PSYCHOLOGICAL ASPECTS OF MACHINE AND WORK-PLACE DESIGN

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INTRODUCTION

Since the earliest applications of the principles of scientific management to the modern industrial situation, there has been a branch of applied psychology that dealt with the problems involved in the selection, training and placement of the industrial worker. It has long been considered the primary function of this relatively new profession to achieve a high level of performance in the accurate application of industrial manpower that the most efficient utilization of the labor force will result; thus insuring the maximum material production per unit of labor effort. The industrial psychologists have made a significant advances in all the many phases of the industrial personnel area by ever improving existing methods of technical aptitude testing, morale surveying, counselling, job evaluation, statistical merit ratings, and by improving the basic principles of criteria which define the results of human effort. Starting with the period during and after the first World War, there has been a growing tendency to question the complete accuracy of the concept that it is necessary to fit a worker to a fixed industrial environment. This increasing doubt was abruptly changed to a recognized fact during the development of the complex military machine systems of World War II. Despite the most discriminating selection and rigorous training of the operators, the elaborate detection, control and weapons systems were repeatedly failing in their assigned functions. Invariably, the failure of the system was found to be a result of the shortcomings of the carefully selected and trained operators. As a result, it became obvious that the systems, as well as their individual components would require redesign of the mechanical components with adequate consideration being given to the limitations of the human abilities of the operator. As a result of these experiences, attention was directed to a glaring lack of consideration of the human element in the design of machines and of the environment in which men work in modern technology, both military and industrial.

It is true that progressive measures had been instigated in the disciplines of both psychology and engineering to furnish the machine designer and industrial engineer with information regarding the most desirable features of industrial work places from the human point of view. But it wasn't until the rapid advance of complex machine systems within the past few years that cooperative efforts of the psychologists, physiologists, physicists, design engineer, and motion-and-time engineers were joined to solve the growing problem.

It will be the objective of this report to provide a comprehensive survey of the literature, abstracted from the texts, references, and periodicals, of the various disciplines concerned with investigating the effects of the human factor as it concerns the design of industrial machines and work places. Pertinent information can be found in the journals of psychology, engineering, physics, anthropology, physiology and other applied sciences. It is evident that each discipline has one or more titles that describe its own research into the man-machine-workplace relationship. Their work has variously been described as biotechnology, biomechanics, psychology, and systems research. It must be admitted that any of these descriptions in appropiate to the subject, and it therefore becomes apparent that no literature survey such as this could ever be termed complete. In view of the obvious dynamic aspects of the subject matter, it seems clear that the science that deals with the intra-disciplinary research into the design and operation of machines for human use is still in its infancy. For the balance of this report, this research is named variously engineering psychology, human engineering, ergonomics, biomechanics, or psychotechnology, according to the particular phase of development under consideration.

To maintain an air of complete impartiality toward the relative importance of contributions by any single discipline toward the advancement of a solution to the problem as stated previously is practically impossible. There is everywhere represented literary proof of the interest existing within almost all branches of the applied sciences in the men-machine problems. This report will attempt to present the foremost advances in the order of their importance to the overall problem. Insofar as possible, information will be categorized under headings of the particular discipline involved. Because of the many overlapping areas of interest, a fine delineation is oftentimes indiscernable.

By previous definition of the subject matter to be investigated, the two fields with a major interest are represented by engineering and psychology. There is a common meeting ground existing at the present time between these two fields known in the broadest sense as 'human engineering'. In spite of the obvious connotations of the phrase itself, it has been widely adopted by those dealing in both industrial and applied psychology. The question inevitably arises then, as to whether the psychologist investigating the technological environment of man and its effect upon human behavior, or the engineering designer investigating effects of temperature, noise and color upon human efficiency, is the practitioner of human engineering. It cannot be denied that both are interested in the broad relationship between man and equipment, but it is much more difficult to evaluate the extent of their respective interests.

Automation - defined as the replacement of man by machines or the use of machines to control machines - has become to some, the pressuring device that demands increasing efficiency from current man-machine combinations. By definition, some degree of automation has existed from the time of the first application of the most elementary machines. The last degree will consist of the use of thinking machines that analyze and subsequently solve their own problems. Before that time, however, there will undoubtedly be an orderly development of ever increasingly complex machine systems that will demand a greater degree of ability on the part of the human operator. Because there is a limit to the strictly human abilities, the factor of designing with these limitations included as one of the parameters becomes mandatory. Throughout this development, the application of even a fundamental knowledge of human psychology and physiology has been necessary, and the lack of it made more serious as the complexities of the machines increased. Another purpose of this report then, will be to recognize the importance of proposed corrections in the background training of those responsible for future industrial machine design.

HUMAN ENGINEERING

At first glance, it may seem that the term 'Human Engineering' connotes too broad a definition in the field of industrial technology to be applicable to the subject of this report. It is true that as far back as World War I the expression appeared in the literature of psychology. In the post-war era, Hartley (1928) remarked;

> Human Engineering will take its place in the not distant future among the professions. When that time comes, men will not be graduated from college with the exception of soon achieving an executive position in industry without previously having completed a pre-executive course in Human Engineering. Psychology and sociology will then become subjects of greater appreciation by industrial leaders. They will cease to be tolerated by some as unarticulated parts of an un-understandable educational device which is supposed to function in some mysterious manner in modern industry.

During the sudden mechanization of the armed forces during World War II, however, military technological leaders formed teams of researchers to study methods of better adapting machine systems to match abilities of operators. The published reports of these investigators have appeared in various journals and publications with a preponderance of 'human engineering' titles. As a result, this term has come to pertain primarily to the process of adapting the physical proportions and abilities of man to machine systems. Various handbooks have appeared, all of which include some sort of tabulated data pertaining to human measurements and limitations and requirements for maximum human efficiency.

Human engineers have for some time looked upon the man and the machine which he operated as interacting parts of one overall system. This concept represents the human operator as an organic data transmission and processing link inserted between the mechanical or electronic displays and the controls of the machine. An input of some type is transformed by the mechanisms into a signal which appears on a display. It may be shown as a pointer reading, a pattern of lights, or a pip on a cathode ray tube. However it appears, the presented information is read by the operator, processed mentally, and transformed into control responses. Switches are thrown, buttons are pushed, or handles are turned. The control signal, after transformation by the mechanisms, becomes the system output, and in some devices it acts upon the displays as well. These latter are called "closed loop" systems wherein the displays do not reflect the human's response.

When the man and the machine are considered in this fashion, it immediately becomes obvious that, in order to design properly the mechanical components, the characteristics of the man and his role in the system must be taken into full account. Human engineering seeks to do this and to provide as much assistance to the system designer as possible. Specifically, the psychologist tries to help his engineering colleague in three different ways. First of all, he studies the psychology of the human as a system component. Second, he assists the engineer in experimentally evaluating prototype man-machine systems. Finally, he teams up with engineers to participate actively in the design of machines. Each of these human engineering functions will be described in detail, beginning with the last and least scientific activity.

It must be here considered that human engineering is not only a science but also a technology; it includes, besides the study of the interaction of the man and the machine, the design of the machine. Beside the engineers designing machines, works the human engineering psychologist, oftentimes taking an active part in the technological processes. He may work on a team and translate scientific findings into electronic circuits which in specific situations will compensate for the human's limitations or complement his abilities. Using procedural analysis techniques, drawing upon his psychological knowledge and attitudes, and employing his common sense and creative ability, the human engineer proceeds to contribute to system development at three levels of complexity.

At the simplest, he designs individual displays, controls, or display-control relationships. At a somewhat more complex level, the human engineering technologist contributes to the design of consoles and instrument panels. At the highest level of complexity, he assists in structuring large systems composed of many mechanical elements and frequently several human beings. In this capacity he helps to determine what information must flow through the system, how it must be processed, how many men are required, what tasks they will perform, and what type of information each one will need. In short, the engineering psychologist helps at this level to determine the configuration of the system.

Human engineering technology is much more extensively practiced by psychologists than is generally recognized by those who are not closely identified with the field. The difficulty of assigning individual credits for team effort tends to level the accomplishments of all the members of the team. As a result, little information is available as to the extent of the specific contributions of the human engineer. During the past two decades, however, every major type of military equipment has received some attention, as have also certain nonmilitary products such as aircraft instruments and cabins, flight control towers, artifical limbs, semiautomatic post office sorting equipment, telephone sets, theodolites, experimental equipment for the earth satellite program, control panels for atomic reactors, and numerous industrial machines.

At this point, the question arises as to the proximity of this practical activity and pure psychology. It cannot be denied that in one sense of the term it is an area of applied psychology. Facts about human behavior are being utilized in the design of machines. Yet in another sense it cannot be regarded as psychology at all, for certainly the design of machines is engineering, regardless of who does it or of the extent of interest on the part of the designer in human behavior. To deny this in favor of the view that system design is applied psychology because of its human reference, converts all engineers to psychologist the moment they take into account the behavior of the human for whom they are designing the machine. It is certainly not customary to consider all occupations oriented toward human behavior to be psychological.

A second difficulty which stands in the way of incorporating the design aspects of human engineering under psychology arises from the nature of the goal of systems design. Whereas the primary aim of the practitioners of the more conventional applied psychology is to control and influence people, the human engineering designer seeks to produce more effective machines. While psychology has, in the past, been applied to improving human performance by selecting, training, and motivating normal men, by curing mentally ill men, and by persuading both to buy toothpaste and television sets, human engineering aims first at building better systems and only secondarily at improving the lot of the operator. Thus, whereas conventional psychology, both basic and applied, in anthropocentric, human engineering is mechanocentric.

In view of these inconsistencies, it is questionable whether the practice of human engineering can be categorized with the psychological discipline. It becomes evident that in view of the increasing importance of this relatively new science, questions as to the training of its practitioners and the relative position in the industrial heirarchy should be soon resolved.

A second way in which psychology assists in the design of machines is through studying the behavior of the man as a machine operator. Research has been undertaken to study selected aspects of the behavior of the man as a system component. The intent being to provide the engineers with information concerning certain of the characteristics of the man in order that the properties of the machine may be made to harmonize with them.

Whereas psychology in the broad sense embraces all manner of human action, engineering psychology deals with a much more restricted variety of behavior. When considering the human in a man-machine system as an information transmission and processing link between the displays and the controls of the machine, his behavior consists of reading off information, transforming it mentally, and emitting it as action on the controls. This performance may be described as of the type in which the operator's responses affect in some way the pattern or sequence of certain of the input events. The operator may signal when a tone comes on and withhold his response when he hears nothing, or he presses one key when he sees a green light and a different key when he sees a red one, or perceives the range and bearing of a radar target and identifies its location verbally, or moves a cursor to follow the motion of a target image. In all these cases, the essential interest in the behavior focuses upon the correlation in space and time between events in a restricted and predefined stimulus 'space' and corresponding events in a preselected response 'space'.

The behaviors studied in engineering psychology can be characterized as voluntary and task-directed or purposive. The operator of a man-machine system is always consciously trying to perform some task. Perhaps it is to follow on a keyboard the successive spatial positions of a signal light, perhaps to see a visual target imbedded in 'noise' and to signal its position, possibly it is to watch a bank of displays in order to determine malfunction and to take action where necessary. In all cases, the operator is voluntarily trying to accomplish something specific; he is not just free associating, or living.

Another characteristic of the human operator's behavior emerges as a corollary of voluntary control. The class of human responses of interest to the engineering psychologist involves chiefly the striate muscles. Because it is through the action of this type of effector that men speak and apply force to levers and handwheels, it is these muscles which play the dominant role in the human's control of machines.

Practical considerations dictate that vision and audition be the sense modalities most often supplying the input to the human transmission channel. Because of the nature and location of the eyes and ears and because of their high informational capacity, they are ideal noncontact transducers for signal energies emitted by the mechanical or electronic displays of machines.

The above-mentioned characteristics define the human reactions investigated in engineering psychology as falling within the narrow confines of the classical category of 'sensorimotor' or 'psychomotor' behavior. But actually, the subject matter is even more limited than this. As was mentioned previously, the main task of the psychologist-human engineer is to provide system-relevant facts concerning human behavior, and it must be emphasized that not all facts, even though they concern psychomotor performance, can meet this criterion. The hundreds of studies conducted with the pursuit-rotor, for example, have generated very few facts having the remotest relation to the design of systems.

Because it is recognized that not all good sensorimotor psychology is necessarily good engineering psychology, steps are being taken to get at the kinds of behavioral information which the engineers really need. In order to do this, the concepts and models of orthodox psychology are beginning to be replaced by physical and mathematical constructs and engineering models. System psychologists view man as a multipurpose computer and as a feedback control system. The virtue of these engineering models is that they furnish ready-made a mathematics which has already proved itself of value when applied to the inanimate portions of the man-machine system and which may turn out to be useful for the human element as well. In addition, they provide the behavioral scientist with a new set of system-inspired hypothetical constructs and concepts which may redirect his research and stimulate entirely novel lines of inquiry.

Another result involves the initiating of a new series of descriptive terms, such as inputs, outputs, storage, coding, transfer functions, and bandpass, to replace the orthodox language consisting of terms like stimulus, response, sensation, perception, attention, anticipation, and expectancy, the comfortingly familar language of the behaviorist and even the clinical psychologist.

The third major contribution of the engineering psychologist to the design of machines is systems evaluation. Like human engineering technology, evaluation studies require a sizeable effort yet receive scarcely any publicity. Evaluations have been performed on headphones, range finders, gunsights, fire control and missile control systems, radar sets, information plotting systems, combat information centers, aircraft control towers, and numerous assorted display and control components. In some instances, the experiments have been carried out in the laboratory with the system inputs being simulated. In other cases, the tests are conducted in the field. But in both situations, the attendant complexities and difficulties of statistical control make this necessary variety of research as trying as any in which psychologists are likely to participate.

The reason that psychology was introduced into these varied evaluations lies in the fact that it possesses methods for dealing with human variability. In contrast, engineers generally had worked only with time-stationary components and, therefore, themselves at a disadvantage when evaluating the performance of devices which were being operated by men.

It is evident that psychology has much to offer in regard to the evaluation aspect of systems design. A question arises, however, as to the value of such research to the field of pure psychology. The use of a complex systems experiment is not considered an efficient method of learning about human behavior. Basic indeterminability of human response has been recognized for a long time. Philosophers and psychologists have pointed up the fact that behavior is an interaction among different kinds of things and that it is arbitrary and misleading to say that one of the things is doing the behaving while the others make up the environment. Thus, in studying the behavior of a man walking, the behavior of the ground under his feet is not being studied. Yet the walking behavior would be impossible without the ground, just as it would without the man. Both, and much else besides, are necessary for the walking to occur, and any measurement of the behavior reflects the characteristics of all of the interacting objects and forces. This is of very little consequence to psychology so long as the parts of the human's environment which interact with his motor output remain unchanged during an experiment. If, in the walking study, the ground underfoot was always of the same general firmness, levelness, and texture, its contribution to the behavior could be neglected. Similarly, if in a tracking investigation the man always uses the same joy stick working through the same system dynamics, it matters not that the performance measured is that of the man-joystick system and not of the man alone.

But let the properties of the objects to which the man applies force be varied, unknowingly or deliberately, and it becomes vital to recognize the contaminated nature of the performance measure. Change the ground from hard to muddy, or the tracking control from joy stick to handwheel, and the altered performance resulting is a composite of direct effects and man-environment interactions impossible to untangle without further research. When this is not recognized and the behavioral shift is attributed exclusively to the man, a scientific blunder is compounded.

Conventional psychology has generally avoided this problem of confounded dependent variables by working much more frequently with sensory and state-of-the-organism parameters that with human output variables. Engineering psychology, however, has deliberately undertaken to work with system variables, with the results almost never being pure human response scores. Although repeated experience has alerted the majority of the experimenting human engineers to the inferential pitfalls of blindly equating system performance with human performance, there are still the few that continue along utilizing fallacious assumptions. The statement has occasionally been made, for example, that human tracking performance is improved or degraded by changes in the nature of the control or by alterations in the control dynamics. Such statements may be true but they are certainly not justified, for tracking performance, as measured, is system behavior which can change radically as a result of altered dynamics without reflecting any comparable change on the part of the man.

But it is not only the dependent variable which gives the human engineer trouble in making psychological progress from system studies. The independent variables are often even more troublesome because they frequently embody many parameters. Taylor (1957) utilizes a comparison of the performance of two boys, one riding a bicycle and the other a pogo stick. When the two machines are compared, four sets of dimensions are involved. If the pogo stick is substituted for the bicycle, the controls are shifted; pedals and handlebars are traded for a spring-mounted step and a pole. Secondly, the system dynamics are changed as they relate to the transformation of human energy into motion along the ground. Third, the sensory inputs to the operators are modified (the displays are altered): with the pogo stick the visual world bobs up and down, with the bicycle it glides by; with the pogo stick the boy's weight is all upon his feet, with the bicycle he feels pressure from the seat. Finally, the task is completely transformed; the psychomotor performance of hopping up and down along a Z axis while simultaneously maneuvering along X and Y coordinates, through shifting balance around these axes, is an entirely different stunt from controlling in X through balancing around X, steering around Z, and pedalling around Y - the latter is the task of the bicycle rider.

In this particular example, even if a measure of human performance as a dependent variable existed, which it does not, it is clear that next to nothing of psychological interest could be learned by manipulating this multiparameter, independent, system variable. Since the displays, the controls, the dynamics, and the psychomotor task are all varied simultaneously, the logic of experiment is so completely violated that it is impossible to partial out the individual effects of any of the components upon the performance of the system or of the man. All that one can know in such a systems test is the combined effects of the dimensionally massive, independent variable - in other words, that one system is better than another. This is of value in deciding between systems, but yields little of value to pure psychological research. It is almost always true that system variables comprise more diverse dimensions than do the variables customarily chosen for psychological analysis.

It is not, however, only the complexity and dimensional confounding typical of system variables which make it hard to derive psychologically relevant facts from man-machine systems tests. A further difficulty stems from the shift in the operator's task which so often results from the manipulation of the physical parameters of the system. It has been pointed out that the psychomotor processes involved in riding a bicycle are entirely different from those underlying hopping about on a pogo stick. Similar radical differences in the operator's task are often to be observed when real systems are compared. One system may require the operator to act analogously to a complex differential equation-solver, while another may require of him nothing more than proportional responding. One radar warning system may require the operator to calculate the threat of each target and to indicate the most threatening; another may compute the threat automatically and place a marker around the target to be signaled.

Clearly, the operators tasks differ so much from one of these systems to the next that it would never have occurred to a psychologist to compare them. The differences are so gross, so obvious, that they obscure the need for relating the tasks, for placing them on some kind of a useful continuum and for scaling the distances in between. Yet these behaviors must be compared in some way and the knowledge made available to engineers if the human is to be employed effectively in man-machine systems. Changing the operator's task from one of these complex psychomotor processes to another may produce startling improvements in system performance, and the principles determining the substitution of the task must be discovered if systems design is to progress.

In citing the above examples of methods contributed by psychologists to the design of machines, it has been pointed out that they act not only as scientists, seeking knowledge for others to use, but also as technologists, actively participating in the planning and design of man-operated mechanisms. In the latter role, they have stepped out of their field and entered that of engineering. Even while acting as scientists, there has been a tendency to move away from psychology as classically conceived, for on the one hand they have expanded their subject matter to include the behavior of systems, while on the other hand they have restricted their interest in human performance to a narrow class of system relevant behaviors.

It should not be concluded, however, that human engineering, in serving the system designer, will only draw from psychology and not contribute to it. It seems to be the concensus of opinion of the majority of the applied scientists that, when psychologists started tinkering with machines and seriously tried to learn how they could better be designed, an opportunity was provided for something to happen of utmost significance to science. This is the destruction of the barrier which has hitherto existed between the psychological sciences and engineering technology and the physical sciences.

Psychologists have conventionally thought and talked in a construct language which is different from that of the applied sciences. Traditionally the concepts of psychology tend to be relatively imprecise. At first, this indefiniteness was regarded as almost a necessity; for while physics dealt with physical things, psychology dealt with the mind, and of course the mind was non-objective. Then later, the mind was abolished, and psychology became anthroponomy, the science of human behavior, and there was less excuse for metaphor. Although officially outlawed, metaphor still exists to a certain extent in the language.

But even when similes are avoided and the concepts are given precise operational definitions, the construct language of psychology is very different from that employed in the physical sciences. First, the vocabularies are as dissimilar as are those of English and German. Secondly and more important, the constructs themselves often differ in the nature of their generality, elegance, and fruitfulness, with those of physics far in the lead. Although psychologists have become more scientific in their instrumental procedures, using better and better research tools and employing statistics of ever-increasing power, they are still working with pretty much the same old types of syntactically impoverished concepts. Today man is conceptualized as doing the kinds of things which he and other creatures with minds have always done: like perceiving, thinking, learning, forgetting, living, and dying. This has tended to result in a perserverative replowing of the same ground, a redoing of the same experiments.

Since psychologists have not conceived of the living organism as an analogue device capable of imitating a wide variety of mathematically describable physical operations, no construct terms have been added to the vocabulary of psychology which overlap directly with those of physics or engineering. Because of this, there has never been any real possibility of describing the behavior of both the man and of the physical objects and events in his environment in the same terms. The language of psychology has had to be used to describe the behavior of the man; the language of physics, the environment. Of course, never before was there a need to develop a scientific notation in which one could express with equal facility the operations of minds and the working of mechanisms.

That need, however, has arisen with the advent of human engineering - when psychologists for the first time began to look carefully at mechanical and electronic processes and engineers started to consider seriously the characteristics of human behavior - brought the problem into sudden, clear focus. It was just not possible to effectively design complexes embodying both men and machines so long as the two components were conceptualized as being entirely different and behaviorally unrelated. Universal concepts and a meta-language of action equally applicable to humans or mechanisms became a necessity.

The emergence of the systems viewpoint was essential to this important, although relatively simple, intellectual discovery. It made two things obvious for the first time. It drew attention to the fact that in many circumstances the behavior of the man was inseparable confounded with that of the mechanical portions of his environment. This meant that psychologists often could not study human behavior apart from that of the physical and inanimate world--that all along they had been studying the behavior of man-environment systems and not that of the men alone. The inseparability of the behavior of living organisms from that of the environment with which they are in dynamic interaction certainly argues against maintaining separate sciences and construct languages; one for the environment, the other for that which is environed.

But the concept of the man-machine system does more than this. Not only does it emphasize the dynamic inextricability of the man and the machine with which he works, it suggests that human and mechanical processes are to some extent interchangeable, although not necessarily equally precise. Thus, the system designer has the choice of having required computations performed by a mechanical computer or by the man--the process is the same in either case, although the accuracy may be vastly different. Again, this recognition that human behavior and mechanical or electronic processes can be surrogates for each other provides an excellent reason for seeking to conceptualize men and machines in terms of the same models.

Engineering psychology has begun to do this as has already been pointed out. It is beginning to adopt engineering techniques, to ask experimentally how well men can differentiate or integrate or amplify, how their gains change or their frequency response characteristics shift. It is starting to apply to human behavior the trans-science concepts and methods of information theory and feedback sero analysis. It has begun to use cybernetics. In short, in starting to contribute to the design of machines, psychologists have begun theoretically and pragmatically to pull together the psychological and physical sciences. It seems safe to presume that some day psychology, biology and applied science will employ the same physicomathematical meta-language when describing the behavior of those particular system components which fall within their purview. If and when this presumption becomes a reality, it will have resulted, at least in part, from the efforts of those engaged in human engineering.

ERGONOMICS AND BIOTECHNOLOGY

As previously mentioned in the introductory section of this report, a complete study of the subject under consideration would entail investigation within many disciplines. It was brought out at that time that the major areas containing the bulk of information relative to such investigation were engineering and psychology. The first section has been devoted in a large part to a discussion of the psychological aspects of the trend toward human engineering, defined as the consideration of man as a link in the machine system. Equally important to the continued development of the necessary techniques is the work of the experimental design engineer. It is the intent of this section to discuss results of engineering research into the more complete utilization of the human abilities in the operation of complex machines, as well as the necessary training to further the effectiveness of the engineer in achieving this goal.

Ergonomics has been defined as the consideration of the stress and strain of the human in a work situation, particularly within the boundaries of a man-machine system. An old and valuable technique of engineering evaluation of a system is that of 'testing to failure'. Since this method is unsuitable for any test of a system involving the use of a human being, the study of biotechnology becomes an important factor to the design engineer. This subject, soon to become a basic discipline in the training of an engineer, embraces those features of human physiology, psychology, and hygiene which are pertinent to the requirements of a thoroughly schooled designer. It is recognized that the conditions and trends of modern life involve in increasing degree the following sociotechnological elements: (1) the interdependence of man and machines, (2) the progressive extension of artificial control of human environment, and (3) the expanding role of the engineer in human affairs. Engineering practice will demand a much more precise formulation of human characteristics for its part in the solution of these problems: a biotechnology to share an equal place with the physical technologies which are the bulwark of engineering training.

In many phases of engineering, essential design criteria are based upon human physiological characteristics. Ventilation is in part based on respiratory needs and, jointly with heating and air-conditioning, serves the needs of body-temperature regulation and thermal comfort. Illumination requirements depend fundamentally upon the properties of the visual sense. In fact, all aspects of environmental control, including also noise abatement, reduction of bacterial, physical and chemical contamination of the air, and functional aspects of industrial design, take their origin from human needs and tolerances. These elements of environmental hygiene, well recognized in engineering practice as it concerns public and industrial buildings, must extend to the design of the factory and its machines.

The structure of the human body, both statically and dynamically, is often an important consideration in engineering design. Applied anthropometry finds important utilization in aircraft cabin appointments, machine design, and comfort seating. As an example, improvements in amputation prostheses may be credited to the collaboration of engineer, physician, and limb fitter.

Here, the engineer performs invaluable service through application of knowledge of analytical mechanics and the strength of materials. Similar training and experience is useful in determining structural limitations in the human body relative to design of safety harness, such as is used by the steeplejack and the aircraft pilot. These problems point to the need for a systematic structural analysis of the human body, and it is but a short step to incorporate the study of anatomical materials, paralleling instruction in engineering materials.

The capacity, efficiency, and endurance of the human machine in physical labor is the concern of every engineer who assumes administrative duties, and doubly so for the production engineer. These factors underlie the principles of scientific management and time-and-motion analysis. When the additional stresses of environmental temperature, pressure, or anoxia accompany the work, physiological tolerance may be a critical concern. Hours of work, on-the-job feeding, rest periods, etc. are also phases of the physiology of work which form an important part of a comprehensive biotechnology.

Understanding of the principles of human psychological, with special reference to industrial and technological pursuits, is a prime objective of the complete training of the design engineer. In addition to the application of these principles in his primary function, his ability to work effectively with others is important to his personal success, as well as to that of the organization to which he belongs. By the age of forty, sixty percent of engineering graduates find themselves in positions of administrative responsibility. This is additional evidence of the fact that the engineer handles men as well as machines and materials.

In considering man as a link in complex machine systems, there are different levels from which the problem may be viewed. First there is the rather broad concept of man as a series or parallel link. An example of a man operating as a series link is provided by a radar operator, which serves as a link between the radar itself and another man or other men. Data in terms of space coordinates are taken from the visual display and relayed by voice or by mechanical aids to other men to be used for navigational purposes. The pilot of an airplane flying on automatic pilot is an example of a man being used as a parallel link. His function is that of a monitor who may override the automatic control at any time but who, at the same time, is free to perform other necessary tasks. Many similar examples can be found of men operating automatic machine tools.

The use of an electro-mechanical system to relieve the human being of a boring and routine type of operation is a recommended one. The inherent danger in using a man in this fashion lies in the fact that, unlike a machine that operates as it is designed to operate, a man may change his mode of operation unpredictably and without warning. What was a moment before a perfectly adequate series or parallel link may suddenly become a closed or broken link. Before this disadvantage can be overcome completely, more information will have to be made available to the designer regarding human stress, fatigue and motivation.

The analogy between man and a servomotor has often been made, and justifiably so. The airplane pilot, for example, operates as a servo. He receives information from his instruments, from the engine sounds, and from the general feel of the plane. He translates these inputs into corrective actions whose results are fed back in return.

The quite complex task of controlling the attitude of an aircraft in heading, bank, and pitch is successfully accomplished thousands of time every day. However, long hours of practice are required before a man can become proficient at it. It has been suggested that training time could be reduced and the pilot's task made less complex by the simple expedient of providing him with immediate knowledge of the effect of his control corrections. Man's responses in a control system are not continuous but intermittent. The man perceives that a correction is required; he then introduces a correction and waits for his instruments to tell him that the correction has been sufficient. An appreciable lag between the correction and the indication will cause overshooting and a more or less continuous oscillation of instability. Lags of as little as forty milliseconds, even though not detected by the operator, have been found to affect performance adversely.

The fact that man responds intermittently and not continuously is important to the design of control systems in another way. When he is operating controls that require continuous correction, as in following a template on a profiler, a man exhibits a natural oscillation of about one-half cycle persecond. To put a man in any system that has an independent, resonant frequency in this range is to invite amplification of these oscillations, with possible dire consequences.

Another level from which the problem under discussion may be considered deals with more specific thing. The human being may be looked upon as a link between displays and controls. He receives an input from a display or group of displays, interprets the information provided, and selects the proper responses. Usually his response is made effective through some system of controls. It becomes evident at this point that the proper design of displays and controls is essential, and their application must be taken into consideration by the engineer.

From almost any standpoint by which one may wish to consider it, human beings receive most of their information from the world around them through the medium of their eyes. This is especially true of the machine operators in industry, as well as anyone engaged in the ordinary pursuits of everyday existence. For this reason visual displays whose purpose is to convey information are important, and if they fail to convey the desired information because of ambiguity, illegibility, or position, they are no longer effective visual displays.

In the main, industry as well as the military services are concerned with displays for specialized tasks, and since these displays are usually visual, their design becomes of primary importance. These displays very often take the form of dials such as speedometers, pressure and temperature gages, altimeters, and the like, Generally, it is important that the information they convey be readily interpretable, speedily and accurately. Therefore, it is vital to know something about the perceptual capacities of those who are going to interpret them in order to design them so that they can be read quickly and without error.

Instrument dials can be divided roughly into three categories. First, there are those that are used for check readings; that is they usually give 'either & or' information and tell the operator that something is 'on' or 'off', or used as warning devices.

Second are the qualitative instruments. These usually indicate the state of something, with the addition of a directional component. Many dials designed for more quantitative purposes are often used by the operator merely for the qualitative information they provide. A good example would be that of the manifold pressure gage and the cylinder head temperature gage in certain types of aircraft. It has been found that these instruments give much more precise indications that the operator requires. All that is necessary to know is whether the readings are reasonable and to be able to tell when they begin to deviate outside of certain limits.

The third type of instrument is the most common one and the most important one, for it provides the operator with fairly precise quantitative information that can be vital to his needs in many situations. When dials of this sort have to be read quickly and accurately, their design is particularly important.

In considering the design of instrument dials, it is evident that there are numerous ways in which they can be varied. Size, shape, size of scale interval, type of scale, type of lettering, type of pointer, are only a few of the variations possible. The effect of all these factors has been studied in a systematic fashion, and three of the most important will be discussed as they affect the design of instruments. These are roughly the size of the marked scale interval on the accuracy of the reading, how scale numbering affects the accuracy, and the effect of different dial shapes on accuracy of interpretation.

There are three perceptual steps that are involved in reading a dial scale when interpolation between marked intervals is required. For example, it does not take long to decide that a pointer is somewhere between two and three when the scale is marked off in five units. It takes a little longer to see that the pointer is between 2.0 and 2.5. Often this is enough accuracy for most purposes, but occasionally it is necessary to interpolate a little more closely. The problem becomes, then, to know just how the distance between the marked intervals affects accuracy of interpolation. Experiments to determine the optimum interval have been performed and the results compiled in a human engineering guide for equipment designers (Woodson, 1954).

Researchers in England (Ergonomics Research Socitey, 1953) made a thorough study of the accuracy with which persons could read dials with different numbering systems. In general, it was reported that scale numbers that are decimals, as opposed to whole number, are harder to work with than those that are not. The best scale numbers are whole numbers that are divisible by ten, whereas scale intervals in 4's are the most difficult. Finally, and not surprisingly, it was found that 8 and 16 scales units between numbered markers are hard to read, but two scale units between numbered markers are simple if enough room is left between them.

Another important consideration in dial design is the shape of the dial; circular, rectangular, semicircular, etc. Results of an experiment in which five dial shapes were tested for single-revolution dials have also been compiled in handbook sources (Woodson, 1954). It was found that by far the most superior display was the open-window one which had the lowest percentage of errors in rapid reading tests. It was pointed out that the open-window is not necessarily the best dial for all conditions. In situations where ample reading time is allowed, or where the scale or pointer is not static but moving, other types of dials would give optimum results.

There is, of course, nothing very profound in these results, but there is no scarcity of examples of scale installations violating these simple facts, because the information was not available to the design engineer, and he had not the proper background for obtaining the information.

Equally as important as the input information to the human link in the man-machine system is the output or control aspect of the problem. Perhaps the best illustration of the possible complexity of this portion is the flight deck of a modern multi-engine airliner. Aircraft designers and their consultants in the psychological disciplines have long been concerned with this problem, and much useful knowledge has come from researches and surveys. A large percentage of aircraft accidents has ever been contributed to 'pilot error', usually resulting from confusion as to location of the many controls so essential to the safe operation of the airplane. The principal responsible factors were the crowding of controls and nonstandardization of control shapes and locations from plane to plane. Another type of error resulted from the fact that sequences of control adjustments were too complicated and, in emergencies, improper sequences were used, or portions of sequences were forgotten. Finally, reversal errors were frequently made. That is, a pilot moved a control in the opposite direction from that which he intended. Superficially, this might be considered the pilots' fault, but it has been established that there are 'natural' directions of movements for controls and, under stress, people are likely to revert to these natural tendencies. If an important control is designed to operate in opposition to these principles, only trouble can be expected in the long run. In those cases where there may be no preferred direction or pattern of movement, another principle has been shown to operate. In brief, a statement of the principle is this: If a new motor-coordination pattern is learned in the course of learning a new skill, and if, later, for some reason, that pattern has to be altered slightly to conform to a new development, then, should an emergency arise, the tendency to revert to the pattern learned earlies is very compelling. A most common example is the instinctive reaction of depressing a clutch pedal when driving a car with an automatic transmission, especially when an emergency stop is required.

As in the previous discussion of visual displays, a few of the improvements resulting from study by design engineers and applied psychologists will be mentioned. The establishment of the preferred control movements has entailed thorough investigation. Indications point to the fact that a toggle switch should flip up for ON, GO, or INCREASE. Similarly, levers whose motion is in the horizontal plane should go away from the operator for ON, GO, or INCREASE, and toward the operator for the reverse of these functions. In the case of handwheel controls associated with a visual display, clockwise movements of the wheel should move displays downward if the display is to the right of the handwheel, and upward if the display is to the left. The reverse should be true of counterclockwise movements.

Another problem that arises when a control is used in conjunction with a visual display concerns the optimum gear ration for the movement of an indicator. Experiments on this problem point to the fact that, when speed is the prime objective, the task can be broken down into three components. First, is the reaction time - the time that it takes to get moving. This is generally a constant factor. A second consideration is what may be called primary movement time - the time required to move the indicator to the correct vicinity. The third factor can be termed secondary movement or adjustment time, and, as could be expected, this is the time required for fine corrective movements once the indicator is in the right vicinity. It has been found that if a pointer is geared to move only a small amount for each revolution of a knob, primary movement time is long; on the other hand, primary movement time is short if the pointer movement is large for each revolution of the knob. Secondary movement times are almost the inverse of primary movement times. The best over-all ratio occurs at that point of a curve where the sum of the three time components is at a minimum, or about midway between 1 and 2 inches of pointer movement for each revolution of the knob.

Still another type of gear-ratio problem has to do with the mechanical cursor that is encountered on many remote plan-position radar indicators used with military equipment. Again experimentation has found that movements greater that 75 degrees there is an optimum gear ratio of about 5 to 1. For excursions of less that 75 degrees, the optimum gear ratio seems to be somewhat larger than that. However, on the basis of the data gathered by researchers (Tufts College; Applied Psychology Handbook, 1949), it is possible to recommend a compromise at around 5 to 1, since the gain in time for higher gear ratios and lower degrees of excursion is not appreciable.

The optimum rates of control movements are determined in part by such factors as the maximum rate of muscle contraction, the maximum rate of innervation, and the effect of fatigue. High rates of movement are commonly required by handwheel controls. Winding movements are a combination of reciprocal movements properly distributed in phase. Their maximum rate is approximately half that of simple back-and-forth movements of similar amplitude. The rate that results in most accurate control depends on handwheel diameter, inertia, friction, and other design features. Experiments have been done to show how cranking speed is affected by crank radius and friction loading of the crank. Two things have been demonstrated. One is that for every crank loading there is an optimum crank radius, and second, that as the friction loading of the handwheel increases, the optimum radius likewise increases slightly.

Since confusion of controls has been shown to be one of the prime causes of errors, particularly where pilots are concerned, much research has gone into ways of avoiding confusion. Different methods of control coding have been extensively investigated, and some general conclusions can be stated.

It has proved possible to shape code controls - that is, to design knobs with different shapes that can be immediately discriminated even when the operator has glove on. If some standardization were adopted so that similar functions on different pieces of equipment had control knobs of the same shape, training problems would be easier, and less confusion would result.

Studies have been made on the ability of people to reach, without looking and operate controls - beside them, above them, behind them, and so forth. If a high degree of accuracy is required, it is best to arrange the controls in a vertical row at shoulder level. A safe distance between these controls has been found to be five inches.

Color coding is another aspect that has been studied very thoroughly. The number of discriminable colors, including all hues with varying degrees of saturation and various degrees of lightness and darkness, is probably greater than 300,000. In the practical situation, however, the operator has neither the time nor the inclination to identify colors by comparison; rather he must be able to identify the colors in an absolute sense. Estimates of the number of such absolutely identifiable colors suggest that there are no more than ten or twelve where spectral hues are concerned. There are many disadvantages to using color for coding controls. For example, many colors already have meaning attached to them - red, green, yellow for danger, go, and caution. Also the amount of illumination available and the type of illumination greatly affects the way colors are seen. These things are not always easy to control.

These are some of the factors that enter into the design of controls for efficient human use. There are other important areas not mentioned, but it is the intent of the above illustrations to present examples of the factors to be considered by the equipment design engineers.

As an example of application of the consideration of ergonomics in the design of machines, mention might be briefly made of the case of a manufacturer of turret lathes. Drawing from the many studies made by the military, medical and scientific organizations and compiled in one of the representative handbooks (Tufts College, 1949), this company's engineers utilized dimensions covering 95 percent of the probable operators of their machine. For instance, the average weight for the thousands of potential lathe operators was found to be 153.1 pounds, ranging from 118 to 202 pounds. In height, the average was 5 feet, 9.2 inches. The upper limit was 6 feet, 2.5 inches, and the lower 5 feet, 3.7 inches. Many other statistics and information about the human characteristics were also used in applying ergonomic principles.

After the statistics were available, it was necessary to utilize them in the actual design. At best these statistics are used only as a guide, and the designer must adapt them to the problem involved. In one situation it might be best to take the upper limits of height or reach, while in another case the lower limit may be the critical factor.

In this particular case, the engineers redesigned one of the existing models of turret lathe using ergonomic principles in two main areas: (1) Manual Controls - these were studied for their location, organization, and handling ease as determined by human limitations of reach, muscular strength, natural limb motion, speed of action, hand grip characteristics, fatigue, and some mental factors such as memory and habit. (2) Speed Selection and Indication - here position, organization, type of information and legibility needs were studied in relation to optical height, form and color, maximum reading distance, eye motions, head motions and color contrast.

Dimensions of both the large and small man were taken into account so that the machine would feel comfortable for about 95 percent of all potential operators. For example, the best height for a control or work area falls between the shoulder and the elbow. Here the height limit of the small man is more desirable since these areas involve mainly forearm motions. Raising the upper arm means lifting more weight, resulting in higher fatigue. With the small man as the determining factor in this zone, the optimum work height falls between 54 inches and 40 inches, making the choice of a 42-inch spindle ideal. The same reasoning applied to the location of the master control lever, put between 45 and 46 inches above the floor level.

Ergonomics was also used to develop the master control lever. This lever now has a ball grip which forms a ball and socket joint in the hand and operates smoothly in all directions. Combined with the speed preselector knob above it, the master control lever replaces one clutch lever and three gear shift levers on the old design. The three gear shift levers were too high and not compatible with natural arm motions and the location of their cylindrical-type grips caused excessive angling of the wrists. Perhaps the greatest improvement in the modified model was the simplified body positioning during normal operation and speed shifting. On the old design the operator had to move sideways at least two feet to shift gears, as well as step backward. This movement was eliminated on new design.

Secondary controls were also relocated and redesigned with less swing. The operator later had only to move his trunk a comfortable 6 inches in all directions to handle controls within his convenient reach, while previously the body movement required was several feet.

Speed indication on the later model consisted of a direct-reading preselector dial, calibrated in surface feet and spindle rpm's. For easier reading it was placed normal to the line of sight by angling about 45 degrees to the cross slide. The height of this indicator was within thirty degrees below the horizontal sight line. This was found to be the most relaxing reading position and caused fewer reading errors. Its distance from the operator's eyes was set within an ideal reading range of 15 to 20 inches. Aside from location, many other factors entered into the indicator design. These included: compactness to minimize scanning; letter styling and color coding.

Safety and maintenance factors inevitable arise in consideration of ergonomic principles. In the redesigned lathe, operators were protected from crushed fingers by gaps not less than one and a half inches between moving and closing parts. Emergency controls were in clear areas, easy to reach and color coded. Sharp edges and corners were softened.

Other broad areas where human considerations are evident are in the individual design of machines for each range of work, and the use of power-operated units wherever needed.

CONCLUSION

All through the literature in the areas of engineering, psychology, physiology, biophysics, and anthropology, can be found increasing evidence of interest in the problems of designing man-machine-environment systems with the most efficient utilization of the man as a link in the system. The very concept of automation implies some reduction in the number of workers involved in any given work process. The workers who remain usually have increased responsibility in terms of costly equipment and materials with which they will be supplied. Along with these increasing demands upon the human operator of complex systems, it is only logical that increasing attention should be focused upon the human factors involved, inorder to obtain optimum machine output.

At first, consideration of such human factors was limited to time and motion studies. Then, personnel selection and placement of the best-qualified workers helped to increase machine productivity. When machines are relatively simple, selection and training achieve the purpose of supplying adequate operators. As machines become increasingly complex and the demands upon the operator's skill and knowledge become greater, a point is reached where selection and training can no longer meet the needs.

The transition of the operator's function from that of a simple manual manipulation toward increasingly complex discriminative, interpretive, and decision-making functions has stressed the need for design in terms of human capability and variability. A most notable example can be found in the field of aviation, where the aircraft design includes a complex pattern of instruments and controls that tax the ability of even the most carefully selected and completely trained pilot. Poorly designed instruments produce errors and confusion. The necessity of integrating the readings of several instruments to determine a single course of action dangerously delays the pilot's responses.

Tht source of basic information concerning the human operator had to come from those sciences which study the human directly; i.e., psychology, anthropology, sociology, anatomy, and physiology. The experimental psychologist apparently had the necessary training and experience to interpret pertinent scientific data in terms of appropiate design recommendations. In addition, he had training in the specialized experimental techniques which could be used to solve specific problems in this applied scientific adjunct to design engineering.

From this activity, the new field of 'human engineering' has emerged. Although it has been composed primarily of experimental psychologists, a wide variety of scientific disciplines is represented. It does not really replace any existing design function but actually broadens the range of design possibilities by adding a valuable member to the design team.

Another term of equal breadth which is intended to cover much of the field of study of designing machines for human operation is ergonomics. It has been defined as the study of human behavior in response to external stress, with particular reference to the stress-strain problems of man at work. Changes in design and in work methods and areas can be expected to result from such study.

It would be pertinent at this point to emphasize that consideration of human factors in design is not new - nor were professional psychologists pioneers in the field. It has often been said that primitive man was a human engineer when he shaped the handle of his ax or club to fit his hand. Certainly engineering designers have taken the human factor into account to some degree for centuries. Even in the application of the sciences of physiology and psychology to design, engineers have pioneered, as has been stated, "ahead of the specialists in those field." (Hatch, 1955)

In order to continue the progress made in the field of human design, it would seem that basic courses in human engineering should be integrated into the formal education of all engineers.

Just as physics is taught by physicists who gather and interpret the basic research data of their field, skilled representatives of this new discipline could provide the necessary cross-fertilization to make such teaching a dynamic experience in the educational process of the embryo engineer.

As with all emergent groups who have common occupational interests, there is a natural desire to band together to facilitate the flow of information and have some organizational structure to advance common purposes. Hatch (1955) has suggested constructively some affiliation with the American Society of Mechanical Engineers. There have been parallel suggestions of organization and affiliation with the American Psychological Association. Certainly psychologists have no monopoly on human engineering, and most engineers would not wish to undergo the intensive and lengthy training for such specialization. This suggests then, a team effort with productive cooperation between the designer and psychologist, and including the assistance of representatives from all the disciplines capable of making constructive contributions to the field.

As so aptly stated by one author (Warren, 1956) "let the engineer learn more about man - and the psychologist more about the machine."

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PSYCHOLOGICAL ASPECTS OF MACHINE AND WORK PLACE DESIGN

by

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It is the objective of this report to investigate the role of the pure and applied sciences in the development of a discipline concerned with the study of human factors affecting the design of machines and working environment.

There has long been in existence a particular division of psychology devoted to studying the problems of man that arise from his industrial occupations. The industrial psychologist has been engaged in the development of the most efficient methods of personnel selection, placement, training, and testing, to mention but a few of the many phases of his activities. As the complexity of machines increased, and this trend was greatly accelerated during the second World War, it was found that many of the more elaborate machine systems were ineffective due to the excessive demands on the abilities of the human operators. As a result, a new area of investigation was opened, which entailed the reassessing of the strictly human characteristics with a view to adapting the machine to fit human requirements. In addition, the machine should be so designed as to utilize the strictly human abilities to the greatest possible extent. To achieve these ends, research teams composed of engineers, psychologists, physiologists, anatomists, and other applied scientists were formed to evaluate the operation of highly complex military machines. The purpose of this research was to make available certain information relevant to human measurements which would be utilized in the design of more effective machine systems. To those engaged in this type of activity, as well as to others associated with them, any study of this nature soon became 'human engineering'. Though the expression itself was not new, it soon became synonomous with one particular type of research, and the application of its principles in any design function.

In this report, the activities of the applied psychologist, one of the earliest investigators of human factors in relation to machine systems, have been analyzed, and his position relevant to the pure science has been defined. It was determined that the role of the human engineering technologist consists of assisting the design engineer in three broad areas. First, he studies the psychology of the human being as a link in the machine system. Second, he assists the engineer in experimentally evaluating prototype man-machine systems. Finally, he teams up with engineers to participate actively in the design of machines. The report discusses at length the implications contained in the definitions of the areas of the human engineer's operations. Two important concepts are emphasized as a result of this discussion; first, attention was drawn to the fact that in many circumstances the behavior of the man was inseparably linked with that of the mechanical portions of his environment; second, it suggests that human and mechanical processes are to some extent interchangeable, although not necessarily equally precise.

Another closely allied field has been called ergonomics, defined as the consideration of the stress and strain of the human in a work situation, particularly within the boundaries of a man-machine system. Thus, ergonomics would consider information regarding the physical measurements of the average potential operator in the design of a machine in order to relieve stresses resulting from improper positioning of indicators and controls. Apparently the exclusive field of the machine designer, it was brought out that many applied sciences contributed to the compiling of the information necessary for efficient systems design.

A discussion of the proposed methods to be utilized in order to broaden the horizons of the engineer was included in the report. The application of supplementary instruction in biotechnology was proposed as one remedy to the problem of over-specialization in the purely applied sciences. Biotechnology, including the study of human physiology, psychology, and hygiene, will soon become a necessary part of the training of the design engineer. This fact is supported by observation that the conditions and trends of modern life involve in increasing degree certain socio-technological elements including interdependence of man and machines, extension of artificial control of human environment, and the expanding role of the engineer in human affairs.

Examples are presented of some of the research already completed in the area of human factors study. Purposely, the most obvious and simple instances of desirable alterations in dials and controls of existing machines are mentioned, in order to more emphatically present the past lack of human consideration in machine design.

The report concludes with the presentation of the various trends in both pure and applied sciences toward increased interest in the problem of obtaining further information relevant to the man-machine concept. There seems to exist an almost universal unanimity of opinion in favor of the formulation of an organizational structure composed of representatives of all disciplines which contribute to the research of man in relation to the machine and his industrial environment.