraft where he wants them at any time; he must know accurately and by independent means the locations of those aircraft; he must be able, at will, to use one, six or twenty aircraft, as he may need; and finally he must be able to reproduce the same situation on different occasions.

These requirements often are difficult and expensive to meet in real life situations. For this reason laboratories which have been concerned with the evaluation of man-machine systems have often turned to the use of complex simulators to acquire the independent control they need for experimental purposes. It seems highly probable that the evaluation of air-traffic-control systems will also have to depend on simulators.

Long-range planning for research in this area should include plans for the development of simulators to be used in the evaluation of air-traffic-control systems and equipment. Consideration should be given to whether it is more economical and productive, to plan to use simulators, or to conduct research with real aircraft, real radars, etc. *(See the discussion on airport lighting, Chapter VI, Section A.)*

C. Tests to Breakdown

An important feature of system studies - a feature, incidentally, not shared by ordinary experiments - should be the "test to breakdown". The test to breakdown is essentially a series of problems, continuously graded in difficulty, designed to measure the information-handling capacity of a system. The necessity for such tests is perhaps obvious. System A may perform slightly better than system B as long as the load on the system is relatively light, but with heavy traffic loads and excessive stress system A might break down completely whereas system B might still be capable of handling some information.

The breakdown is not necessarily a well-defined point. Frequently there is a continuous curve between the percentage of information handled by a system and the amount of the load on it, but the slopes of two curves for different systems might start at the same point and diverge markedly as the load increases. Or, two curves might start at different levels at light loads, converge with moderate loads, and the diverge in the opposite direction under heavy loads. **In any event the test to breakdown gives the design engineer important information which cannot be obtained in any other way.** It is an essential part of human-engineering systems research.

D. Some General Considerations in the Evaluation of Systems

System studies on military radar equipments have been under way for several years in government and university laboratories. Since many of these systems are similar to those envisaged for future air-traffic-control systems, it is instructive to know about and anticipate some of the kinds of errors which turn up in Combat Information Centers and similar systems employing radar.

Man-Versus-Machine Errors

One principle which seems to be university confirmed in systems studies is that there are many sources of variability and error in all systems. Some of these sources of variability clearly have a human origin; others are patently machine errors. Many engineers accept the inevitability of the human sources of error, but they tend to underestimate the prevalence and magnitude of machine errors. We do not deny that many items of equipment can be constructed with extraordinary precision, but the precision which is claimed for complex equipments, like radar, has seldom been attained in actual operational use. As an illustration, the actual effective range of military radars when put into field or fleet use frequently is only 50 to 75 percent of the theoretical range.

Another point which needs to be made is that human errors can very often be reduced by proper design of equipment. For example, the research on errors in reading altimeters, discussed in Chapter V, has shown dramatic reductions in human errors with changes in dial designs *(see Grether, 1949)*.

Quantitative-Versus-Qualitative Errors

Qualitative or gross errors result when the wrong kind of action is taken. Qualitative human errors occur, for example, when an operator fails to notice that two radar pips are on a collision course, or when a controller mistakenly assigns two aircraft to the same altitude. Complete failure of an item of equipment would constitute a qualitative machine error.

Quantitative or precision errors are those errors in which the right kind of decision is made, but the amount of the response is incorrect by some amount.

Quantitative human errors result when the radar operator misreads the location of a pip on a radar scope by some amount, or when a controller tells a plane to vector to 245° instead of 247°. Quantitative machine errors arise when a radial of 180° shown on an omnidirectional range indicator is actually a radial of 176°, or when there is a "bend" in the approach course defined by a localizer beam.

The distinction between qualitative and quantitative errors is important for the statistical treatment of data.

Time Delays As Sources of Error

An especially important source of error in many systems comes from time delays. Since radar and air-traffic-control systems are ordinarily complex assemblages of men and machines, the passage of information through the system takes time. In present air-traffic-control centers, for example, it is not at all uncommon to find time delays as long as five minutes from the time information is requested by a pilot until instructions can be returned by the controller. In radar-directed flight, the time delay of the system starts with the appearance of a pip on the scope; includes the time required for the radar operator to size up the situation, reach a decision, and issue oral instructions; and ends when the pilot starts to execute movements in response to the instructions.

The systems we are concerned with work with rapidly moving targets, and the average speed of the aircraft may be expected to increase substantially in the future.

Time delays in systems introduce errors because, when the information gets to its action station, the information is old information--the aircraft has moved. If time delays were constant in a system, they could be corrected by suitable computers. Unfortunately the time delays are not constant. Further, the amount of the correction is not easy to compute for any particular time delay, because the error is a function of the speed, range, altitude, and course of the aircraft.

Time errors can be converted into equivalent errors in terms of feet of altitude, degrees of azimuth, or miles of distance. Time errors become increasingly important when air traffic conditions are changing rapidly, or when we must make estimates of future conditions. Needless to say, these time delay errors are extremely important to the ground controller who must try to prevent collisions.

The Combination of Errors in a System For a Single Item of Information

For a single type of information, the errors in various elements of a system add algebraically when suitably weighted. In a radar system, for example, the final error in the position of an aircraft which maneuvers in response to controlled instructions is the algebraic sum of the amount of the calibration error in the radar, the error made by the operator in reading the radar scope, the error due to movement of the aircraft during the delay in the system, the error made by the controller in forwarding instructions to the pilot, and the error due to the pilot's inability to correct the movements of the aircraft exactly as requested.

Constant Versus Variable Errors

In the example cited above, some of the errors in the system are relatively constant over long periods of time; others may fluctuate merkedly from moment to moment. For some purposes it is useful to distinguish between *constant* and *variable* errors.

Calibration errors in a radar, for example, are constant over substantial periods of time. Parallax errors in the way a radar operator reads a radar scope may also introduce human constant errors. Errors in interpolation in reading the location of a pip, on the other hand, are variable errors--they vary from moment to moment.

Time delays are also variable errors in the system because they ordinarily fluctuate greatly depending on the problem faced by the controller or radar operator. Errors introduced by improper centering of the sweep line on a radar scope constitute machine variable errors.

The Accumulation of Errors in a System

The constant errors arising from components in a system add algebraically when all measurements are expressed in a common metric. For example, if there is a constant error of +400 yards due to the fact that a radar operator reads to the nearest edge, rather than the center, of a pip, and a constant time error of -200 yards, the combination of the two gives a constant error of +200 yards.

Variable errors add according to a more complicated rule. If the errors of components of a system are designated by $\sigma_a, \sigma_b, \sigma_c$.. then the variable error of the total system is represented by

$$\sigma_t = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2}$$

This is true if the errors in the various components are uncorrelated. If the errors are correlated, the rule is still more complicated, for the sum of the errors becomes

$$\sigma_t = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \ldots \pm 2r_{ab}\sigma_a\sigma_b \pm 2r_{ac}\sigma_a\sigma_c \pm 2r_{bc}\sigma_b\sigma_c}$$

Where ^{r}ab is the coefficient of correlation between a and b.

Since component errors are uncorrelated in many systems, we shall discuss some of the implications of only the simpler rule (the first formula above). One important consequence of this kind of accumulation of errors is that improvement in the more accurate elements of a system results in only a negligible reduction in the total system error. For example, if a machine component contributes a root-mean-square error of 10 and the human component contributes a root-mean-square error of 50, the variable error of the two in combination is only 51. If all the machine error could be eliminated, the total error of the system would be reduced to that of the human, that is, to 50.

In this case, then, making a perfect machine would reduce the total error of the system by 2 per cent. Now let us suppose that the design engineer concentrates his efforts on the error made by the human in the system and succeeds in reducing it from 50 to 40. The total error of the man-machine combination is now equal to $\sqrt{10^2 + 40^2}$ or 41.2 Thus, decreasing the human error by one-fifth results in a reduction of the total system error by 19 per cent, that is, from 51 to 41.2.

Another illustration of the same sort can be stated with reference to a visual display. A cluttered visual display might be capable of extreme accuracy if the viewer of the display took a long time to study it. An uncluttered display, however, might be more advantageous if it reduced the interpretation time substantially and so reduced the total system error, even though the uncluttered display gave a slightly greater quantitative reading error.

These illustrations are perhaps sufficient to indicate the intricate nature of the error relations involved in complicated man-machine systems and to emphasize the necessity for analyzing for sources and magnitudes of component errors in systems.

Which Error Is Important?

An important principle which has come out of systems studies is that constant errors in a system are usually much less important than variable errors. The reason for this is easy to see. Once a constant error has been identified and measured it is easy to correct. **Variability is the true indicator of instability in a system.**

Let us take a practical example. If radar operators always read the location of pips as 400 yards short of their true position, a simple correction in the electronic circuits or even in the dials would correct for this error. The real difficulty arises from the fact that radar operators will give a series of readings the first of which may be 100 yards short, the next 200 yards too great, the third 10 yards short, and so on. It is these variable errors which are the difficult ones to correct.

E. Research Methods in Systems Studies

The experimental methods used in systems studies have been adopted with modifications from the techniques of experimental psychology, time-and-motion analysis, and applied statistics. In a sense it is correct to say that there are no unique methodologies peculiar to system studies, but rather that existing methods have been modified to solve particular problems.

New techniques for carrying out system studies will undoubtedly be developed in the future, and the exploration of new ways of solving systems evaluations should be a part of long-range planning for research in this area. We shall describe briefly some of the kinds of approaches that have been used successfully in system analyses and evaluations. The list is by no means exhaustive, but it should serve to illustrate some successful applications. We include this special discussion of systems research methods because we feel that the analysis of man-machine systems must be put on a firm scientific footing at the earliest possible date.

The Critical-Incident Technique

One successful method of detecting sources of error in man-machine systems is to use the critical-incident technique. Dr. John C. Flanagan of the American Institute for Research had a great deal to do with the development of this technique while he was head of the Air Force psychology program during World War II. Persons experienced with particular operations are asked to provide detailed factual accounts of specific experiences relating to the operations of the system. The value of such accounts is dependent on the accuracy of memory and the ability to single out critical happenings.

This technique was employed by Fitts and Jones (1947, 1947a) in the studies referred to earlier on "pilot errors" in using instruments and controls. It has been effectively used by Gordon (1949) in the determination of the critical skills required of air transport pilots, and in developing an objective flight examination for the CAA Air Transport rating. It has also been used by Nagay (1949a) as part of a job analysis of air route traffic controllers. Both of the latter studies were conducted by the American Institute for Research under the sponsorship of the NRC Committee on Aviation Psychology,

The use of the critical-incident technique is limited to systems that have been in use for some time. Also even when the greatest care is taken to collect factual descriptions of actual events, selective memory effects and personal bias cannot be entirely eliminated. In general this technique is most valuable as a preliminary step in systems research, and should be followed up by further studies using supplemental methods.

Job Analysis and Operational Analysis

Many standard procedures such as job analysis and operational analysis techniques, which have been widely employed in industrial psychology for various personnel studies, are often useful in systems studies. For example, motion picture records of pilot behavior have been subjected to analysis (see Channel, 1947). Because these procedures are widely known it will not be necessary to describe them here.

Systematic Opinion Surveys

Little can be said in favor of surveying opinions if an alternative is available. Opinions may agree with performance, or they may not. About all that need be said here is that if one decides to survey opinions he should at least do so systematically, sampling extensively the people who are most likely to have valid opinions. Fortunately there are a number of refined techniques for polling opinions and it is easy to secure expert advice in this area.

Analysis of Variance Techniques

Analysis of variance techniques have proven so successful that they are now being widely adopted in experimental psychology, in industry, and in systems studies where the interactions of complex factors must be assayed. The latter applications are still sufficiently novel so that they merit some discussion.

Analyzing Total Error into Parts. Briefly, the statistical procedure known as the analysis of variance consists of partialing the total error variability in a set of data into error components attributable to identifiable sources. Having partialed out components of the total error, the experimenter can then do two things. (1) He can apply tests of significance to the various components to discover whether they are so large that they could not have occurred by chance. (2) Having identified the non-chance sources of error, he can then go on to express true magnitudes as percentages of the total error.

Importance of Experimental Design. An important point to stress about the analysis of variance is that it will work only with carefully designed experiments in which the important variables are counterbalanced in specific ways and trials are run in certain prescribed orders. Only by such careful planning can the experimenter be sure that important effects can be measured without contamination from unsuspected, or irrelevant, sources of error.

In general, multiple-variable, analysis-of-variance experiments yield much more information per unit cost (or trials) than conventional experiments. One way of illustrating the power of this technique is to cite an illustration of a systems-analysis experiment performed on a simple radar system by psychologists at The Johns Hopkins University. The experiment was concerned with two radars, two target simulators, and several radar operators. The experiment was designed to determine the relative contribution to the total error variance of the radar system made by each of the following seven possible sources of error:

1. **Disagreement between two target simulators of the same construction.**
2. **Disagreement between two radar units of the same type.**
3. **Disagreement between operators in their reports for identical targets which appear on the same PPI's.**
4. **Disagreement of any one operator with his own reports when he ranges on the same targets at different times.**
5. **Disagreement in the performance of radars in the morning as compared with the afternoon.**
6. **Disagreement in the performance of any one radar.**
7. **Disagreement in the performance if the radar has been left in "standby" condition the preceding night as compared with its performance if it was turned off the preceding night.**

Finding answers to these questions required an unusually complicated experimental design in which combinations of radars, target simulators, and operators were systematically varied in the morning and afternoon for several days. For our purposes here, it is important to note that these questions could be simultaneously explored.

One of the most interesting results of this experiment was that the largest source of error variability was shown to be due to whether the radar had been left in "standby" condition overnight preceding the experiment. Another large source of error, greater than the variability of an operator's reports on identical targets on different occasions, was the variability in the performance of the radar from day to day. Unless a carefully controlled experiment of this sort had been done, it would have been easy to infer that the day-to-day variability arose from the operators and not from the radars. This was, in fact, the working hypothesis the experimenters adopted before they did the experiment.

Procedures for Studying the Most Efficient Arrangements of Men and Machines

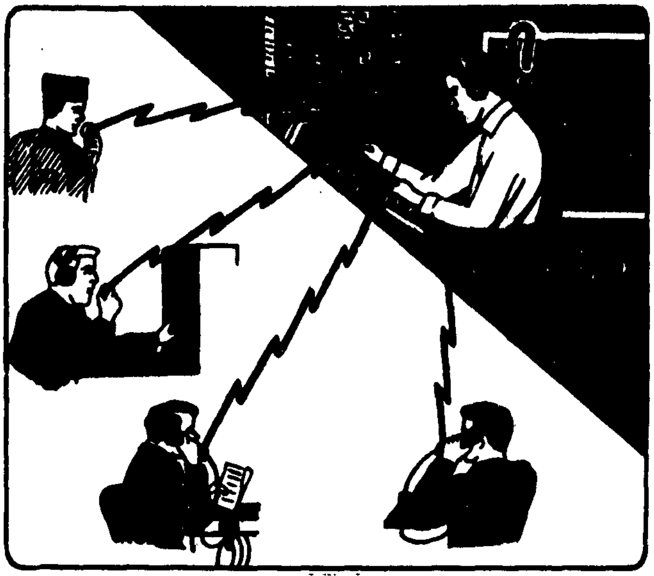
Recent work has shown that modified and refined time-and-motion procedures can be applied successfully to the study of complicated systems such as the flow of information in combat information centers, and the arrangement of instruments on instrument panels. Although these techniques have most generally been used for the re-arrangement of already existing systems, they can also be used for first-approximation layouts of systems still on the drawing boards. The latter, of course, should be the chief goal of human-engineering efforts.

Generally speaking, layout studies have involved the following steps:

1. **An analysis of the function of the system,** usually by means of interviews and discussions with supervisory personnel. In the case of systems still in the planning stage, the information is obtained from design engineers or the ultimate consumers of the system.
2. **An analysis of the functions of each element in the system.** Here again the information is obtained from interviews.
3. **Identification of various man-machine links between elements of the system,** and the estimation of the importance, frequency of use, or "strengths" of the links between the components. The links in the system may be any of a variety of different ones: visual, auditory, tactual, electrical, mechanical, and so on. This information can be obtained by a variety of techniques, the best of which involve observation or recording of elements of the system during actual or simulated operation. Channel (1947), for example, has used motion-picture recording to analyze the activities of Navy pilots in operating controls in the cockpits of multi-engine aircraft. Fitts et al (1950) have used similar techniques in studying the use of instruments during landing approaches.
4. When the links between components have been identified and their strengths measured, **the next step is one of arrangement of the components so that the distance of the link paths are inversely proportional to their strengths.** Graphical methods are now available to yield theoretically ideal solutions (see **Chapanius, Garner and Morgan, 1949**).
5. **The theoretically ideal layout of any system often has to be compromised** because of spatial limitations or other engineering requirements. Frequently, modifications of the ideal layout can be best studied by manipulating small-scale models in consultation with construction or design engineers.
6. **The final step consists of the evaluation of alternate layouts** according to such criteria as indices of visibility, walking, talking, crowding, and accessibility. The real test of the overall efficiency of the layout comes, however, when the speed and accuracy of the system are measured in simulated or actual operating conditions. Tests to breakdown are especially important here.

F. Identifying the Weak Links in the Present Air-Navigation and Traffic-Control Systems

Although it is beyond the scope of this report to consider all the specific systems studies that would contribute to the development of an effective air-navigation and traffic-control system we can give several illustrations of profitable topics for systems research.



Causes of Variation in Arrival Time at Destination

We have seen that it is highly desirable to predict aircraft arrival times precisely. By properly planned systems research, we can seek to determine the relative importance of various factors that contribute to this variability. We might, for example, determine first the variance due to such obvious factors as **(a) variability in the human pilot and his crew, (b) the weather and errors in predicting the weather, (c) errors in aircraft instruments and navigational aids, (d) delays in the communication of information, and (e) traffic conditions.** If we knew the relative importance of these five factors we would know a lot about what priorities to give to different research and development projects.

Causes of Variation in Aircraft Speed and Flight Path During an Approach to Landing

If maximum runway utilization is to be achieved, aircraft must make their approaches to a landing in a uniform and predictable way, i.e. on a predictable course with predictable speed and rate of descent. Research is needed to determine why different aircraft now vary so greatly in the way they make their final approach to a landing.

Properly designed systems research projects should give the answer. They should indicate the relative importance of such factors as **(a) different types of aircraft, i.e. Convairs, Martin 202's, DC-6's, Constellations, Stratocruisers, etc., (b) variation between different aircraft of the same type, i.e., two Convairs of different ages, etc., (c) weather conditions around the airport, (d) different airport layouts, different runways, etc., (e) the operational procedures prescribed by different airline companies, the military, etc., (f) differences between pilots, (g) variability in**

the same pilot from day-to-day, (h) different procedures followed by approach and final controllers, and (i) differences between and within controllers. It should be mentioned here that ANDB has recognized the need for answers to these problems and has contracted with the Franklin Institute to study the problem.

The difficult aspect in planning such an analysis is not how to collect records on a large number of approaches by different aircraft at different airports, etc., but how to identify the separate variances attributable to each of the factors listed above. However, properly designed systems studies should make it possible to do this. The problems of crew compliment as affecting safety and efficiency have been outlined by the Flight Safety Foundation (1948).

Important Sources of Error and Variability in Air-Route Traffic Control Centers

Even though future traffic-control systems may be quite different from present ones, there is much that we can learn from careful and continued systems research on present systems. For illustration, a special study could be made of time delays in present systems. Communication and decision-making could be studied to determine the time required to receive, process, and transmit information of various types through various parts of the present system.

G. Personnel to Do Human-Engineering Research

At this point we should like to say a few things about a most important question relating to human-engineering research: *Who is qualified to conduct human-engineering experiments?*

There are many university laboratories where students are trained in experimental psychology. Three or four laboratories are beginning to offer some of the additional training necessary to prepare men for human-engineering research. There is, unfortunately, no place where students can be trained in the methods of system analysis, nor are there, properly speaking, people who can be called system analysts: This report may seem to imply that most psychologists are especially qualified to do human-engineering and system research. This is not at all correct. Some psychologists are competent in this area, but they constitute an exceedingly small percentage of all the psychologists in the country.

A better way of getting at this problem is to ask: *What qualifications should a human-engineering researcher have?* If he is to specialize in system research he should have a thorough grounding in pure and applied statistics, particularly in the newer developments in sampling techniques, the analysis of variance, and design of experiments. If he is to do laboratory research on displays, communication problems, etc., he should have a thorough training in experimental psychology and a board knowledge of human sensory, perceptual, and other capacities, and human learning ability.

He should be familiar with the facts and principles of engineering psychology. He should have a good grounding in the physical sciences and familiarity with the rudiments of the engineering specialties. He must be able to communicate easily with engineers and physicists. Finally, he must be a person with bold imagination, a person who can transfer and adapt techniques from other disciplines, modifying them to suit his needs. Such men are scarce. *(See Kennedy and Bussey, 1949).*

On the whole, the average engineer is much less adequately trained for human-engineering research than is the average experimental psychologist. However, as we have mentioned elsewhere, the engineer who is aware of the human aspects of engineering design, the applied mathematician, and men with wisdom gained through operational experience, all have something to contribute to a systems research team.

H. Recommendations

Research Objective VIII. Optimum Man-Machine Systems Engineering.

The term "systems" as used here includes the entire assemblage of men and machines engaged in air navigation and traffic control. The contribution of human engineering to the efficient overall design of this man-machine system should include the following:

a. **Systems evaluation**-comparison of the new and the old.

b. **Systems analysis**- the identification of sources of variability of errors.

c. **Systems research**-the discovery of principles governing efficient man-machine combinations.

All three kinds of studies should receive major emphasis. In achieving this research objective, cooperative research participated in by men trained in different scientific disciplines is usually necessary.

Problem Area 1. Human-Engineering Analysis of Existing Systems.

Systematic studies should be made of existing air-navigation and traffic-control systems in order to discover sources of variability, delay, and error. These studies should have the following objectives:

a. To provide facts needed in planning better systems for the future.

b. To solve some of the problems of present systems.

Our study of present air traffic control procedures, summarized in Appendix I, is an example of the kind of work that is needed, although it is not nearly as thorough a job as we should like to see.

Illustrative research problem. There is need for an analysis of the relative importance of different factors now causing variability in the estimated arrival time of aircraft, including factors attributable to pilots, controllers, communication lags, weather, and instrument errors.

Problem Area 2. Human Engineering Research Studies, Analyses, and Evaluations of New System Components. Studies should be made of all new systems, and of new component parts of systems, at the earliest possible stage in their development, so that features that are desirable from a psychological viewpoint can be embodied in the final production item and undesirable features eliminated. As far as possible these systems studies should be planned jointly by research teams, including pilots, controllers, engineers, applied mathematicians, and engineering psychologists.

Illustrative research problem. Integrated studies evaluating distance-measuring equipment should be planned by a research team to determine how well this new equipment meets the needs of ground controllers and pilots and how well it functions as part of a total navigation and traffic control system. Such studies would supplement those conducted to determine the engineering and electronic acceptability of the equipment.

Such man-machine systems studies require special research facilities that are not now available. It will be necessary to manipulate entire systems including human operators. The load on the system, the communication and display of information, and the tasks to be performed by the various humans in the system must be under the control of the experimenter, and must be subject to exact repetition. Many of these elements must be simulated.

Exploratory studies are needed to determine how the equipment needs for research in this problem area can be met, what kinds of facilities are needed, and how an integrated approach to systems research can best be accomplished.

Illustrative research project. A study should be made to determine what the simulator requirements are for human-engineering research on air-navigation and traffic-control systems. This study might well include work on the criterion problem. As another illustration, a research team including scientists from several specialized fields, equipment designers, and operating personnel should be organized to study ways and means of providing more efficient methods and techniques for carrying out human-engineering systems research.

Problem Area 3. Human-Engineering Research on Proposed Systems. Insofar as possible, scientific studies should be made of proposed new systems and system components, in order to discover basic principles of systems design, and to determine, before the characteristics of a new system are frozen, what features should be embodied in its design.

CHAPTER IX

PUTTING HUMAN-ENGINEERING DATA TO USE

A. Closing the Gap Between Research and Application

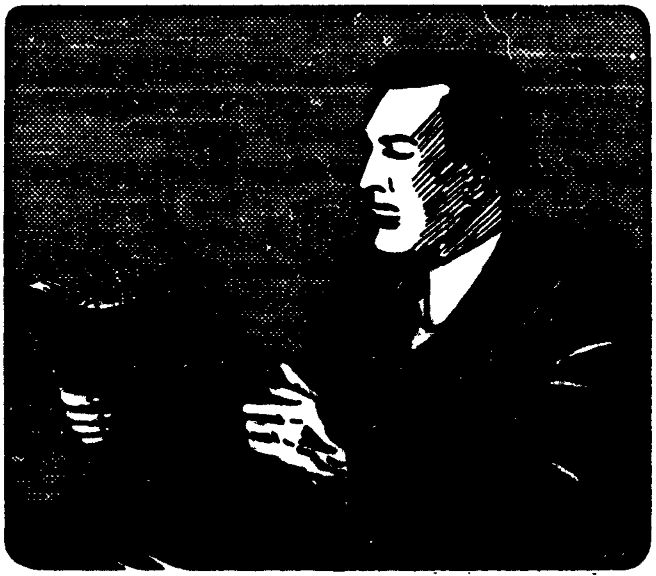
Two points should be emphasized in planning an applied research program. The first point has been implied throughout this report. It is that if we are going to do research at all, then systematic or basic research usually is more efficient than research that tries to deal independently with many small specific problems.

The second point is that once such systematic research is completed, the work of the applied research worker is still not over. He is responsible for seeing that his findings are made available to the planning staff and to the design engineer in a form which they can easily apply to the problem at hand. Failure to do this leaves a serious gap in any applied research program.

Ways of Making Research Findings Available to Engineers

The human-engineering research worker can communicate information to engineers by means of written reports or by face-to-face contacts. Each method has its advantages and disadvantages. Which will be used depends in part on the nature of the problem, and in part, of course, on where the research worker is located, geographically, in relation to the engineer.

Special Reports. Special reports can deal with separate experiments, with series of related experiments, or with problem areas. It is obvious that separate experiments must be published if the findings are to be of permanent value. However, when an engineer has to make a practical decision, he usually does not have time to search the experimental literature for an answer to his problem. For this need additional special reports are much more useful - reports that review and summarize what is known in a problem area. Comprehensive summaries of this nature are those of Kappauf (1949) on legibility problems, of Orlansky (1949) on aircraft controls, and of Chapanis (1946) on the optical quality of windscreens, just to cite three specific illustrations. Even more useful than these reviews are Human-Engineering Handbooks.



Human-Engineering Handbooks. It has been recognized for several years that the field of human-engineering needs to summarize its basic information in handbook form, in somewhat the same manner as has been done, for example, in the IES Lighting Handbook *(Illuminating Engineering Society, 1947)*, or in handbooks of chemistry and physics. The major effort in this direction has been the work of Tufts College in preparing a Handbook of Human Engineering Data for Design Engineers (1950), supported by the Office of Naval Research. We feel that this handbook should meet part of the need of engineers working on air-navigation and traffic-control equipment. However, this and other present sources stop far short of providing a completely satisfactory summary of what is known about human capacities in relation to equipment problems, and they can never be kept entirely up-to-date on current research.

Special Consultants. Often it is essential that engineering psychologists work personally with engineers and planning groups. Personal association provides a beneficial give and take of ideas regarding problems and possible solutions.

One way of accomplishing this sort of joint effort is through the use of special consultants. The effectiveness of a consultant depends largely on who and what the consultant is - on how conversant he is with research findings, how well he can work with others, and how well he understands and considers the many different aspects of equipment-development work.

One of the chief limitations of the use of special consultants is that their services are intermittent. They may not be around when they are most needed and they may not be able to follow an item through its full design and development.

Full-Time Consulting Psychologists. Another way in which the gap between research and application can be narrowed is through the use of engineering psychologists who devote most or all of their time to working closely with engineers on the development of specific items of equipment and systems. Several government laboratories such as the Aero Medical

Laboratory, of the Air Force, the Naval Research Laboratory, and the Navy Electronics Laboratory support human-engineering staffs that devote part of their time to such activities. Several university research organizations and private consulting groups also have engineering psychologists on their staffs who devote most of their time to consulting work with engineers.

Who Should Apply Human-Engineering Data?

Agencies such as ANDB, and the groups within the CAA and the Military services that are working on air-navigation and traffic-control development programs, can secure help in the application of psychological data in any of the ways indicated above, i.e. by contracting for special reports, by using special consultants, by contracting with a consulting firm that provides competent human-engineering service at an applied level, or by turning for help to one of the government laboratories that has psychologists on its staff.

In this connection it should be mentioned that the persons doing basic research in a given problem area may in some cases be the best persons to render consulting services on problems in that area. Each research contract will probably have to consider separately the question of whether the contract will support basic research and its publication only, or will provide both for research and for additional help in the application of the research to practical problems.

B. Problems on Which Help Should be Sought at a Non-Research Level

System Planning

It is believed that the Air Navigation Development Board, and its associated agencies, should seek the aid of human-engineering consultants and research advisory groups such as the NRC Committee on Aviation Psychology in connection with further broad planning for an overall system, especially in regard to such broad questions as what men should do and what machines should do.

Specific Instrument-Design Problems

Consultation help is available on specific questions regarding the best way to display certain types of information, the best designs for legibility, check-reading, quantitative reading, etc. The direct assistance of experts in particular problem areas will in most cases prove highly beneficial to the design engineer.

Evaluation Projects

We have already recommended that statisticians and engineering psychologists participate in systems evaluation projects, especially in planning such projects. While it undoubtedly will be desirable to have one or more such persons associated continuously with evaluation projects, the use of additional consultants, especially at the planning stage, may often prove highly beneficial. A lot of research know-how, as well as know-how about specific design and planning problems, can be made available through the wise use of consultants and research advisory groups.

C. Recommendations

In this section we have pointed out that it is important to plan not only for research, but also for putting research findings to use. We have also indicated some of the steps that can be taken to insure better utilization of existing information about human-engineering methods and problems. We recommend the following research objective to cover the important area of application:

Research Objective IX. Maximum Application of Existing Human-Engineering Information.

The final step in an applied research program is the application of research findings to practical problems. In fact, this is both the justification for the research, and the test of its worth.

The first question that should be asked in planning research on an applied problem is whether there are any existing data that will answer the question. It is our belief that there are now many areas of engineering design where existing data are not being applied, and where valid answers to critical questions do already exist.

The second question that should be asked is whether a problem calls for research, or for consultation by experts. Several considerations enter here. It obviously is not feasible, however desirable it may be, to settle all design questions by recourse to research. Time and cost prevent this. Most design questions involve a weighing of many different engineering, human, and economic factors. Thus single research studies seldom provide a complete answer to complex practical problems. The aims, therefore, should be the following:

a. *To anticipate the most general and most important question and to support research on these questions.*

b. *To settle the more specific and the less important questions, or those questions that require an immediate decision, by using the best scientific information and advice already available.*

Through the continued support of long-range research over a period of years more and more immediate practical problems can be settled on a factual, scientific basis; but in the meantime the best possible use should be made of the existing information.

Problem Area 1. Utilizing Human-Engineering Data in Systems Planning. Extensive use should be made of human-engineering data, and of consultants who have expert knowledge of the data available in the various areas of psychology, in overall systems planning.

Illustrative project. The help of experts in human-engineering and in personnel and industrial psychology should be sought in making decisions about how best to utilize human abilities in an air-navigation and traffic-control system, i.e. decisions about what men should do and what machines should do.

Problem Area 2. Utilizing Human-Engineering Data in Designing Specific Items of Equipment. Emphasis should be given to writing equipment specifications so that human-engineering requirements are met. Relevant data about human performances should be applied throughout the various stages in the design and development of new equipment. One of the best ways to insure that this is done is for engineering psychologists to work closely and continuously with design engineers. In a few instances this is now being done, but the practice should be greatly increased

Illustrative projects. Agencies that undertake to develop new flight instruments should insure that they have the assistance of aviation psychologists who have studied pilot display problems. Similarly, agencies that undertake to develop new radar equipment for air traffic control should arrange for continuing help from engineering psychologists who have studied radar display problems.

Problem Area 3. Providing Human-Engineering Handbooks, Engineers Guides, and Summary Reports on Special Problems. Existing information on topics of importance for the development of air-navigation and traffic-control equipment should be summarized in handbooks and special reports. In some cases the preparation of such summaries should be specified as part of the work to be done under a research contract; in other cases, this work should be included as part of a survey of problems in a given area or made the subject of a separate contract.

The Navy, through its contract with Tufts College for a Human-Engineering Handbook, has been supporting work in this problem area for several years. However, this Handbook alone does not cover all of the needs for human engineering data in the air traffic control field.

Illustrative project. There is a need for a technical guide to the methods of systems research. Such a guide might be developed, for example, by taking Chapter VIII of this report, greatly amplifying it, and publishing it as a special report.

APPENDIX I

THE PRESENT SYSTEM OF AIR-TRAFFIC CONTROL

This appendix has been prepared for the use of persons who are not familiar with how traffic-control works today. Most of the necessary information for it was collected incidentally in our survey of ten air route traffic control centers and airport control towers described in Appendix II. Details agree with those in an "*Operational Description of the Present Air-Traffic-Control System*", published by the Civil Aeronautics Administration, Washington, D. C., April, 1948.

A. Functions of Air Route Traffic Controllers

The major human elements in the present traffic-control system are (1) **the pilot, (2) the tower ground controller, (3) the tower local controller, (4) the tower approach controller, and (5) the individual sector controllers in the ARTC center.** These elements are shown in fig. I-1. The administrative superstructure to this system can be disregarded for the present purpose.

The functions and responsibilities of various human beings in the present traffic-control system overlap and it is perhaps inevitable that the actions of two operators sometimes conflict. For example, a local controller in an airport tower may plan to expedite takeoffs by directing the pilots in a pair of departing aircraft to turn in opposite directions after taking off, thereby reducing the permissible minimum separation of the two aircraft. The approach controller may, however, have planned to direct an inbound aircraft to one of the quadrants involved in this operation and may therefore require a modification of the plans of the local controller.

The duties and responsibilities of each of the five people involved in a typical traffic-control sequence are outlined as follows:

The Pilot. The pilot is responsible for the safety of his plane and its human cargo. Penalties such as personal destruction, financial liabilities, and vocational difficulties result from unsafe operation. The civil pilot is bound by Part 60 of the Civil Air Regulations to conduct his flight in a manner which is not only safe, but which cannot be construed by anyone else as unsafe. Military pilots are bound by somewhat different military regulations. The responsibilities which are invested in the pilot by such regulations are the source of a good deal of conflict in authority.

The Ground Controller in an Airport Control Tower. One of the three kinds of authority exercised in an airport control tower is control over the ground operation of aircraft. This includes the movement of aircraft around and on the parking ramp and on the taxiways and runways not in use. It does *not* include the turnoff of a landing aircraft to a taxiway, or the movement of a departing aircraft onto the active runway for takeoff. The *ground controller* is responsible for the safety, guidance, and expeditious flow of taxiway aircraft.

The Local Traffic Controller in the Airport Control Tower. The *local controller* is responsible for the safe separation and expeditious flow of all takeoff and landing traffic and all airborne aircraft within a radius of 3 miles from the airport. His authority at the present time is primarily advisory because of the responsibility for safety in the terminal area that is vested in the pilot. The directions issued by the local controller may be, but only occasionally are, rejected by pilots. In this case, the controller issues amended instructions.

The Approach Controller in the Airport Control Tower. The *approach controller* is responsible for the safe separation and expeditious flow of arriving traffic at the terminal. This control is exercised only when the arriving aircraft is operating under an Instrument Flight Regulations (*IFR*) plan. Such flight plans clear the aircraft to some fix (sometimes as far as 20 miles from the terminal), at which point the pilot must contact the approach controller and proceed under new directions. Holding and stacking procedures and the control of the aircraft's entry into the landing system are the responsibility of this controller. Control of an arriving aircraft passes from the approach to the local controller when that aircraft is close enough to become an important unit in the local traffic situation.

Individual Sector Controllers in an ARTC Center. ARTC controllers are responsible for the safe separation and expeditious flow of en-route air-craft from the time when these aircraft have reached the first assigned en-route altitude after takeoff until they reach the approach control fix at the terminal airport. Individual sector controllers monitor and control the path of a flight through their own sectors and coordinate this flight path with the paths of all other potentially conflicting flights in their own and adjacent sectors. Control is based on an estimate of what the traffic situation will be at specific fixes 15 minutes in the future, and is continually projected ahead by use of the relayed position reports of aircraft as they pass over these fixes.

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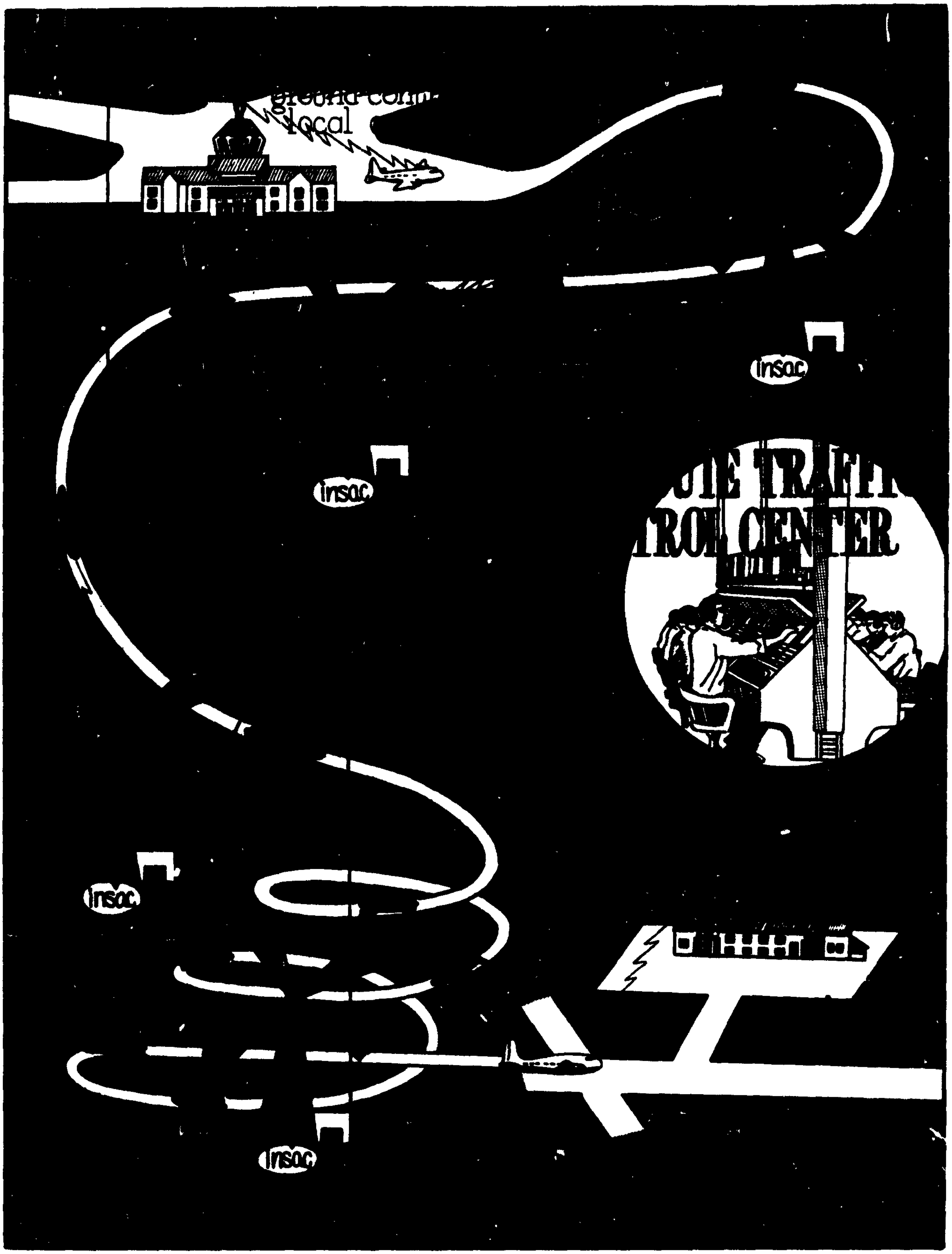
[1] This appendix was prepared by Bryce O. Hartman.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ARTC personnel are conscious of the overlap between their own authority and the authority and responsibility of pilots. For this reason, *ARTC* clearances are sometimes started with "*ARTC advises*...".

Assisting Agents. In addition to the different individuals listed above, there are assisting agents in the system. Persons located in Interstate Airways Communications Service (*INSAC*) stations relay messages between pilots, *ARTC* center personnel, and towers. This communication function is performed in addition to their other communications duties. *INSAC* stations also operate a Flight Assistance Service, which is an information and flight-plan filing center at terminals.

The Weather Bureau provides weather information through its Flight Advisory Weather Service (*FAWS*) located in *ARTC* centers. A *FAWS* meteorologist briefs both pilots and *ARTC* center personnel on weather conditions. This service is performed in addition to his duties in compiling, analyzing, and relaying weather data through *INSAC* facilities. Airline company dispatchers and communicators expedite and assist controllers and pilots.

B. Typical Operational Sequences

In figure I-2 are shown the major units that together make up the air route traffic control system. Six agencies can relay requests and instructions from a pilot to the *ARTC* center and back to the pilot. The itinerant pilot may file a flight plan through the Flight Assistance Service of *INSAC*, through an airport control tower, by telephoning the center directly, or by going to the center in person. Airline company pilots may use these facilities, but more usually they communicate through the company dispatchers. Military pilots use military facilities where they are available, but also have access to all the civil facilities. Any pilot in the air may communicate with the *ARTC* center through the *INSAC* radio stations along the air ways.

The Proposed Flight Plan. The initial step in a controlled flight occurs when the pilot files a proposed flight plan with any of the six agencies listed in the preceding paragraph. This proposed plan is relayed by telephone to an Air Route Traffic Control Center. Here it is copied down by the assistant controller who is working the airlane sector through which the aircraft will initially fly. The proposed plan is then placed in the "suspense" file where it may remain for as long as an hour or more before some action is required on it.

Request for Clearance. Having decided to depart on his flight the pilot again contacts the *ARTC* center through one of these six agencies and requests clearance which he has already filed. The proposed plan is then removed from the "Suspense" file and is considered by the controller for the appropriate sector. This controller coordinates the flight path with all the other existing flight paths in his and other sectors within the center. If another center is involved, the controller, or his senior controller, contacts the other center. This other center then coordinates the proposed flight with all the flights under its control.

From a succession of such actions, a flight plan clearance is developed. If the traffic picture relative to the proposed flight is fairly simple, the clearance will be completed for the entire flight. If the traffic picture is complex, the clearance may be granted only for an initial part of the route, and the pilot directed to contact the center when he reaches a certain fix for the remainder of the clearance.

The controller then calls the agency that relayed the request and gives it clearance. This agent (usually a tower controller) then relays the clearance to the pilot, who accepts or rejects it. If the pilot rejects or questions part of the clearance, the relay channel is reactivated until a clearance acceptable to both the pilot and the center is issued.

The controller now codes this clearance onto a flight progress strip and places it on the Flight Progress Board in the column appropriate for the first reporting fix specified in the clearance.

Takeoff. Under the direction of the tower controller the pilot now taxis out, takes off, and climbs on a specified heading and at a specified speed to the initial altitude specified in the clearance. The tower notifies the center by telephone of the actual takeoff time, and the center controller corrects the flight progress strip that represents this flight.

Position Reports. At each radio fix specified in the clearance, the pilot contacts the nearest *INSAC* communications station and reports his position and time over the fix. The *INSAC* station relays this information by telephone to the center, where the controller enters it on the flight progress strip and moves the strip to the next fix column on the Flight Progress Board. As the aircraft approaches an adjacent sector in the area, the strip for that flight is passed to the controller for that sector.

Entering New Control Areas. When the aircraft reaches the boundary of the area handled by a given *ARTC* center, the center contacts the adjacent center by telephone and turns control of the aircraft over to that center. This system of en-route reporting, revising of information, and passing along of control from one ground controller to another continues until the time the aircraft reaches the approach control fix at the terminal airport. Revisions of the clearance and exchange of information are made through *INSAC* facilities and company radios.

Approach and Landing. At the approach control fix, the pilot contacts the approach controller in the terminal airport tower by radio. Under the direction of the approach controller he flies his airplane to the point where he can make a landing. During the final stage of the landing he is under the direction of the

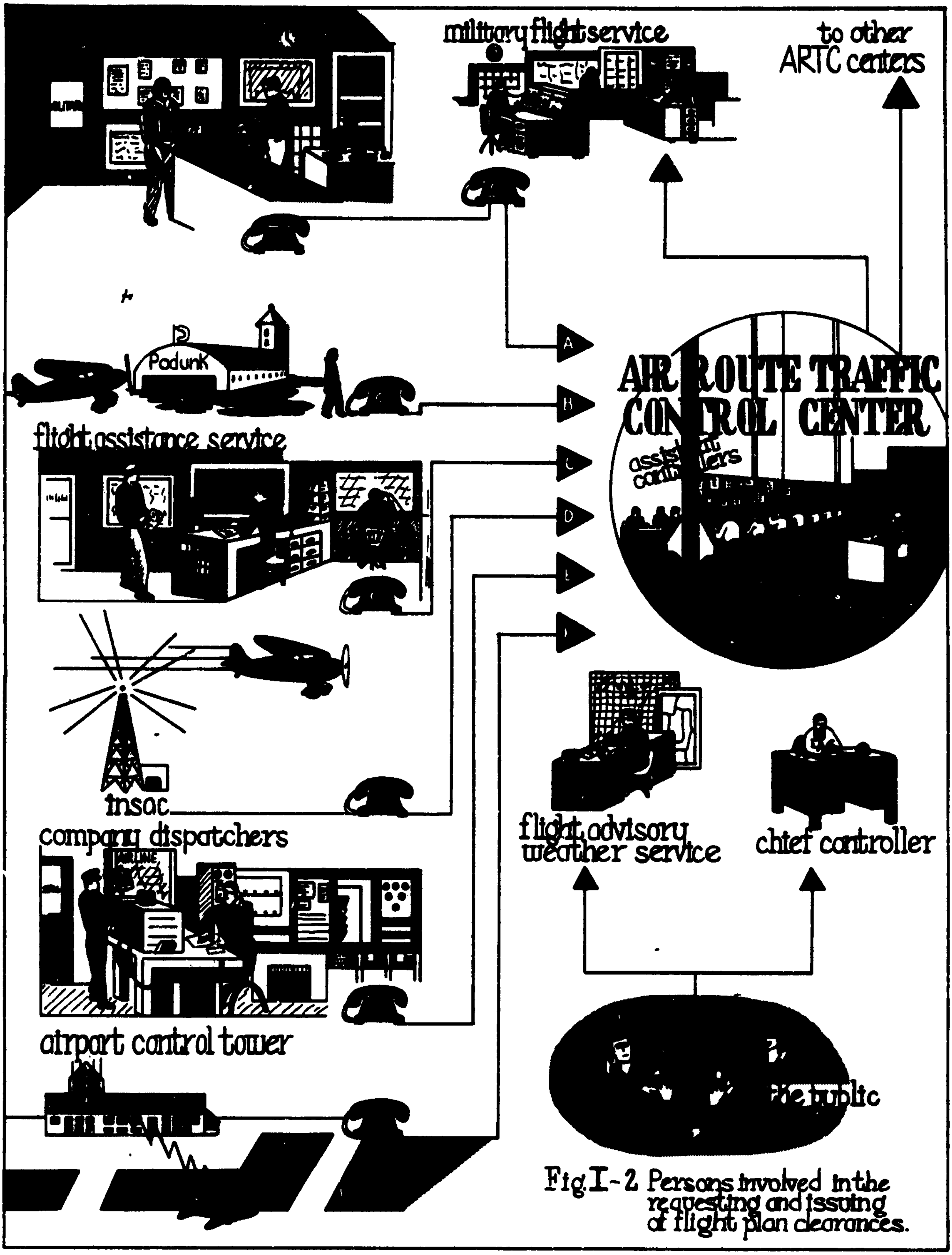


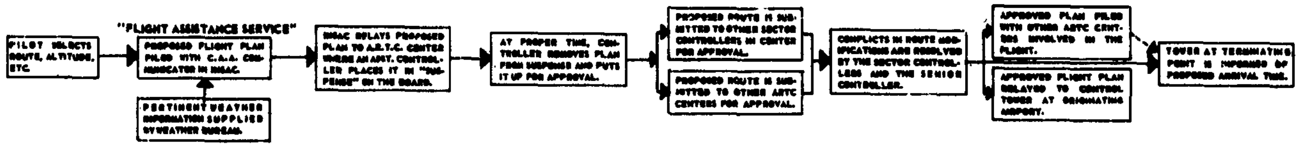
Fig. I-2 Persons involved in the requesting and issuing of flight plan clearances.

local controller. As he taxis to the ramp and parks he is under the direction of the local ground controller.

Termination of Flight. The time of touchdown on the landing is relayed by the tower to the center where the controller who last had the flight progress strip for this flight closes the flight clearance and removes the strip from the board. The tower at the point of origin also receives the touchdown time by telephone and removes the flight progress strip from its active board.

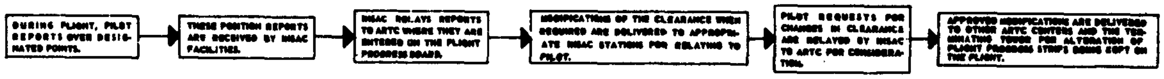
The procedure outlined here is undergoing revision as a result of the installation of direct center-to-pilot radio facilities. Much of the relaying of information that is now required will be eliminated by this change. These direct radio facilities, however, are being installed only at terminal areas and some relay of information will be necessary on the en-route portions of the flight.

In figure I-3 is shown a block-diagram of the step-by-step sequence of communications made, and action taken from the time a pilot initiates a flight plan request until he arrives at his destination. This figure shows what happens when the requesting pilot is an itinerant pilot. Slight variations in the sequence will occur according to the classification of the pilot, but an idea of the complexity of the system of relaying and communicating of flight plans and flight data is represented by the diagram.

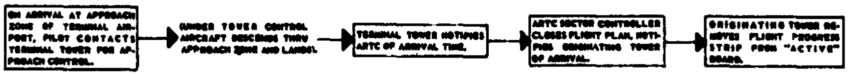


A. PROPOSED FLIGHT IS FILED AND APPROVED WITH MODIFICATION

B. APPROVED PLAN IS DELIVERED, FLIGHT IS INITIATED, AND DEPARTING INFORMATION IS DELIVERED TO ARTC



C. ENROUTE DATA, INSTRUCTIONS, AND REQUESTS FLOW BETWEEN AIRCRAFT AND ARTC, WITH INSAC AS RELAY



D. ARRIVAL OF AIRCRAFT AT DESTINATION TERMINATES THE CONTROL AND MONITOR FUNCTIONS OF ARTC, ORGIN AND DESTINATION TOWERS

Fig. I-3 – Simplified diagram of the sequence of Communications to and from the ARTC Center during a typical IFR Flight by an itinerant pilot.

APPENDIX II

A SURVEY OF THE OPINIONS OF SIXTY AIR TRAFFIC CONTROLLERS AND TOWER CONTROLLERS REGARDING PRESENT AND FUTURE TRAFFIC-CONTROL SYSTEMS

A. Purpose of the Survey

A group of people who are well-informed about present problems of traffic-control are the men who are now working in Air Route Traffic Control (*ARTC*) Centers and Airport Control Towers. Although these men work with today's traffic and today's equipment, their experience with present problems should provide a valuable springboard for a look into the future.

At our second meeting in June 1950, we agreed that a survey should be made of the opinions of traffic controllers. We all felt that such a survey was needed to guide our thinking about traffic-control problems. Accordingly most of the members of the working group visited one or more traffic control centers and interviewed a few controllers. In addition, a systematic survey was made of centers in eleven cities in the eastern half of the United States and standard interviews were conducted with senior personnel at these centers. **The present section is limited to the findings of this systematic survey.**

The primary purpose of the survey was to identify bottlenecks in the present air-traffic control system as seen by the people actually handling traffic. A secondary purpose was to determine what new types of equipment these men felt would be of greatest help in their work.

B. Procedure

The *ARTC* centers visited are shown in Table I. These centers were chosen to represent a wide range of traffic problems. Cleveland, for example, has a heavy load of civil over-traffic which neither originates nor terminates in its area. New York, Boston, and New Orleans all work with transoceanic traffic, but each of these centers has its own peculiar problems. Atlanta has terrain complications. Cincinnati has extensive military over-traffic.

The persons interviewed were either chief controllers or senior controllers (watch supervisors). They were interviewed individually. All were asked the the following three standard questions in a relatively free interview situation.

1. *What are the "bottlenecks" and what is slowing you up in the present air traffic control system?*
2. *What kinds of equipment, either equipment you have heard about or gadgets that have not yet been designed, would you like to have for use in an air traffic control center? (The term "control tower" was used when interviewing tower controllers.)*
3. *What operations or things done by the controllers whom you supervise could be done as well or better by machines or pieces of equipment?*

Table I

Places Visited and Number of Persons Interviewed in the Survey of Air Route Traffic Control Centers and Airport Control Towers.

	Number of Interviews	
Place	*Center*	*Tower*
Atlanta, Ga.	5	2
Boston, Mass.	2	0
Chicago, Ill.	3	3
Cincinnati, Ohio	5	2
Cleveland, Ohio	3	2
Ft. Worth, Texas	4	3
Houston, Texas	0*	3
New Orleans, La.	3	3
New York, N. Y.	3	2
San Antonio, Texas	4	3
Washington, D. C.	3	2
Total	35	25

*Houston had no *ARTC* center.

C. Results

The responses given by Air Route Traffic Control personnel to the three questions are summarized in Tables II, III, and IV. The responses of Control Tower personnel are summarized in Tables V and VI.

The bottleneck mentioned most often by *ARTC* personnel was *communications*. Only one person out of 35 failed to talk about communication problems in response to the nondirective questions asked by the interviewer.

Bryce O. Hartman conducted the survey and wrote this appendix.

These men who are now directing traffic feel that the difficulty of transferring information from one person to another is the greatest limitation of the present system. Controllers say that delays of 4 minutes in contacting other centers are common, and delays as high as 12 minutes are frequent where relaying agencies, such as an airline office, are involved. Controllers agree that at those times when the present traffic control system reaches saturation, communication usually is the first function to break down.

Controllers believe that the shortcomings of present navigational facilities and procedures center around three problems. The first problem is to determine the locations of en-route aircraft with the accuracy that is required for control of traffic under minimum separations. The second problem is to obtain enough flight-path information and to acquire sufficient authority adequately to control "direct" and high-altitude flights. The third problem is to establish by-pass facilities for better separation of en-route and terminating traffic at large terminals.

Chief Controllers expressed concern about two extremely important problems arising out of present operating procedures in *ARTC* centers. Controllers and their assistants sit opposite each other at the flight progress boards. As a result, the assistant receives very little on-the-job training. Two chiefs stated that they have no assistants ready to assume controller duties, even though they have some men who have been working at the assistant's job for over two years. Chief controllers fear that critical personnel shortages will occur because of this inability to train men on the job. In addition, all the chiefs agreed that the new flight progress boards do not allow efficient use of the assistant.

Because of their physical separation, the assistant cannot aid the controller when the latter becomes overloaded.

Controllers agree that the excessive amount of coordination of information that is now required within the center and between the center and outside agencies, is another important bottleneck in the present system. At present, a controller wears a headset and can dial any other controller in his own center. However, the interphone equipment is seldom used for this purpose. More frequently, controllers and senior controllers walk about and talk directly to other controllers. For example, a controller who is preparing a clearance for a flight that will pass through another sector in the area needs to know what altitude layers are available. He usually will walk over to the controller for the other sector and ask him for an altitude that is available for the speed and direction of the flight involved. If the proposed flight path crosses several sectors, this person-to-person coordination is repeated several times. If the controller is very busy, the senior controller may do some of this walking and talking for him. If both are busy, the coordination may be accomplished by shouting to other sector controllers. As the traffic load on the center increases, face-to-face coordination increases, and use of the interphone decreases. However, the interphone and longline telephone system is used for coordination with all agencies outside the center (airline offices, other centers, towers, etc.). The delays that result from the communication bottleneck complicate this phase of coordination. It should be mentioned here that most controllers think that the amount of coordination now necessary is excessive. They point out that there now exists a certain amount of duplication which increases the load on the communication system and contributes to that bottleneck.

The most frequently mentioned request for equipment from *ARTC* controllers was for radio facilities that would help to solve the communication problem *(see Table III)*. At present most centers have no direct radio link with pilots. Some people strongly favor a radio network that will permit direct communication with aircraft anywhere in their area. Radio facilities for the terminal area only are now being installed and used at some centers. These facilities for direct communication are now used primarily for an extension of approach-control functions, i.e. for the entry of aircraft into the terminal area. This equipment also permits some exchange of traffic-control information with over-traffic. The limited range of the radio facilities now being installed prohibits any further use.

Most controllers who expressed a need for further navigational aids felt that the Omnidirectional Range and Distance Measuring Equipment would be of great value. They also suggested that an extended discussion of additional navigational aids is pointless until they find out how effectively *VOR* and *DME* will work. Most controllers showed the same cautious attitude regarding traffic displays derived from radar. They want an opportunity to use radar longer before expressing specific opinions. Their suggestions about automatic flight progress boards were tempered by uncertainty about the technical feasibility of such devices. Mechanical interlock systems* were mentioned commonly. This may be because such systems are now installed in some centers.

Airport control tower chiefs and watch supervisors are less critical than *ARTC* personnel regarding the operation of the present system. They feel that there are some serious problems in radio communication *(see table V)* centering around congestion of the frequencies. They report that inadequate airport design is complicating their operation. One controller said that all the airports in which he had ever worked were build without regard for the future development of aviation. Lack of

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1. In this kind of interview one is often more interested in what the person chooses to talk about than what specific things he says.

TABLE II

Summary of "Bottlenecks" Cited by Air Route Traffic Controllers
(N = 35 Interviews)

"Bottleneck" Cited	Persons Mentioning the Item	
	Number	Percent
1. *Excessive communication lags*	34	97
Delays in relaying information	32	92
Errors in relaying information	3	9
2. *Inadequate navigation facilities and procedures*	30	86
Insufficient number of fixes	16	46
Insufficient altitude layers	8	23
Insufficient by-pass facilities at terminals	8	23
Insufficient control over and information on "direct flights"	6	17
Insufficient control over and information on high-altitude flights	6	17
Lost-aircraft procedures	4	11
Conflict between traffic of adjacent terminals	4	11
3. *Present methods of center operation*	26	74
Excessive number of manual operations in using boards	13	37
Insufficient flexibility in use of personnel	12	34
Insufficient opportunity for training personnel	12	34
Fatigue of personnel	10	29
Insufficient staff for peak loads	9	26
Excessive number of activities per controller	9	26
Excessive posting and calculating	8	23
Inadequate weather information	5	14
Controllers become mechanical	4	11
Insufficient authority	2	6
4. *Excessive information coordination*	22	63
Delays in intercenter coordination	16	46
Delays in intracenter coordination	8	23
Excessive routine information	5	14
Excessive duplication of information	2	6
5. *Personal problems*	11	31
Poor public relation with pilots and with other agencies	8	23
Excessive administrative duties	4	11
Early disability requiring semi-retirement	3	9
Insufficiently defined legal authority	2	6
6. *Excessive separation minimums*	12	34
7. *Wide range of aircraft performance* (speed and rate of climb)	10	28
8. *Insufficient military coordination and variation in military equipment*	7	20

TABLE III

Summary of Equipment Desired by Air Route Traffic Controllers

(N = 35 Interviews)

Equipments Desired	**Persons Mentioning the Item**	
	Number	*Percent*
1. *Additional radio communication facilities*	28	80
Direct center-to-aircraft channel	26	74
Remoted to area	10	29
Pushbutton messages	4	11
2. *Navigation aids*	24	69
VHF Omnidirectional Range	11	31
Distance Measuring Equipment	11	31
Surveillance radar	11	31
Off-set course computer	4	11
More holding fixes	4	11
ADF facilities	3	9
Airborne radar	2	6
Airborne emergency signals	1	3
3. *Traffic control displays*	22	63
Radar-type displays	12	34
Remoted into area	3	9
Identification of aircraft	3	9
Altitude information on scope	2	6
Daylight screen	2	6
Automatic failure signal	2	6
Computers	6	17
Weather display and automatic poster	4	11
Three-dimensional traffic display	3	9
Map and terrain displays	1	3
4. *Automatic flight progress boards*	22	63
Automatic posting of flight data	16	46
Automatic position reports from aircraft	8	23
Airport Time Utilization Equipment	3	9
Automatic issuance of clearances	3	9
Automatic duplication of flight progress strips	2	6
Automatic failure signal	2	6
5. *Land lines communication*	22	63
Mechanical interlock (altitude)	17	49
Misc. changes in interphone systems	13	37
Conference features on long lines	4	11
Teleautograph	1	3

dual runways, inadequate taxiways, and insufficient parking space are the airport deficiencies mentioned most often. Controllers actively engaged in approach control are concerned about navigation facilities which either expedite or restrict the flow of aircraft into and through the primary holding stack.

Tower controllers report that a major human bottleneck in present traffic-control is the unfamiliarity of itinerant pilots with procedures at a specific airport. The controllers suggest that this is partly due to the time necessary for an itinerant pilot to orient himself once he lands on the runway.

According to tower controllers, the information coordination problem is bothersome but not severe. One of the criticisms they often express is directed against the delays encountered while trying to telephone the Air Route Traffic Control Center in instrument weather.

Tower controllers, in discussing the equipment they want (*see table VI*) are primarily interested in equipment that will expedite the flow of traffic through approach control and onto the runway. The navigation and communication equipments they want and the improvements in airport design they request all point toward this goal.

The responses of tower personnel to question three (human operations that might better be done by machines) did not justify tabulation. Almost half the group interviewed stated that there was no operation in the tower that fitted this category. Of the remainder, five (20%) suggested push-button messages to aircraft and (20%) suggested automatic posting of flight progress strips.

Table IV

Summary of Opinions of Air Route Traffic Controllers
Regarding Human Operations that Should Be Done by Machines
(N = 35 interviews)

	Persons Mentioning this Item *Number*	 *Percent*
1. Posting flight information	18	52
2. Calculating and estimating	16	46
3. Coordinating information (mechanical interlock and teleautograph)	10	29
4. Position reporting and recording	8	23
5. Duplicating flight progress strips	7	20
6. Issuing standard instructions to aircraft	6	17
7. Recording information to be used in the future	6	17
8. Relaying data (instantaneously)	4	11
9. Posting weather information	3	9
10. Visualizing flight paths	3	9
11. Recording the time	2	6
12. Giving a pilot the traffic picture	2	6
13. Counting flight progress strips	1	3
14. Warning of collisions	1	3
15. Detecting errors	1	3

Responses to Question 3 are summarized in Table IV, which is self-explanatory. Controllers felt that some routine operations could be handled by machines, but that planning and decision-making operations could not be mechanized.

*The present mechanical interlock system is an altitude reservation system between towers and centers. A panel of lights simultaneously duplicated and operated at both places indicates the availability or nonavailability of altitudes in the primary stack for approach control.

TABLE V

Summary of "Bottlenecks" cited by Airport Tower Controllers
(N = 25 interviews)

"Bottleneck" Cited	**Persons Mentioning the Item**	
	Number	*Percent*
1. *Inadequate radio facilities*	20	80
Congestion of frequencies	15	60
Excessive phraseology	6	24
Lack of channel to remote GCA	3	12
Simplex of channels for two-way flow	2	8
Poor intelligibility	2	8
2. *Inadequate airport design*	19	76
Inadequate taxi-ways	12	48
Inadequate single runways	12	48
Insufficient parking space	5	20
Inadequate field lighting	5	20
Inadequate tower visibility	5	20
Excessive vehicular traffic on airport	1	4
3. *Inadequate navigation facilities and procedures*	17	68
Delays due to approach and ILS procedure	8	32
Excessive separation minimums	5	20
Insufficient number of holding fixes	5	20
Inadequate control of short flights	4	16
Conflict between outbound and inbound flight	4	16
Breakdown of *ARTC* functioning	3	12
Single point focus of range stations	3	12
Conflict between over-traffic and terminal traffic	3	12
Inadequate equipment maintenance	2	8
4. *Excessive coordination of information*	17	68
Excessive delays in relaying information	8	32
Excessive coordination with *ARTC* centers	7	28
Inadequate weather reporting	5	20
Inadequate interphone system	4	16
Insufficient coordination with military	3	12
Excessive duplication of information	1	4
5. *Variability in aircraft performance*	16	64
Unfamiliarity of pilot with terminal procedures	13	52
Variability in equipment	4	16
Inaccuracy of pilot performance	3	12
Variability in airspeeds	2	8
6. *Personnel problems*	11	44
Understaffed	6	24
Lengthy training	5	20
Excessive regulation of procedures	3	12
Insufficient authority	2	8
Unnecessarily strict physical examinations	2	8

TABLE VI

Summary of Equipments Desired by Airport-Tower Controllers
(N = 25 interviews)

Equipment Desired	**Persons Mentioning the Item**	
	Number	*Percent*
1. *Navigational aids*	21	84
Surveillance and approach radar	20	80
VOR and *DME*	8	32
All-runway Instrument Landing System	6	24
Taxi-control radar	5	20
Airborne traffic displays	4	16
Direction-finding equipment	3	12
Airborne automatic *ILS* approach equipment	2	8
Visibility-measuring devices on approach lane	2	8
2. *Communication aids*	18	72
More radio frequencies	8	32
Teleautograph for weather information	8	32
Altitude interlock with centers	7	28
VHF equipment	6	24
Automatic aircraft position reports	5	20
Improved microphones	2	8
Interphone headsets	2	8
Direct phone lines between towers	1	4
3. *Airport design improvements*	18	72
Dual runways	8	32
Improved tower design	6	24
Improved airport lighting	5	20
Improved taxiway lighting	5	20
Improved tower lighting	3	12
Improved approach lighting	2	8
More aircraft parking space	1	4
4. *Terminal procedure improvements*	7	28
Extend approach control authority	3	12
Standardize airport regulations	3	12
Restrict variety of airport operations	3	12
Standardize airline procedures	1	4

APPENDIX III

THE CRITERION PROBLEM[1]

In the development or modification of any operational system, technique, or instrument, there is some specific goal to be achieved. We state at the outset that we want to achieve a particular kind or level of performance, often an improvement over the performance of some existing system, technique, or instrument. Very often, however, this goal is elusive when we attempt to specify exactly how we are going to know when it has been achieved. This makes the problem of evaluation of the new development difficult.

In some cases our goal is so general that we cannot easily quantify our approach to it. In other instances we may not have a real opportunity to measure directly against our final goal until it is too late for the direct measurements to be useful in designing the total system, e.g., when our goal is the absence of mid-air collisions. *In any event, we are always faced with the need for a careful specification of the ultimate goal or final criterion,* for this largely determines the programming of research on the intermediate problems of the system.

The model or models *(final criteria)*, against which we compare the new development or modification may take one or more of several forms including the following:

a. *A theoretical ideal level or kind of performance.*
b. *A list of desired performance characteristics, determined on the basis of careful study of the intended system.*
c. *A series of planned operational tasks (with predetermined critical levels of performance on a number of relevant variables).*

The problem of establishing the general model or goal to be used in the research is the essence of what is known as the criterion problem. It is at the heart of a large portion of the problems discussed in this report. The criterion problem, therefore, is one of unique and general concern in the planning and focussing of any research program that deals with the performance of man-machine systems. The present appendix is written as a general summary discussion. The detailed analysis of the criterion problem will be possible only as separate research projects become established.

A. Manifold Nature of the Criterion Problem

As implied in the introduction there are many levels of criteria, and they can be applied at many levels of research. We shall distinguish here between two rather distinct phases of this problem and identify these as the *model phase* and the *prediction phase.*

The *model phase* is directly concerned with the formulation of the goal which we are attempting to attain. This goal or final model gives the theoretical specification of the complete system, the separated details of which are determined by lower level criterion considerations.

The *predication phase* of the criterion problem has to do with the specifying of important variables that can be measured individually and that predict final adequacy of the system. Throughout work on both of these phases one must be prepared to deal with a multiplicity of relatively independent criteria. Each one of these (speed, avoidance of gross errors, accidents, etc.) may serve some purpose as a separate objective and as a measurement against which we may compare various proficiency features of the system. The relative importance of these separate measures often requires research.

The Model Phase

When certain specific goals are to be reached and a system is being developed to attain these goals, the requirements of the system must be rigorously specified so as to assure that the final operational objectives will be met. The relative weight or importance to be attached to various components of the system should be derived from a careful analysis of these objectives as well as from the relation of the proficiency and interactions of the components to the objectives. The common contrary procedure of simply ordering a system out of a group of available entities and small systems merely because they are available, gives no assurance that their combination will offer the best possible or most practical system for attaining the goal.

The model phase of the criterion problem is one that is too often taken for granted. It is actually the beginning point of any program of research and development on operating systems. The problem is solved by certain classical methods in engineering fields, but is made more complex in systems where

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[1] This appendix was prepared by Dr. T. G. Andrews at the suggestion of the NRC Committee on Aviation Psychology.

the variables of human behavior have been added. The model phase of the criterion problem requires a systematic analysis of the goal and the model to assure that we are solving the right problem and that we are not operating with false problems. In other words, the actual formulation of the central problem of the research effort should be determined by proper criterion analysis in the model phase.

One central point of the present report is that the general model viewed up to now as the one to be effected in air-traffic-control systems is not to be taken as final but must be thought of as open to radical changes in terms of ways of attaining the intended system goals, once the underlying goals have been specified from a long-range point of view. This requirement is formulated in Research Objective VIII, Chapter VIII.

It may be assumed, as a point of departure, that one major aspect of the final criterion represents *safety*. To point up why the "criterion problem" is a problem, however, we may cite but a few of the difficulties which might be met in preparing to use a safety criterion.

One would be the difficulty of conceptualizing the real meaning of the criterion and its place in the system. Another difficulty would be the establishment of measurable variables that are critically relevant to safety. A third would have to do with the many practical problems of obtaining access to the necessary information, such as information about pilot and controller behavior in critical situations, in instances where administrative policies may not allow equal availability of all items of information or where no adequate records are available.

The Prediction Phase

The prediction phase of the criterion problem is faced when we are developing, modifying, or testing limited portions of the system being constructed, whether these parts be men, machines, or man-machine relations. Each portion cannot be rigorously tested in the complete system and so must be evaluated in terms of certain "intermediate" performance measures which have proved to be, or are guessed to be, variables in the goal or ideal model. Thus intermediate criteria developed for the evaluation of any segment of a system, such as a communication system, will reflect the function which that segment performs in the total air-navigation and traffic-control problem.

There are several levels of intermediate criteria which are predictive of final criteria. These progress from basic laboratory experiments, to simulators, field tests, and operational studies. Within this hierarchy, it is imperative that relations be established between the various levels, including the final model. Of special importance are the particular problems of objectives, design, and uses of simulators, for it must always be recognized that simulator data are intermediate or transitional in character and are not themselves the final goal.

In the present report many analyses in terms of intermediate criteria are presented, including analyses of problems relating to the roles of men and machines, links in communication systems and their relative efficiency, visual displays, and problems of direct vision. In each case, the search has been for limiting aspects of human, machine, or environmental conditions that may influence directly or indirectly the amount of error or damage predictable in the system. These functions then are predictive of damage or inefficiency. The attainment of stability within the tolerance limits of each function represents a *predictive criterion*. That is, we infer that when these proximate or intermediate criteria are attained we also attain one of the major final criteria, *safety*.

B. Measurement and Functional Relations in the Criterion Problem.

As indicated above, the criterion problem is essentially a problem of validation of procedure and equipment against some goal, purpose, or set of aims for the system. Solution of the problem, especially the predictive phase, involves testing hypotheses regarding the functional relations between certain man-machine aspects and aspects of the goal, in this case safety and efficiency.

The study of these relations obviously requires experimentation. This work in human engineering necessitates a search for proximate criteria *(predictands)* and predictor variables. These variables on each side of the implied prediction equation should be cardinally measurable and must be chosen and weighted in such a way as to minimize the errors of prediction.

This search for variables in human engineering research has led to the accumulation of considerable systematic information regarding certain important families of variables to apply to new problems as they arise. Nevertheless, each new problem raises new questions about its own peculiar tolerance limits on the many human-engineering variables previously studied.

This change of tolerance limits is especially true as new systems produce different patterns of coupling men and machines, and as new requirements for speed and accuracy develop in increasingly complex tasks. For example, the requirements for speed of object detection and recognition on the part of the submarine night lookout are in some respects similar and in other respects quite different from those of the pilot of an ultra high-speed aircraft.

Each predictor and predictand variable, whether a direct "job sample" or a derived variable in the experimental laboratory, must have a high degree of reliability. This characteristic implies regularity of behavior from one time of measurement to the next. Regularity or reliability is usually quite satisfactory for time measurements, but in the case of error analyses the demands of reliability may be such that very extended research is necessary in order to get enough data on which to base a reliable conclusion.

Proximate and intermediate criteria and good predictor variables are especially necessary whenever conflicts arise in the model between engineering requirements and human limitations. An example of this situation was presented in Chapter VI in connection with the optical qualities of windows in streamlined aircraft. Such conflicts are to be attacked by criterion research and a process of objective optimizing, that is, by a comparison of consequences of various compromise designs in terms of the final aims specified in the model. Here, especially, exact data on tolerance limits are required so that the problem can be analyzed properly. In such cases, critical levels must be modified from ideal levels to practical levels, but the possible variation can only be determined by carefully designed research and by specific attention to the criterion problem.

In making analyses of prediction of error, studies have indicated that variability is an important indicator to be used as a proximate criterion of negative value. This determination is discussed in detail in Chapter VIII. It is obvious that variability, as a negative criterion, should have tolerance limits determined for many operations and many man-machine units. Variability is a peculiar variable to use as a predictor or predictand because of certain mathematical characteristics of its scale. Therefore, new measures of variability may be required for its appropriate use in certain criterion analyses in human engineering problems.

There are several stock methods of criterion formulation that have survived as useful parts of any program of research and development. Among these stock methods are the following:

Rational analysis, which has to do mainly with the final model and the logical considerations of its reformulation for testing and evaluation of components. The rational analysis technique is usually the point of departure for programming research studies that will produce satisfactory final as well as intermediate criteria. These analyses frequently produce variables or possibly measurable aspects of a system that have what is called "face validity". The complete rational analysis is at its best when it is performed mathematically, but this is not a restriction.

Job analysis and *job specification* are techniques usually applied to a system for which the model is already determined. In this case the problem is one mainly of selecting the operator for a particular task or linkage in a system once the exact nature of the task or linkage requirements are specified. The term operator is used here to mean man or machine or man-machine unit. Job analysis is mentioned in Chapter VIII. Also, a form of job analysis is implied in the problems of optimal division of responsibility between men and machines discussed in Chapter III.

The critical incident technique is a variant of the job analysis method. This technique is also described in Chapter VIII. It applies far more broadly than to personnel problems, where it has received most attention to date.

The development of predictors is a stage in criterion analysis that follows the selection of measureable criteria at various levels, the latter being thought of as the "development of predictands". The first search is for several measurable aspects of the ideal model or of intermediate models that themselves will predict the final model. Given these measurable aspects, the next problem is to determine the most discriminating measures of proficiency of the various components that will predict these various criteria, when these measures are expressed singly or as a composite. Among the discriminating predictors of negative type are the various errors in the components of a system. It is obvious that certain types of component errors are more important than others. This fact is the same as saying that they have differential predictive value. However, the latter expression of relative value implies research and empirical determination.

Regression analyses are needed as tests of the adequacy of the development of predictors and predictands in the criterion. These analyses are rigorous statistical tests of the tolerance limits available for any given combination of proficiency variables or indices of merit and any pattern or composite of criterion variables. Such tests are useful in developing or choosing the various indices, and they indicate the overall adequacy of the system at any stage of its modification. The statistical methods most frequently used in such testing are multiple regression, parametric analysis of functional relations, discriminant function, multiple factor analysis, analysis of covariance, and canonical correlation.

Even though many research tools are available from previous studies, considerable research effort is needed in the development of new and more efficient experimental and statistical methods for critical evaluations at various criteria levels in human engineering.

GLOSSARY

ABILITY– the present level of performance of an individual as determined by his past training and development *(see aptitude, capability, capacity).*

ABSOLUTE SENSORY THRESHOLD– the least amount of a specified kind of energy which can be detected by a particular receptor or sense organ *(as the minimum visible amount of radiant energy).*

ANALYSIS OF VARIANCE– a statistical procedure whereby the total variability within a set of data may be divided into components attributable to identifiable sources, e.g. to differences between operating methods, forms of encoding information, etc.

APTITUDE– an individual's ability to acquire some particular skill with training *(see ability, capability, capacity).*

CAPABILITY– the upper limit of an individual's ability at a given time assuming that he has received optimum training *(see ability, aptitude, capacity).*

CAPACITY– the full potentiality of an individual in performing a given task, as developed by training and limited only by his native constitution *(see ability, aptitude, capability).*

CENTRAL PROCESS– brain or central nervous system activity, as distinguished from sensory activity which is referred to as peripheral.

CHANNEL– a communications path, typically a sense organ or sensory modality as used in this report.

CHECK READING– inspecting one or more instruments for the purpose of detecting deviations from a null or normal condition.

COMMUNICATION THEORY– a mathematical description of message formulation and reception *(see information, message, redundancy).*

"CONSTANT" ERRORS– deviations from the desired performance which remain relatively constant for long periods of time (as calibration errors). Constant errors represent a bias in the performance of a man, machine, or system *(see also variable errors).*

CONTROL– a device (knob, lever, pedal, etc.) manipulated by an operator.

CRITERION– a standard or basis for judgment; in particular, a score or measure used as the basis for saying that one system (or individual, or device) is better than another.

DISPLAY– a device or method for presenting information to a receptor. Each form of display provides a different way of encoding messages.

ENCODING OF INFORMATION– putting information in a specific form for transmission or presentation.

EXPERIMENTAL DESIGN– the planning of experiments, but more specifically planning the conduct of experiments in the light of particular statistical methods which will be used to analyze the results.

HUMAN ENGINEERING– a branch of applied psychology which aims to determine human capacities, to provide principles governing the design of machines for efficient human use, and to insure an effective integration of men and machines for the accomplishment of an over-all task.

INFORMATION– the ignorance-reducing characteristics of a signal or stimulus. The amount of information carried by a stimulus depends on the number of alternative signals which might have been transmitted at that time. To the extent that successive messages are redundant, the actual information of each is less than its potential information.

JOB ANALYSIS– the study of jobs with particular reference to the specific tasks and component operations which are being performed.

LEGIBILITY– that characteristic of a visual display, often but not necessarily, printed or written material, which determines the speed and accuracy with which it may be read.

LINK ANALYSIS– the study of successively-used displays and/or controls, and of operating connections between all men and machines in a system, for purposes of achieving a system layout which will keep key links as short as possible.

MASKING– the partial or complete obscuring of one auditory signal or message by the simultaneous presentation of another auditory signal or message.

MESSAGE– one or more signals or stimuli, which may or may not carry information.

NOISE– audible noise, but also more generally a disturbance or perturbation of a message which produces random variations or "clutter" in the display.

NORM– a standard representative value for a group or type; in statistical notation the mean, median, or modal score for subjects taking a given test or working at a given task.

OPERATIONS ANALYSIS– the analysis of routine records on day-to-day operations - as records of completed flights under varying weather conditions.

PERCEPTION– awareness of relations; integration of experience. The perception of spatial or temporal relations and the perception of rates of change are especially important for the use of many displays.

PERTURBATION– disturbance superimposed on or added to the information needed by the recipient of a message. The greater the perturbation, the less is the probability that the course of action chosen will be the desired one.

PICTORIAL DISPLAYS– any display which makes use of the same continuum as that on which the information itself is scaled, and presents, it without distortion of critical relations (*e.g.* represents length by length, angle by angle, etc.)

POSITION TRACKING– a tracking task in which movement of the operator's control is associated with a direct displacement or movement of the tracking reticle, cross-line, or indicator. Contrasted with rate tracking.

PURSUIT REACTION– a task that involves keeping one thing lined up with another. May require following or compensatory movements.

QUALITATIVE READING– consulting an instrument to determine the direction of departure from a null or normal condition.

QUANTITATIVE READING– consulting an instrument in order to obtain the numerical value of the indication.

RATE TRACKING– a tracking task in which movement of the operator's control regulates the rate of movement of the tracking reticle, cross-line or indicator.

REDUNDANCY– reduction in the information carried by successive signals or messages due to inter-signal or inter-message dependencies: as, for example, in an exact repetition of a message (*see information*).

RELIABILITY– repeatability or consistency; a measure of the likelihood of getting the same results if an experiment or observation is repeated.

SAMPLING– working with relatively few observations, people, or situations in an experiment designed to predict what will happen in the general case. Representative sampling of the intended operator group and the intended situational applications are required.

SENSITIVITY– *of displays:* a measure of the responsiveness of a display based on the relation of the amount of change produced in the display by a given change in the condition or situation displayed.

– *of sense organ:* a measure of the function of a sense organ which varies inversely with the least energy or energy changes which can be detected (*see threshold*).

SIMULATOR– a device which faithfully reproduces one or more portions of an operational task. The most important question for the design and use of simulators is that of how faithfully and completely the operational task must be simulated if the device is to be valid (*see validity*).

STATUS INFORMATION– information which does not change rapidly, which remains relatively fixed and up-to-date for long periods (contrasted with transient information).

STORAGE (OF INFORMATION)– memory. This term is used here in place of memory to keep the present discussion consistent with the vocabulary of communication theory.

SYMBOLIC DISPLAY– a display that portrays information in terms of intermediate or transformed scales.

SYSTEM– an entire assemblage of men and machines.

SYSTEM ANALYSIS– the discovery and identification of sources of error or variability in a system, the measurement of these errors, and the arrangement of man-machine elements to improve system performance.

SYSTEM EVALUATION– testing or comparing different systems.

SYSTEM REQUIREMENTS– what a piece of equipment must do, or what an operator must know or do in order that the system functions properly.

SYSTEM RESEARCH– programs directed toward discovering general principles applicable to the design and development of new systems.

THRESHOLD– *of a runway:* the beginning of the runway; the line of demarcation between approachway and runway.

– *of a sense organ:* the least amount of energy or energy change which can be detected.

TRACKING– a pursuit task wherein a reticle, cross-line, or indicator is kept lined up (as adequately as possible) with a moving pip or target.

TRANSIENT INFORMATION– information which may change rapidly and for which the operator requires a display capable of showing moment-to-moment changes (contrasted with status information.

VALIDITY– agreement between performance scores on some test or device and the performance which this test or device reputedly measures; as the validity of a simulator - the simulator being valid only if performance on the simulator is related to performance at the task which it simulates.

VARIABLE ERRORS– deviations from average or standard performance of a man, machine, or system due to random factors which affect each observation separately. Variable errors produce lack of precision.

VISIBILITY– *meteorological:* the distance along a horizontal path at which an indefinitely large and dark object can just be seen by daylight.
– *physiological:* detectability or sensitivity for visual stimuli.

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