chapter

1

HUMAN ENGINEERING— A DESIGN PHILOSOPHY

The application of human-engineering principles in the design of things which are to be used by people is not an exact science. Rather, it is a philosophy or an approach to problems of designing and constructing things which people are expected to use — so that the user will be more efficient and less likely to make mistakes in the use of the article. In addition, it is an effort to make such articles more convenient, more comfortable, less confusing, and, in the end, less exasperating or fatiguing to the user.

The principles, guides, and recommendations presented here are by no means a law unto themselves. The designer must use initiative and imagination as well as his own good engineering knowledge and judgment to make them work. Two principal factors must be kept in mind in order to provide a well-human-engineered product:

> Do not assume that you, as a designer, necessarily represent a Model of People as a Whole in your mental and physical characteristics or likes and dislikes.
>
> Remember that nothing is designed except for the use of or by Man.

YOU DON'T NECESSARILY REPRESENT THE USER

All too often the designer assumes that because he is human, he is typical of all people who may eventually use the equipment he designs. This is why we find tables and chairs too high or too low — or why there isn't enough room in the cockpit of an airplane. Fortunately, designers can design lots of things which will fit a majority of the user population — based on the designer's own good judgment. However, as designs become more complex, as they have in the past few years, and the integration of men and machines into whole operating systems is necessary, we need more than common sense. Besides the engineering sciences and arts, it has now become necessary to bring many new skills and scientific disciplines into the act — in order fully to integrate Man, Machine, and the Environment.

The designer who is successful in human-engineering his product must develop the humility to recognize his need for assistance from these many disciplines. Many specialists are hard at work trying to learn more about how man reacts and behaves — and especially how he interacts in complex man-machine systems. The information they are developing should be understood and used by the designer along with his own important knowledge and skills. Good human engineering is a team effort, and everyone who is part of this team must develop respect for others on the team — recognizing the need for an interdisciplinary approach to design problems.

HUMAN ENGINEERING DRAWS HEAVILY UPON MOST BASIC SCIENCES AND MANY TECHNICAL SPECIALTIES

Psychology	Operations analysis
Medicine	Computer technology
Physiology	Electronics
Anthropology	Thermodynamics
Biology	Industrial design
Neurology	Mechanical engineering
Acoustics	Illumination engineering
Optics	Chemical engineering
Chemistry	Cybernetics
Physics	Industrial hygiene
Mathematics	Time and motion study
Psychiatry	Education

Many designers may find it hard to understand just what these disciplines have in common. One of the first facts a truly interested designer must recognize is how little he really knows about people: i.e., how they see, hear, react, think; how big or small they are; how far they can reach or bend; how strong they are.

The average designer cannot be an expert on all of these factors. In fact, even the experts themselves still don't have a complete picture of the human being — especially as he fits into a complex operational system.

EVERYTHING IS DESIGNED FOR PEOPLE

This categorical statement is invariably questioned at first glance; therefore it is important to understand why we must accept it to develop a sound "human-engineering philosophy." If one were to analyze each and every object designed or constructed (in an objective manner, that is), he could not escape this fact.

A modern lead pencil was designed because people needed a writing tool with readily erasable marks — not because we like to design little sticks of wood with lead in them and rubber erasers on one end. A 90-passenger airplane was designed to transport people, not because we like to design wings and tail sections. Houses were designed to house and protect people and their possessions, not because we like to design walls and roofs. Even a newspaper is designed for people and not for the fun of running a printing press. With the advent of modern technology, especially the development of automatic devices, there has come a mistaken idea that these devices, at least, were not designed for people. Nothing could be further from the truth. Although their operating interfaces leave fewer people to worry about, their maintenance and programming involve people who must make them perform for a human-directed purpose. A complex computer is not built merely for the pleasure "it" gets from running at great speeds. A ballistic missile isn't designed just because we like to see amazingly complex hardware sitting on the launching pads.

All of these things were and are designed and constructed to extend Man's capability in some way — and are therefore built for Man! If we keep man in mind as the central reason for design, we will have learned the first rule for good human engineering. This concept is often referred to as "designing from the man — out." That is, we start with the man and provide what accessories he needs to carry out or reach a prescribed objective. The cave man fashioned a club in much this manner. He realized that he needed to extend his reach and to increase the lethality of a blow for protection from adversaries. Later he recognized the great advantage of attacking his foes or killing animals from a greater distance — thus came the sling and eventually the bow and arrow.

WHO DESIGNS FOR PEOPLE?

Frequently, human engineering is considered to be something which is applied to a very limited list of design problems. Typically we consider human engineering as being applied to such things as aircraft cockpits, electronic consoles, missile-launch control centers, air-traffic control centers, military vehicles, and, now, space vehicles. Unfortunately we have tended (particularly in the United States) to ignore some of the more common, everyday problems — in terms of not applying good human-engineering principles. For example, very little has been done in the design of homes, home appliances, factory layout or factory machinery, schools, hospitals, offices, libraries, automobiles, buses, trains, ships, farm implements, books, toys — or even sporting goods! In Europe, more emphasis has been applied to domestic problems, particularly with reference to industrial-worker efficiency. In America, the emphasis has been primarily on military-equipment problems. In this revised edition of the *Human Engineering Guide* we have made an effort to give attention to more types of problems and thus make the book useful to a larger population of designers, including:

- Architects
- Building contractors
- Electrical-appliance designers
- Farm-implement manufacturers
- Automobile manufacturers
- Illuminating engineers
- Highway engineers
- Commercial-transportation vehicle manufacturers
- Plumbing-fixture manufacturers
- Furniture manufacturers

A special word should be said to the INDUSTRIAL DESIGNER. Industrial designers and stylists play a unique and important role in modern design. They have brought beauty as well as functional utility to many of the things we use in modern society. These people will continue to play an increasingly important role in matching man to machine. Bringing a look of quality and efficiency into product design has a very definite psychological effect on the way we, as buyers, accept and use the final product. People tend to select and buy things which "look better." They also tend to treat the products with more respect, and in many cases operate them and maintain them better, because they are proud of the product. Since the industrial designer and stylist does play such an important role in society, it is perhaps more important for him than any other specialist to understand and apply human-engineering principles.

A stylist can influence a buyer to purchase a poorly human-engineered product over one that is well human-engineered just by the way he styles the package. Therefore, he has a moral responsibility to see that he human-engineers each product, besides making it "pretty." It is easy to find examples of the effect of "style" on products. A single product may go through many style cycles over a period of several years — cycles which have seen good design spoiled for the sake of change. The designer who allows this to happen is negligent, and is a curse to society and to engineering progress. Fortunately, styling can change without abrogating good human engineering — and the public will still buy what is presented to it over the counter. In other words, if a well-designed product also has good looks, the public will choose it. The designer must give the customer a choice (for that is human nature — to compare and choose), but there is no reason that all of the choices cannot be well human-engineered. The important thing to remember is that good human engineering comes first, then style!

MANAGEMENT also has a responsibility to produce products which are representative of good human engineering. More than once, a company president has come into the engineering department and insisted on adding that extra piece of chrome decoration. If management people don't understand the meaning of human engineering, they can very easily destroy an effective design — thinking that they are creating more sales appeal. The chances of a "repeat customer" for a product which is hard to use or difficult to maintain is very slim indeed.

THE SYSTEMS APPROACH TO DESIGN

Wherever people (users) are concerned, we must remember that everything is relative. That is, a light of given intensity will appear brighter at night than it does in daytime. The speed of your automobile will appear greater on a crowded street or a winding, narrow mountain road than it does on a six-lane, straight, and uncrowded freeway. A complex task will seem much easier to perform in the quiet of an office with no outside interruptions than it would if you were in a noisy, crowded room with many other people, telephone interruptions, or with questions being fired at you while you were trying to perform the task at hand. The repair of a radar antenna would be much simpler and faster on a warm sunny day than in the middle of a blizzard.

When approaching a new design, the designer should consider many factors beyond the article itself — e.g., the way the article will be used, the environment in which it will be used, whether or not it may be used by several different types of people, or whether the person who uses this article may be doing something else at the same time. All of these factors will influence its use. Even the intelligence level, manual dexterity, or amount of training of the final user should be considered by the designer.

The United States Air Force recognized the importance of taking a systems approach to weapon-system development, including the "people problem". Several years ago they took steps to put the "people problem" on equal status with the "hardware problem," and established their Personnel Subsystem concept, or PSS as it is referred to sometimes.[30] It became evident that many of their hardware systems were not meeting operational readiness dates because they did not have adequate manning when the systems were delivered. They further realized that many factors were involved in this "people problem" in addition to just numbers of people. Human-engineering considerations were not being sufficiently applied to the product, and no one knew enough about what the new operators and maintenance technicians would have to do to operate the equipment, so the right kinds and numbers of people were not trained for the jobs. Furthermore, they realized that their new systems hadn't been tested with typical Air Force personnel, so, by the time systems were delivered, highly experienced industrial specialists had to remain on to keep the equipment running. It was obvious that much of the equipment was just too complex for the typical G.I. Thus, the PSS concept was adopted and made a mandatory part of new contracts to assure a total systems approach to all future developments. In essence, the concept centered around the idea of concurrent development of both hardware and personnel to support the system. It included nine specific parts: (1) gathering and maintaining an adequate Personnel and Equipment Data file (PED), (2) applying and verifying good human engineering in design (HE), (3) developing systematic Qualitative and Quantitative Personnel Requirements Information (QQPRI), (4) development of Training Concepts in advance (TC), (5) development of adequate Training Plans (TP), (6) providing early Training Equipment Planning Information in order to start procurement early (TEPI), (7) proceeding with a timely Training Equipment Development program (TED), (8) planning and producing Technical Orders and Manuals to support training and eventual equipment support (TOTM), and (9) providing a continuous Personnel Subsystem Test and Evaluation program to assure that the system could, in fact, operate with the types and numbers of people planned for it (PSTE).

PERSONNEL AND EQUIPMENT DATA

Recognizing the need to keep track of all the data developed during a program, the contractor is required to do the same for all data developed relative to human engineering, manning, personnel development, training-equipment development, training, and results of testing men and machines together. This data must be made accessible at all times for monitoring the progress of the development, for adjusting to design changes, etc. Such a collection of data provides a valuable record from which much can be learned and passed on to future developments also.[10]

HUMAN ENGINEERING

It was quite apparent to the Air Force that in many earlier developments human engineering was regularly applied "after the fact"! Since this invariably leads to a mere "fixing up" of design deficiencies, human engineering has been placed at the top of the list of priorities and is required in the earliest phases of design conceptualization — then carried out faithfully through predesign, detail design, manufacture, and testing of all hardware. Human-engineering principles apply to the prime equipment, the ground support equipment, and training equipment.[21, 23]

QUANTITATIVE AND QUALITATIVE PERSONNEL REQUIREMENTS INFORMATION

In order for the user to be prepared, in terms of numbers and types of trained personnel, on time, it is necessary for each contractor to determine what kinds of tasks people will perform on the new equipment he is developing — what special skills will be needed, and how many people should be prepared to man the new system adequately.[9, 12, 15, 29]

This requires that rough descriptions must be made of each task as soon as any idea of what the new equipment will be like is available. As design firms up, these descriptions are refined. Basic task and job descriptions provide core data from which operational and maintenance procedures, criteria for training planning, and course curricula are developed. Although this particular requirement has been enforced by the Air Force for many years, the PSS concept now requires that this effort be integrated closely with all other aspects of PSS and especially with design.

TRAINING CONCEPT

Training concepts for the new system must be established early. This is done jointly with the Air Force. Development of the overall concept for a system is a natural out-growth of the work done in previous steps. The concept naturally originates with the contractor, since he alone knows exactly what his new equipment will demand of the user.

TRAINING PLANS

As soon as training concepts are firmly established, a fully developed training plan must be worked out to insure timely prosecution of the training program. The plan ordinarily includes a step-by-step program of training contractor personnel, then customer cadre, and, finally, military field personnel, who must be ready to take over the equipment when it is delivered.

TRAINING-EQUIPMENT PLANNING INFORMATION

Major training equipments must have sufficient lead time for development in order to be useful to the training program. Therefore planning must begin early in the development of system concepts. Agreements must be reached with the customer and specifications prepared in time to allow for design and fabrication. Smaller equipments (particularly mobile training-units, part-task trainers, etc.) are proposed and joint Air Force Contractor conferences held to agree to an overall training-equipment plan of development.

TRAINING-EQUIPMENT DEVELOPMENT

Training-equipment development proceeds in the same way as any other hardware development and includes all of the many considerations of design, fabrication, logistics, and maintenance. Human-engineering principles must be applied to training equipment just as they are applied to prime equipment. It must be remembered that training equipment has an earlier delivery-date requirement than prime equipment, since it must be ready for training — which is in advance of prime-equipment delivery.

TECHNICAL ORDERS AND TECHNICAL MANUALS

Like QQPRI, technical orders and manuals were handled formerly as a separately negotiated item, coming under a separate set of regulations, and carried out by an entirely independent group of contractor and customer personnel. Unfortunately, this patchwork approach had been a constant source of confusion, since the inter-relationships between the principal hardware items and the manuals which purported to describe them, and provide guidance for their operation and servicing, were frequently unsuccessful until many revisions were made. The new PSS concept brought this part of the system development into line with the hardware development.[17]

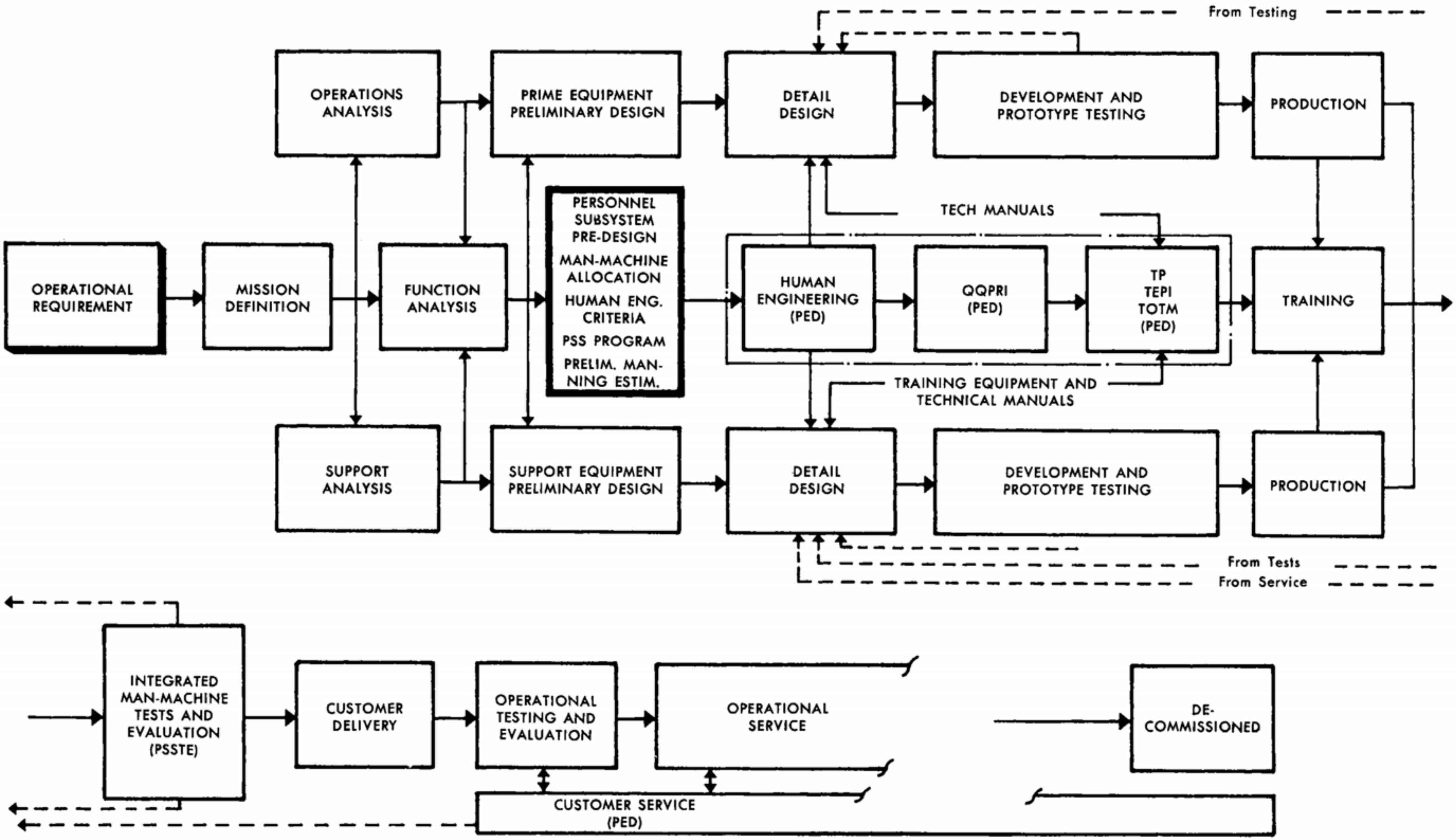
PERSONNEL SUBSYSTEM TEST AND EVALUATION

No one has ever doubted the need for testing a complex piece of hardware to make sure it works. Before PSS, however, little attention was paid to the need for testing the over-all system of men and machines together. This is perhaps the most important part of the PSS concept. PSSTE refers to all man-machine testing, including all of the intermediate as well as the final system tests.[32]

Although the magnitude of a PSS program varies from one system to another, depending on the need, all of the basic elements are generally included. For certain small or less complex systems it is logical for elements of PSS to vary in magnitude and importance. The basic theme of concurrence, however, remains. These principles have been demonstrated as sound and practical through repeated experience in military system-development programs. With modifications to meet unique commercial or industrial demands, they have application to nonmilitary hardware and other types of consumers' goods with complex man-machine interfaces.

Many people are not aware that PSS starts as early as pre-contract studies — or that all of the elements should appear in contract proposals. For more complete information, the reader is referred to Air Force ARDC Manual 80-3.[30] In addition, it is suggested that an adequate organization within a company is necessary to carry out a PSS program or contract. It is not satisfactory to try to accomplish this with PSS specialists spread out in various organizations throughout the company. The Air Force establishes a specific group in its Systems Project Office (SPO) for each project. This group is made up of a specialist from each one of the areas described in the PSS requirement; therefore it is important for a company to do the same in order to "interface" with the customer. This recommendation is in opposition to many company organizations in which some project engineer takes on the PSS responsibility in adidtion to many other duties. This assumption by a single person cannot provide the necessary integration required for so important or complex an operation as PSS, and is to be avoided if possible.

A diagram of a typical PSS–Hardware System Development Cycle is shown on the next page, as a general guide to the relationships and time phasing necessary for successful man-machine system development. Slight modification and possible simplification would make it equally appropriate for a commercial development.



A TYPICAL MANNED WEAPON-SYSTEM DEVELOPMENT MODEL SHOWING THE PSS-CONCEPT INTERACTION WITH EQUIPMENT DEVELOPMENT

CATEGORIES OF PERSONNEL-EQUIPMENT DATA

The breadth of coverage required in documenting personnel-equipment data will vary from one system to another. The following comprehensive outline should be useful as a guide for identifying most of the possible interacting data requirements. Inclusion of such a complete outline is meant only to provide a check list, however, and should not be taken to mean that all items would necessarily be required for all systems. (The outline is based on Marks, *A Data Organization Model for the Personnel Subsystem.*[16]

SYSTEM REQUIREMENTS

Effectiveness

1. Accuracy
2. Reliability
3. Reaction time
4. Capability
    - a) Destruction*
    - b) Pay load
    - c) Information handling
        - (1) Sensing
            - (a) Electromagnetic
            - (b) Chemical
            - (c) Objects (mass or volume)
            - (d) Documentary information
            - (e) Atmospheric
            - (f) Underwater
            - (g) Geological
            - (h) Seismological
        - (2) Storage
            - (a) Capacity
            - (b) Access
        - (3) Processing
            - (a) Internal
            - (b) Transfer
        - (4) Evaluation
            - (a) Identification
            - (b) Measurement
            - (c) Classification
        - (5) Display

Policy

1. Fiscal
2. Scheduling
3. Personnel
    - a) Resources
    - b) Procurement

(1) Assessment
(2) Career-field requirements
(3) New system requireemnts

c) Application of force
(1) Assignment
(2) Retention-rotation
(3) Military-civilian*

Vulnerability*

1. Resistance to destruction-ECM
2. Mobility
3. Site nature

*Items marked with an asterisk bear only military significance.

Environment

1. Ambient
   a) Climate
   b) Weather
   c) Temperature–humidity
   d) Light
   e) Safety
2. Geographic

Geographic coverage

1. Range
2. Deployment

Maintenance
Support

1. Installation maintenance
2. Food service
3. Medical
4. Transportation
5. Supply
6. Logistics
7. Security

Personnel (direct requirements or constraints)

1. Manning
2. Training

OPERATIONS

Pictorial descriptions

1. Mission profiles
   a) Ground-support portion
   b) Airborne portion–spaceborne portion
   c) Malfunction profiles

2. Function flow-diagrams
3. Block diagrams
4. Mission segment analyses
5. Work-load time-line analyses
6. Organization charts

Narrative descriptions

1. Operating concept
2. Functions lists
3. Operational plan
   a) Unit organization
   b) Test and check-out procedures
   c) Procedures (task descriptions)
4. Crew performances

Functional performance criteria (time, accuracy, etc.)

Operating conditions

1. Temperature
2. Humidity
3. Shock
4. Acceleration
5. Air flow
6. Toxicity (gaseous or liquid)
7. Acoustic noise–vibration
8. Irradiation
9. Isolation and confinement
10. Pressure
11. Restrictive personal equipment

Auxiliary materials

1. Job aids
2. Manuals
3. Technical orders
4. Handbooks

Position lists

1. Duty descriptions
2. AFSC (Air Force Specialty Classification)*
3. Manning

MAINTENANCE

Reliability goals and data characteristics

1. Program review and considerations
2. System-reliability requirements
   a) Design analysis
   b) Requirement formulations
   c) Parameters
3. Testing program
4. Manufacturing program

Procedures

Crew performance

Preventive-maintenance cycle

Maintainability

1. Repairability (concepts and specifications)
2. Availability
   a) Time equipment operating satisfactorily
   b) Down time
      (1) Active maintenance down-time
      (2) Supply down-time
      (2) Waiting or administrative down-time

Materials

Parts lists

Position lists

1. Duties
2. AFSC*
3. Manning

EQUIPMENT CHARACTERISTICS

Includes Operating Equipment, Check-out and Test Equipment, and Special Tools — excludes Maintenance Characteristics and Training Equipment

Descriptions

1. Photographs
2. Drawings
3. Blueprints
4. Schematics

Theory of operation

Performance characteristics

Reliability characteristics

HUMAN ENGINEERING
(Including biomedical)

Human-engineering plans

Man-machine function allocations

Equipment design

1. Displays
2. Controls

Layouts

1. Work space
    a) Operating consoles
    b) Maintenance consoles
    c) Seats, bunks, lavatories
    d) Hatches, ladders, storage

Design trade-offs

Maintainability Design

1. Test points
2. Access points
3. Trouble-shooting procedures

Life-support functions

1. Subsistence
    a) Food
    b) Water
2. Environmental control
    a) Temperature–humidity–ventilation
    b) Protective clothing
    c) Restraint and anti-g protective gear
    d) Noise and vibration attenuation
    e) Radiation detection and protection
    f) Isolation procedures
3. Waste disposal

Safety

1. Biomonitoring
2. Emergency equipment (including escape and survival)
3. Procedures

TRAINING

Purposes

1. Knowledges
    a) Job procedures
    b) Other stored information
        (1) Job related
        (2) System related
2. Skills
    a) Perceptual
        (1) Detection
        (2) Identification
        (3) Instrument and display reading
    b) Psychomotor
        (1) Tool- and test-equipment usage
        (2) Console-equipment operation
        (3) Flight-control operation

c) Cognitive
    (1) Data interpretation
    (2) Judgments–decisions
    (3) Numerical computations
    (4) Work planning
d) Communications
    (1) Oral
    (2) Written
    (3) Other (telegraph, signal light, etc.)
e) Integrated-task performance
    (1) Time-shared tasks in real time
    (2) Crew performance

Curriculums

1. Formal
    a) Lesson plans
    b) Training schedules
2. OJT (on-the-job training)
    a) Training plans
    b) Training schedules

Techniques

1. Lecture
2. Demonstration
3. Audio-visual
4. Practical (performance training)
5. Automated

Materials

1. Training equipment
    a) Training functions
        (1) Demonstration
        (2) Practice
        (3) Transition
        (4) Trouble shooting
        (5) Data flow
        (6) Procedures
    b) Assumptions
    c) Special problems
        (1) Unusual skills
        (2) Skill combinations
    d) Existing training equipment
    e) Training-equipment design trade-offs
        (1) Development cost- and time-estimates
        (2) Modifiability estimates
        (3) Maintenance factors
        (4) Installation factors
        (5) Related uses
    f) Applicability of equipment
        (1) Factory training

- (2) Individual training
- (3) Crew and unit training
- (4) Proficiency maintenance training

g) Recommended training equipment
- (1) Types
  - (a) Simulators
  - (b) Training devices
  - (c) Training aids
  - (d) Training attachments
  - (e) Training parts
  - (f) Training accessories
- (2) Gross description and theory of operation
- (3) Photographs
- (4) Performance specifications
- (5) Drawings
- (6) Schematics
- (7) Features
  - (a) Learning
  - (b) Transfer
  - (c) Programming
  - (d) Safety
- (8) Maintainability
- (9) Reliability

h) Training-parts list
- (1) Nomenclature
- (2) Federal stock number
- (3) Manufacturer's name
- (4) Proposed use of part
- (5) Initial quantity
- (6) GFE or CFE
- (7) USAF Bulletin 507 classification

2. Instructors
   - a) Curricula
   - b) Task descriptions

Special problems

1. Training methods
   - a) Unusual skill combinations
   - b) Unusual skill demands
2. Training equipment
   - a) Development lead-time
   - b) State of the art
   - c) Special installations
   - d) Power requirements
   - e) Climatological modification

Training-equipment design and layout

1. Instructor station
2. Trainee station

PERSONNEL SUBSYSTEM TEST AND EVALUATION

Developmental materials

1. Test plans
2. Test outlines
3. Scenarios for performance tests
4. Item pools
5. Pilot forms

Equipment

1. Mock-ups
2. Dynamic simulators
3. Flight or support equipment

Administration materials

1. Administrators' manuals
2. Test booklets
3. Auxiliary test materials
4. Simulation equipment
5. Scoring formulas

Analysis materials

1. Raw-score data
2. Item analyses
3. Reliability studies
4. Validity studies
5. Score diagnosis for training
6. Norms

SELECTION

Test batteries

1. Paper-and-pencil
2. Situational
3. Psychomotor
4. Biographical information
5. Physiological measures
6. Physical measures

Relevant experiences

1. Civilian occupations
2. Military occupations

Other special qualifications

MISCELLANEOUS

Security measures*

Communications nets

Research studies

Housing (ground functions)

Food service (ground functions)

TASK DESCRIPTION

Indicators

1. Visual
   a) Label
   b) Light
   c) Pictorial
   d) Scale–digital
   e) Printed materials
   f) Complex system–environmental relationships

   Challenge each of the above Visual with

Color	Texture	Acceleration
Brightness	Movement	Informational Content
Contrast	Distance	Coding method
Temporal aspects	Noise	Level of abstraction
Configuration	Vibration	

2. Auditory
   a) Pure tones
   b) Speech
   c) Complex non-speech

   Challenge each of the above Auditory with

Frequency	Configuration
Loudness	Timbre
Signal to noise ratio	Movement
Temporal aspects	Direction of source

3. Tactile

   Challenge each Tactile with

Vibration	Configuration
Intensity	Texture
Temporal aspects	Movement

4. Proprioceptive
   a) Static
   b) Dynamic

   Challenge each of the above Proprioceptive with

Pressure	Movement
Tension	Noise
Temporal aspects	

5. Other sense modalities (vestibular, olfactory, etc.)

Responses

1. Passive
    - a) Activity (name of response)
    - b) Equipment involved
    - c) Behavior
        - (1) Decisions
            - (a) Selection of response from possible alternatives
            - (b) Time aspects of response
                - 1) When to initiate
                - 2) Pacing or coordinating with other man-machine units
            - (c) Determination of response adequacy from feedback data
        - (2) Discriminations (other than Indicators; classify as Indicators)
        - (3) Memorial
            - (a) Access to short-term shortage
            - (b) Access to long-term shortage
        - (4) Interpretations
        - (5) Monitoring (other than Indicators; classify as Indicators)
    - d) Nature of procedure
        - (1) Fixed
        - (2) Variable
2. Active
    - a) Control
        - (1) Activity
        - (2) Equipment involved
            - (a) Valves
            - (b) Switches
            - (c) Levers
            - (d) Push buttons
            - (e) Wheels
            - (f) Pedals–rudder
            - (g) Joysticks
        - (3) Behavior
            - (a) Discrete adjustment
            - (b) Continuous adjustment, undimensional
            - (c) Continuous adjustment, multidimensional

            Challenge each of the above Behaviors with:

Force	Temporal aspects	Clothing contraints
Direction	Bodily relations	Environmental conditions
        - (4) Nature of procedure
            - (a) Fixed
            - (b) Variable
            - (c) Motor

b) Non-control
    (1) Activity
        (a) Calibrate–adjust
        (b) Remove–install
        (c) Repair–Overhaul
        (d) Clean–Purge–Bleed
        (e) Test–check-out
        (f) Inspect
        (g) Connect–disconnect
        (h) Service–fill–lubricate
        (i) Trouble-shoot–diagnose
        (j) Preserve–package–store
        (k) Communicate–report–record
        (l) Transport–carry–hoist–move–load–unload
    (2) Equipment involved
        (a) Operational
        (b) Test
        (c) Support
    (3) Behavior
        (a) Oral communication
        (b) Other communication
        (c) Manipulation
        (d) Discrimination
    (4) Nature of procedure
        (a) Fixed
        (b) Variable
        (c) Circuit analysis
        (d) System analysis

Feedback
(Same classification as for Indicators)

Performance criteria
1. Time
2. Accuracy

Criticality
1. Level
2. Probable error factor

Time to perform (hours and fractions)

Place of performance (console, components AGE operation)

Frequency of performance
s (once a shift)
d (once a day)
2w (twice a week)

Task newness

LEVELS OF ANALYSIS AND SOME RELATED TECHNIQUES

LEVEL OF ANALYSIS	PURPOSE	APPLICABLE TECHNIQUE
System	To determine effectiveness of system in performing a specified mission	Operations-research methods[8, 18]
Subsystem	To determine best way of meeting a specified requirement of the mission	System analysis Integration matrix
Function	To determine best combination of components required to make up subsystem	Man-machine system analysis[28] Function analysis
Task	To determine best allocation of man's capabilities to perform required functions	Task analysis Time-line analysis[13] Logic models[23, 27] Information theory[1]
Subtask	To determine best method of utilizing man's capabilities to perform the assigned tasks	Operator load analysis[23] Operator sequence diagrams Decision theory Information-flow analysis
Element	To determine best method of utilizing man's capabilities to perform assigned subtasks	Time-and-motion analysis Elemental task analysis

THE SYSTEMS APPROACH IS APPLICABLE TO ALL PROBLEMS

The Personnel Systems concept just discussed is not necessarily applicable to all problems involving people and equipment. This amount of detail would be entirely too time-consuming and costly for most everyday applications. Frequently, it is not feasible to approach a problem from the very beginning; i.e., major decisions may already have been made in the systems design. In spite of this, the systematic approach inherent in PSS is still applicable to even minor modification of or addition to an older system. Regardless of whether you are designing a man-machine system "from scratch" or merely giving a product a "face lifting," the following general steps are considered vital to successful problem solution:

INFORMATION PHASE — Acquire sufficient information about the operational requirements, constraints, environmental conditions, and type of people who will use the design to be able to state positive and concise objectives for the impending design.

PLANNING PHASE — Explore alternative approaches for meeting your stated objectives, keeping in mind such factors as economy, ease of manufacture, reliability of product, and ease of maintenance or servicing.

SELECTION PHASE — Select the design which seems to optimize all factors listed in Information and Planning phases, above. Proceed with your design, utilizing accepted human-engineering design principles found in other sections of this book.

TEST PHASE — Construct breadboards, models, or mock-ups of your design to evaluate or test it against the stated objectives. In cases where dynamic parameters may be critical to the operation, it may be necessary to provide simulated operational evaluations.

FIELD TEST PHASE — Depending upon the nature of the design, it may be necessary to test your final design under actual operating conditions — utilizing actual personnel who will evenutally use the end item. In many commercial applications, it is desirable to perform follow-up customer surveys to provide feedback information useful to later design improvement.

The designer must have the user (operator) in mind when he designs an equipment. He should be able to describe, verbally, exactly what the operator has to do in operating (or maintaining) the equipment. Too often this task of writing down the job or task has been left to a human-factors specialist. The designer should learn to do this himself, if for no other reason than that it forces him to anticipate difficulties he may have been creating for the user. Both designers and human-factors specialists are also concerned with engineering questions, such as, "Should a function be performed manually by an operator, or should it be made automatic?" This question cannot be answered with a simple statement of "yes" or "no" at the present time. There are, however, certain factors which may be considered in arriving at a fairly sound decision — one that still needs to be tested. Several human-factors experts have prepared tentative lists of statements which compare man vs. machine. The following table is included here as a composite of several such lists:

MAN VS. MACHINE

MAN EXCELS IN	MACHINES EXCEL IN
Detection of certain forms of very low energy levels	Monitoring (both men and machines)
Sensitivity to an extremely wide variety of stimuli	Performing routine, repetitive, or very precise operations
Perceiving patterns and making generalizations about them	Responding very quickly to control signals
Detecting signals in high noise levels	Exerting great force, smoothly and with precision
Ability to store large amounts of information for long periods — and recalling relevant facts at appropriate moments	Storing and recalling large amounts of information in short time-periods
Ability to exercise judgment where events cannot be completely defined	Performing complex and rapid computation with high accuracy
Improvising and adopting flexible procedures	Sensitivity to stimuli beyond the range of human sensitivity (infrared, radio waves, etc.)
Ability to react to unexpected low-probability events	Doing many different things at one time
Applying originality in solving problems: i.e., alternate solutions	Deductive processes
Ability to profit from experience and alter course of action	Insensitivity to extraneous factors
Ability to perform fine manipulation, especially where misalignment appears unexpectedly	Ability to repeat operations very rapidly, continuously, and precisely the same way over a long period
Ability to continue to perform even when overloaded	Operating in environments which are hostile to man or beyond human tolerance
Ability to reason inductively	

In general, if any part of a task cannot be anticipated (in terms of the exact response required — at any given instance or under any given set of conditions), that part of the task should be given to man, to allow him to interpret, assess, and make judgments and decisions as to the best choice of response appropriate to the specific condition, time, and place.

It has often been said that a man in a system provides a means for allowing graceful degradation in system performance. Man is able to assess a complex situation and "save" the system even though the mission is only partly completed. Fully automated systems will "quit" unless previously prescribed conditions are met.

Another important factor to consider in determining whether a man is to be "aboard" the system or should have part in its control is the man's own safety. Man (operator) should have sufficient control over his own destiny to take over in the event his own safety is on the point of being compromised.

With the advent of vehicles and systems such as may be used in space operations, it is generally considered desirable to have man along as a reliability factor. He may be able to repair a subsystem and forestall an aborted mission.

A final guiding principle is that machines should always be considered the servant of man. Automaticity should be applied to relieve man for more important tasks for which he is peculiarly suited — such as exercising judgment, planning and making decisions, etc. Machines should relieve him of such routine tasks as storing informational details, performing calculations, or applying continuous and repetitious or well-defined motions. Do not consider tasks in isolation, however, for man seldom performs a task completely by himself. The choice is really one of "man plus machine vs. machine"!

HUMAN RELIABILITY

Human reliability has important implications not only in the way we design interfaces between man and machine, but also in deciding how to use man in a system. Quantification of human reliability is an extremely difficult and possibly impractical task. It is desirable, however, to consider human reliability from the standpoint of identifying relationships between human characteristics and certain factors which may degrade performance reliability. The primary consideration is to minimize human error potential through proper design.

Let us consider first the broad relationships between task characteristics and probability of error-free performance. Assuming that man can perform best under so-called normal conditions, we may classify types of performance according to their inherent reliability from best to worst.

1. Simple, discrete response to a single discrete signal.
2. Simple but varying response to single, successive signals.

3. Single discrete response to multivariant signals requiring sampling, judgment, and decision.

4. Successive, independent response to multivariant signals requiring sampling, judgment, and decision.

5. Complex concomitant responses to random-variant signals requiring extrapolation, interpretation, and decision.

6. Complex response to complex inputs including concurrence with another operator.

The above list could be described in many ways, but is indicative primarily of the relationship between probability of error and complexity of task. What is more important than the actual list of tasks itself is the effect on such tasks of introducing undesirable environments into the problem. For example:

Reducing the amount of time allowed for performing a task.

Introducing abnormal temperature conditions.

Subjecting the operator to shock, vibration, or severe oscillations.

Failing to provide adequate or proper illumination.

Imposing restrictions to movement through special clothing or other similar constraint.

Failing to provide compatible interface design.

Increasing the work load or introducing "noise" in the task or environment.

Introducing physiological or physical stress (acceleration, weightlessness, Coriolis, muscle strain, etc.).

Imposing general stress (from loss of sleep, confinement, isolation, etc.).

Introducing emotional stresses (fear, anxiety, boredom, etc.).

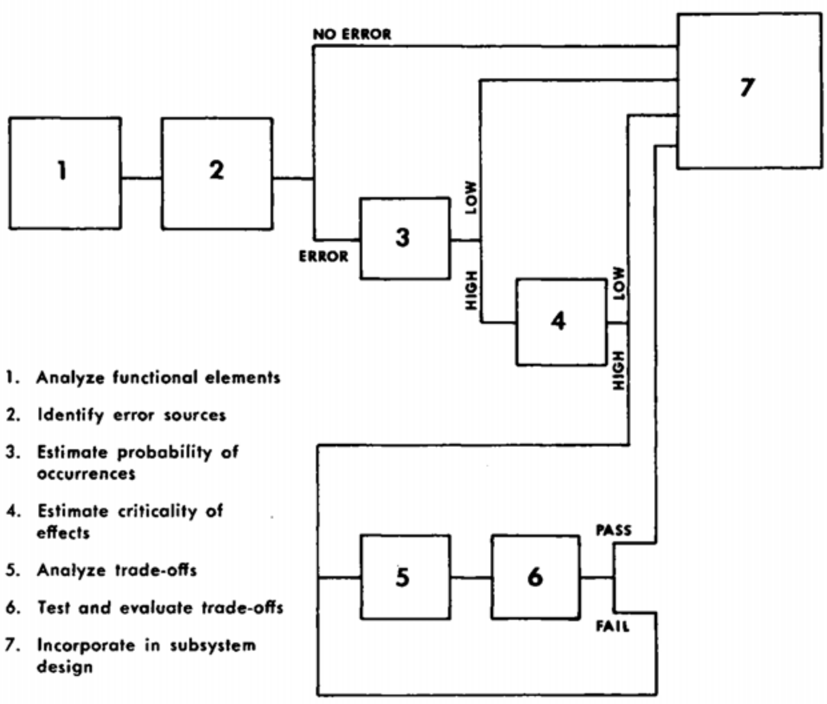
Designers should create work-task configurations which maximize the operator's response characteristics least prone to error or are least affected by environmental variations. They should consider the effects of motivation; i.e., design tasks which are reasonably challenging, but not discouraging. It is necessary to learn something about the types of users of the product — intelligence, education, skill, etc. — to be successful. One must also beware of the trap which is caused by observing how many times an operator still manages to perform fairly well in spite of poor design or environmental conditions. We would, generally, not design a piece of hardware to operate close to its maximum limit, and so should not force the human to do so either. Special attention should be given to situations where a combination of stresses may degrade the operator's performance even though he is able to overcome any one of the stresses separately.

Unfortunately, too little is known about the effects of combined stress. Designers must assume that good human engineering should be applied across the board in order to maintain human performance reliability at required levels. At best, human variability is such that performance is subject to error from time to time for completely unexplained reasons. Therefore we should not add to this burden by deliberately creating an error-producing design or environment.

An analysis of a proposed system will ordinarily enable one to categorize each subsystem and the associated human tasks according to the functional significance of human error. For example:

FUNCTIONAL SIGNIFICANCE SCORE	CRITICALITY TO MISSION PERFORMANCE
0	No operational effect
1	Degrades performance, but does not abort the mission
2	Results in failed mission
3	Results in loss of man or equipment

By making an error analysis of a system operation and subjecting it to a rating scale as shown above, it is possible to arrive at a gross but valuable indication of what part the operator contributes to over-all system reliability.



Basic Analytical Flow-Diagram Showing Human-Error Prediction and Control Sequence (after Rabideau[20])

THE HUMAN AS AN INFORMATION PROCESSOR

Consideration of the human operator's capabilities and limitations provides insight into better ways in which he can best be used as a component in a man-machine system.

AS A RECEIVER

Proper inputs to the senses (seeing, hearing, touch, etc.) result in man's being a highly reliable receiver. His time constants are relatively long, 25 to 150 milliseconds, and his sensitivity ranges are limited, approximately 20 to 20,000 cycles per second in the sound spectrum and from 4000 to 7000 angstrom units in the electromagnetic spectrum. His rate of perceived input seems to be not much greater than 10 successive items per second. His input capacity is easily saturated, and care should be taken to avoid messages to him that are overlapping, competing, or visually and aurally incompatible.

AS A TRANSMITTER

Man can utilize the outputs of another man or piece of equipment in a system and transmit these as inputs to other men or other pieces of equipment by voice link, knobs, push buttons, switches, and so on. All of man's outputs are motor responses, and these are relatively slow and low-powered. For steady-state conditions, his output in highly developed skills (typing, or playing a musical instrument) seems to be limited to approximately 25 bits per second (6 or 7 letters or notes per second). Maximum human capacity is about 40 bits; the probable operating rate for typical unskilled tasks may be around 2 bits per second.

AS A COMPUTER OR EVALUATOR

Man is an exceptionally good evaluative computer. From intermittent information on a PPI display he is able to estimate courses, velocities, times, and points of interception with considerable accuracy. Man is able to make decisions based on past experience and patterns of visual or auditory inputs. He is the only available computer able to solve problems by logical induction.

AS A CONTROL MECHANISM

Man's transfer function within a control system is highly dependent upon what is expected of him. In hovering a helicopter he does a remarkable job of maintaining a fixed position which would require the solution of some nine simultaneous equations if done by a computer. In flying an airplane, the pilot is faced with the task of simultaneously responding to several instruments which give him the results of his control movements. Given the usual lag in the system, the likelihood of his anticipating the results of his control movements — so as to pull out exactly on the target — is very remote. If "anticipatory" circuits are used in the system to display the effects of the control movements in advance, his job can be done with extreme precision.

For these and other similar tasks, such as maneuvering a space vehicle, it is desirable to use electronic aids to integrate and differentiate for man — and use him as a simple amplifier in the system. Man's motor output seems to have a band width of about 10 cycles per second and a "natural" periodicity of about ½ to 1 cycle per second. Care should be taken to avoid putting him in a system with a resonant frequency which will be amplified by this ½-to-1-cycle oscillation tendency.

INFORMATION-HANDLING AND DECISION-MAKING CAPABILITIES

Television channel	3×10^7 bits per second
Telephone channel	2×10^4 bits per second
Teletype channel	60 bits per second
Maximum human capacity	40 bits per second
Human operational rate	2 bits per second

Among the characteristics of man which make it possible for him to be used in the functions described above are his sensory capacities, motor responses, memory, flexibility, and computational ability.

SENSORY CAPACITIES

Under proper conditions of illumination, man can see color, brightness, and form. The range or amplitude over which the eye can function covers more than 8 logarithmic units; i.e., taking the lowest intensity at unity, the highest will have a value of about 100 million. The eye responds to as little as 4 or 5 quanta of energy and under ideal conditions can detect the presence of an object which subtends about a half second of visual angle. This is equivalent to seeing a wire, 1/16 inch in diameter, a half mile away. He can hear, touch, taste, and smell with varying degrees of sensitivity. The energy in 1×10^{-10} erg/sec is enough to cause an auditory response. This is only slightly greater than the energy released by the collision of air molecules in random Brownian movement. The loudest sound he hears, without pain, contains roughly 10 billion times as much energy.

The sensitivity of both the eye and the ear is close to theoretical limits for resolution of a physical system. In fact, there is reason to believe that in some cases of hypersensitivity the person actually hears the sounds produced by Brownian movement.

MOTOR RESPONSE

Man can talk, push buttons, use hand cranks or joysticks. He can point, write, push pedals, and so on. All of these outputs are usable and have been used in man-machine systems. It must be remembered that his motor performance characteristics vary considerably, depending upon the mode of response. The design engineer can use these characteristics in two ways: (1) to provide those movement characteristics which are desired as input to the controls, and (2) to eliminate those movement characteristics which are undesirable.

MEMORY

Man has good long-term memory for generalized experience, but rather poor immediate memory for most sensory functions. This is especially so in audition. His access time is slow, compared with that of a computer, but he is able to recall generalized patterns of previous experience to solve immediate problems. As yet, no computer can do this.

FLEXIBILITY

Man is very flexible and can perform well in many different jobs if his limitations are not overlooked. As the requirements placed on him become more complex, however, this same flexibility may result in a decrement to the system's performance. Use the machine to relieve the man of as many routine jobs as possible, but use the man to supply the judgments and flexibility of which machines are incapable.

COMPUTATIONAL ABILITY

Man learns to do numerical computations, but in the main his time constants are such that he is a relatively poor numerical computer when under stress. No computer can match him, however, for the more qualitative, nonnumerical computations.

These characteristics are common to all men in some degree. It must be remembered that men differ widely in their capacities, body sizes, training, and skills. Until "quality control" is utilized in the acceptance of new models of the human being, the engineer should design equipment which can be used adequately by any member of the population likely to use it.

Man's performance usually tends to deteriorate as a function of time on the job. This is seldom a result of physiological tiring per se. It results, rather, from boredom, inattention, and lack of motivation. Care should be taken in designing the man's job so that he is not forced to operate near his maximum load limits for very long. In addition, control over his ambient environment must be exercised. Tolerance to a single stressful condition may be exceeded when several environments interact at the same time. Design for the "normal" whenever possible, and this will allow the operator to perform more nearly to the specifications you expect of him.

STANDARDIZATION AND HUMAN ENGINEERING

The importance of standardization has been recognized in business and industry for many years. It has a special significance in human engineering. Used wisely, standardization will lead to improved human performance. Sometimes, however, the use of standardization as a means of improving human performance is confused with the mere desire to standardize for the sake of "standardizing." Standardization improves human performance in several important ways. For example:

> People become accustomed to using a device in one way and can be expected to recognize, understand, and operate it without unnecessary training, explanation, or guidance.
>
> When a device operates in the same way on one equipment as on another, people (once they have learned) will operate the new equipment with less chance for error.
>
> A standard tool will more likely be used properly, thus avoiding possible damage to equipment.
>
> Standard procedures provide less chance for accidents and injuries, since people are familiar with the hazards and are more apt to recognize them — even in a new operation.

Designers should take advantage of certain design characteristics which lead to early familiarity by the user. In other words, people "expect things to operate in a certain way." Sometimes we refer to these expectations as population stereotypes — or the way in which the ordinary person will react to an operation or device. A typical example is in the water faucet. People "expect" the control on the faucet to turn to the left (or counterclockwise) to let the water run and to the right to turn the water off. Wherever such stereotypes exist, it is advisable to follow them!

In other design areas there may not be apparent stereotypes. When one is unsure, it is advisable to perform tests on a sufficient number of "typical" users, to ascertain whether there may be confusion in operating the new design. A number of standards are included in succeeding pages of this Guide. Many of them have been developed by experiment, and others were created by professional committees. Only those standards which appear (in the opinion of the authors) to be compatible with recognized human-engineering principles are included, however, since there are, unfortunately, many standards which contribute to operator problems.

Undesirable effects can result when standards are created without considering the needs of the future. Standards have sometimes become ingrained in the user population — and later been found to be deterimental to operator efficiency. The typewriter keyboard arrangement is typical.

Although a much improved keyboard was created a few years ago (one which increased typing speed at least twofold), it has been impossible to change to the new keyboard because of the overwhelming number of old machines and the problem of training new typists and, more so, retraining those "wedded" to the old system. Another example of potential standards "failure" occurred with the advent of "shape-coded" control knobs. Codes were good only if the knobs remained in an "upright" position, for their identity was lost when they were miniaturized.

The following list of recognized population stereotypes provides the reader with an idea of the types of human reaction which may be considered "expected or natural."

GENERAL POPULATION STEREOTYPE REACTIONS

- HANDLES USED FOR CONTROLLING LIQUIDS ARE EXPECTED TO TURN CLOCKWISE FOR OFF AND COUNTER-CLOCKWISE FOR ON.
- KNOBS ON ELECTRICAL EQUIPMENT ARE EXPECTED TO TURN CLOCKWISE FOR ON, TO INCREASE CURRENT, AND COUNTER-CLOCKWISE FOR OFF OR DECREASE IN CURRENT. (NOTE: THIS IS OPPOSITE TO THE STEREOTYPE FOR LIQUID.)
- CERTAIN COLORS ARE ASSOCIATED WITH TRAFFIC, OPERATION OF VEHICLES, AND SAFETY.
- FOR CONTROL OF VEHICLES IN WHICH THE OPERATOR IS RIDING, THE OPERATOR EXPECTS A CONTROL MOTION TO THE RIGHT OR CLOCKWISE TO RESULT IN A SIMILAR MOTION OF HIS VEHICLE, AND VICE VERSA.
- SKY-EARTH IMPRESSIONS CARRY OVER INTO COLORS AND SHADINGS: LIGHT SHADES AND BLUISH COLORS ARE RELATED TO THE SKY OR UP, WHEREAS DARK SHADES AND GREENISH OR BROWNISH COLORS ARE RELATED TO THE GROUND OR DOWN.
- THINGS WHICH ARE FURTHER AWAY ARE EXPECTED TO LOOK SMALLER.
- COOLNESS IS ASSOCIATED WITH BLUE AND BLUE-GREEN COLORS, WARMNESS WITH YELLOWS AND REDS.
- VERY LOUD SOUNDS OR SOUNDS REPEATED IN RAPID SUCCESSION, AND VISUAL DISPLAYS WHICH MOVE RAPIDLY OR ARE VERY BRIGHT, IMPLY URGENCY AND EXCITEMENT.
- VERY LARGE OBJECTS OR DARK OBJECTS IMPLY "HEAVINESS." SMALL OBJECTS OR LIGHT-COLORED ONES APPEAR LIGHT IN WEIGHT. LARGE, HEAVY OBJECTS ARE EXPECTED TO BE "AT THE BOTTOM." SMALL LIGHT OBJECTS ARE EXPECTED TO BE "AT THE TOP."
- PEOPLE EXPECT NORMAL SPEECH SOUNDS TO BE IN FRONT OF THEM AND AT APPROXIMATELY HEAD HEIGHT.
- SEAT HEIGHTS ARE EXPECTED TO BE AT A CERTAIN LEVEL WHEN A PERSON SITS DOWN!

SPECIAL TOOLS FOR HUMAN ENGINEERING

Although the typical designer or engineer has his own special set of tools with which he creates drawings, tests concepts, and measures performance of hardware, it is important to recognize that human engineering requires other tools with which the average designer may be unfamiliar. Some of these tools he may have used for purposes other than human engineering. It is important that he understand how to use these tools to help fit the machines to the man.

Drawings with full-scale cutouts are quite useful, for instance, in exploring better arrangements for controls and displays on a panel. If the cutouts can be pasted on a drawing (use rubber cement so that they can be removed easily) and the drawing is placed at the proper angle and position with reference to a seated operator, reach distances and legibility can be checked to make sure that the operator can operate and see controls and displays easily. Relationships between displays and controls can be tested for ease of association or adequacy of the arrangement in terms of sequence of operation.

Miniature scale-models can be used effectively for testing the arrangement of men and equipment to determine proper spacing for clearances, traffic flow, and location of general light fixtures. In fact, such models have been used in selecting colors for room walls, floors, equipment, etc.

Full-scale mock-ups are quite useful for trying out arrangements for console placement, seating, hatches, windows, storage, and many other effects relating to general habitability. Such mock-ups should first be made of the most flexible and easily changed materials possible: e.g., cardboard. Later they can be made of wood and plastic, or Fiberglas, and in some cases of metal. A number of common errors are made by industrial manufacturers in use of full-scale mock-ups. First, they often start out with wood or metal materials and thus reduce the possibility of change. This leads to compromises of the human element for the sake of avoiding expense in changing the mock-up. A second error, which is really a basic error in concept, is that mock-ups are too often thought of only in terms of something to demonstrate the product to the customer; i.e., they are sales tools rather than engineering tools. A mock-up for engineering purposes does not have to be "pretty"!

Simulation of dynamic aspects of a man-machine system is probably the most sophisticated tool that can be applied to human-engineering problems. It usually involves driving displays with computer inputs which are coupled to actual controls so that the operator can be placed in the loop. This allows the designer to test the man-machine system as "a whole," and is very desirable for complex control problems. It is not always necessary to have everything included in such simulations. For instance, the simulation of an aircraft control or instrument system does not need to have an ejection seat, or a canopy over the operator. It's not that these items would interfere with the simulation, but they are costly and do not aid in meeting objectives of the test.

In some cases, total integrated simulation may be necessary. This is especially true in the case of space vehicles — primarily because such a simulation, in actuality, replaces the normal engineering flight-testing phase of the vehicle. In other words, it is not possible to flight-test a space vehicle before delivery to the customer, because of the high cost of launching. Full simulation should strive for as much realism in all its elements as seems necessary to prove that the man (or men) and the machine can and will operate satisfactorily as a total system in the expected environment. Such simulators are suitable also for flight training and familiarization.

Simulation of the type just discussed requires extensive computer facilities. Computers are one of the human engineer's most valuable tools for other reasons also — just as they are for general engineering and research. The implications of the computer for human-engineering research include (1) organization and reduction of statistical data, (2) hypothesis seeking, by finding new relationships, and (3) hypothesis testing, through modeling and simulation.

In addition to the human-engineering tools just discussed, many other smaller instruments and tools are required for measuring purposes. Included are such things as:

Light measuring devices

Sound measuring devices

Temperature and humidity measuring devices

Toxicity measuring devices

Ventilation measuring devices

Force measuring devices

Human-body measuring devices (anthropometric tools)

Visual spectrum analyzers

Radiation measuring devices

Perceptual and motor-performance measuring devices

Obviously such a list could be extended for several pages. One thing which should be apparent, however, is the fact that there are tools for obtaining objective measures of the man-machine factors involved in design, and these should be used wherever possible — in opposition to the "personal-opinion approach" to man-machine design.

It is also important to recognize that certain facilities are necessary to support the use of the tools for human engineering. In other words, human engineering cannot be done entirely at a desk. Even the smallest effort requires reasonably sophisticated facilities for performing typical human-engineering testing. The following list is presented as a guide for those persons wishing to set up a testing facility for the solution of human-engineering problems.

HUMAN ENGINEERING LABORATORY REQUIREMENTS

Function	Facilities
Aerospace medicine and physiology	Medical examination room Biochemistry laboratory Physiology test laboratory Human and small-animal centrifuges Altitude chamber Temperature chamber Small-animal housing
Engineering psychology	Sound test laboratory Visual test laboratory Sensory-motor laboratory
Human engineering design	Mock-up laboratory Simulation laboratory Personal-equipment laboratory
Life support engineering	Atmospheric laboratory Closed-ecology laboratory Toxic test laboratory

NOTE: The above list is not intended to be all-inclusive, or to imply that all of the elements are required in every situation. Rather, it provides some indication (to the uninitiated) of the types of activity and facilities for human-engineering work.

PERSONNEL REQUIREMENTS FOR A HUMAN-ENGINEERING ORGANIZATION

Many industrial organizations, introduced to the need for human-engineering specialists in their organization for the first time, are at a loss as to what types of specialists they should employ. The following are suggested, in order of hiring priority, for a general human-engineering group. It should be noted that these specialists are "in addition" to upper-level ENGINEERS and DESIGNERS who should also be members of a human-engineering group.

ENGINEERING PSYCHOLOGIST — with an advanced degree and/or several years' experience in equipment and man-machine system design, or both.

PHYSIOLOGIST — in many cases physiologists have equally broad experimental experiences as the Engineering psychologist, and are considered of equal priority for initial hiring.

EXPERIMENTAL PSYCHOLOGIST — preferably one who has specialized in human performance measurement, statistics, and laboratory research.

PHYSICIAN — preferably with training as a flight surgeon.

ANTHROPOLOGIST — experienced in human body measurement relative to equipment design.

MANNING AND TRAINING SPECIALIST.

BIOCHEMIST.

RADIOBIOLOGIST.

OTHERS — junior-level scientists representing experimental psychology and physiology; technical support personnel, such as laboratory technicians, personal equipment specialists, mock-up technicians, and draftsmen.

bionics, cybernetics, and neuro-engineering concepts

BY JOHN M. COYNE

Of increasing interest to the human-factors engineer are the numerous researches being conducted on self-organizing, self-regulating, and self-adapting systems. Engineered analogues of these neuro-behavioral functions which characterize the performance of living organisms range from the complex information storage and processing of analogue or digital computers to the facilitory or inhibitory relaying of pulse-coded information by component artificial neurons. The analoguing of these behavioral functions at all levels of complexity has been approximated by a variety of electronic, electrochemical, and electromechanical devices.

BIONICS and CYBERNETICS represent two interactive and interrelated areas of research which have both drawn from and contributed to the design and development of complex man-machine systems. The historically senior partner of this cooperative, cybernetics, was formalized and named by Norbert Wiener, a professor of mathematics at the Massachusetts Institute of Technology, in a 1948 introduction and subsequent 1954 and 1961 elaborations.* The junior (in time) partner, bionics, was both titled and launched by Major Jack Steele, MC, USAF, in an Air Force–sponsored symposium at Dayton, Ohio, in 1959.†

To identify and differentiate these closely related areas of investigation, we might review the definitions formulated by a principal investigator in each of the areas. Wiener, who identifies cybernetics as the study of communication and control functions common to both living and engineered systems, elaborately states:

> "It is my thesis that the physical functioning of the living individual and the operation of the newer communication machines are precisely parallel in their analogous attempts to control entropy through feed-back. Both have sensory receptors as one stage in their cycle of operation: i.e., in both of them there exists a special apparatus for collecting information from the outer world at low energy levels, and for making it available in the operation of the individual or of the machine. In both cases these external messages are not taken *neat,* but through the internal transforming powers of the apparatus, whether it be alive or dead. The information is then turned into a new form available for the further stages of performance. In both the animal and the machine, this performance

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*N. Wiener, *The Human Use of Human Beings,* Doubleday, 1954, and *Cybernetics, or Control and Communication in the Animal and the Machine,* 2d ed., Massachusetts Institute of Technology Press and Wiley, 1961.

†J. E. Steel, *et al., Bionics Symposium: Living Prototypes, the Key to New Technology,* Air Force, Wright Air Development Division, Technical Report No. 60-600, 1960.

> is made to be effective on the outer world. In both of them, their *performed* action on the outer world, and not merely their *intended* action, is reported back to the central regulatory apparatus." (The Human Use of Human Beings, p. 26)

By way of contrast and comparison, McCulloch, in his own cryptic style, offers his definition of bionics:

> ". . . Jack Steele coined legitimately the word Bionics from *Bion,* a living thing, and *ics,* the science of. Being born as an integration of science and art it is clearly illegitimate, with no official past but a promising future enlivened by hybrid vigour. The integral is definite from a scalpel to a soldering iron. It seeks, from an intimate knowledge of biological systems for communication and control, to improve the design and performance of artifacts, chiefly electronics, to match the reliability, and flexibility, the adaptability and the economy of nature's prototype."*

Essentially, the focus of cybernetics and that of bionics converge on the same phenomena from different perspectives. The phenomena are those of developing engineered analogues of adaptive and regulatory behaviors characteristic of living organisms, and the perspective differences are in the levels of abstraction and complexity at which these neurobehaviors are modeled. Cybernetics might be described as focusing on the *macro*-modeling of the *processes* involved in self-communicating information-feedback and adaptive performance-modification which characterize the more complex behaviors of animals and machines, whereas bionics concentrates more on the *micro*-modeling of *component* functions of artificial neurons and simulated nerve networks, building more complex function analogues of such processes as visual or auditory pattern-recognition from these basic components. The cybernetics approach derives the components in terms of the funtcion. The bionics approach reproduces the function by an expedient assembly of determined components.

Underlying the concept of both cybernetics and bionics is the principle of differential information-feedback loops which permits the responding system to modify selectively its subsequent responses in terms of goal approximations attained by its previous responses. Thus described, such an adaptive system requires (1) a capability for holding some criterion representation of a postulated goal condition, (2) an effector mechanism for adaptively seeking that goal condition, and (3) a feedback sensor circuit for the detection and correction of the system's approximation of that goal condition. To permit such a purposive search, the information feedback from the system's responses must provide for an iterative differential analysis between its *actual* status and the postulated *desired* (goal) state. This, of course, constitutes negative feedback, which permits the progressive damping of search oscillations around the specified goal. Positive

*W. A. McCulloch, "Syllabus on Biotechnology Course," University of California Extension, 1962.

feedback would provide information only to the effect that change is occurring, and, lacking data on goal approximation, it would amplify the search oscillations, producing excursions progressively farther away from the specified goal-state. In the case of a ***progressively adaptive*** homeostatic system, the process is appreciably more complex. In this situation the goal itself, rather than being a determinable ***state,*** is more likely to be a non-stable oscillating status. (The terms "state" and "status" are being used differentially: state — a static, determined condition; status — a dynamic, varying process.) This condition introduces Heisenberg's "uncertainty principle" and requires that we convert our sensor system from a fixed-threshold comparitor circuit to a variable-threshold goal-tracking detector. That such on-line, covariable, self-stabilizing computational systems exist is repeatedly demonstrated in a variety of living organisms. That engineering analogues of these complex integrative functions are realizable will require considerably more "software" research on these regulatory functions as they operate in living organisms. But that such analogues would have valuable application in the engineering development of complex systems scarcely needs justification.

The living prototype of this homeostatic regulating system is postulated to involve (1) selectively sensitive areas of the ventricular surfaces of the hypothalamus, (2) the activating reticulum of the brain stem, and (3) the sequential programming functions of the limbic end-brain.* The periventricular membrane of the hypothalamus which borders the third ventricle has been shown to contain a series of stimulus-specific sensor areas which are presumed to be arranged in an intercoupled system for the integrative, on-line monitoring of vital body parameters such as O_2/CO_2 ratio, pH ratio, H_2O balance, metabolic rates, body temperature, toxicity levels, osmotic pressures, etc., which covariantly affect the behavioral efficiency of the total organism. A critical deviation from the tolerance envelope in any parameter disturbs the homeostatic equilibrium of the entire system and introduces ***directional*** compensatory searches in the accommodation limits of other, related parameters. These compensatory changes in threshold seem to be effected through the activating mechanisms of the reticular formations in the brain stem, which, in turn, are "programmed" by the intrinsic functions of the frontal aspects of the limbic endbrain.

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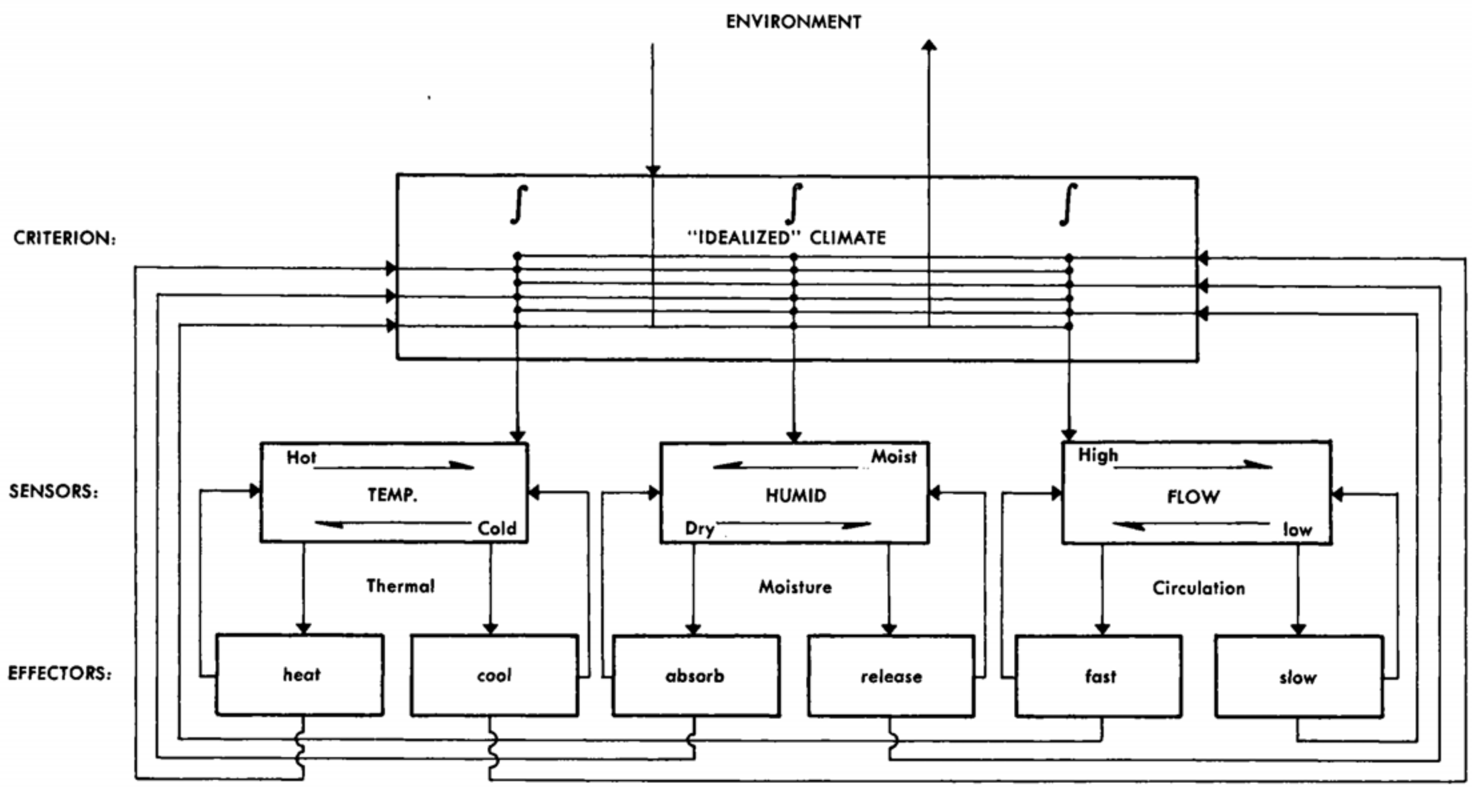
*W. R. Ashby, *Design for a Brain*, Wiley, 1952; W. B. Cannon, *The Wisdom of the Body*, Norton, 1932; J. M. Coyne, *Neuro-Engineering*, Proceedings of San Diego Bio-Medical Symposium, April 1963; E. Fonberg and J. Delgado, "Inhibition of Food and Defense Conditioned Reflexes," *Acta Physiol. Pol.*, vol. 11, 1960, pp. 696-698; K. H. Pribram, "A Review of Theory in Physiological Psychology, in *Annual Review of Psychology* (Palo Alto, Calif.) vol. 11, 1960.

A simplified physical-system analogue of the covariable functioning of this living homeostatic system might be conceptualized as a sophisticated environmental-control process. This environmental-control system would include a bidirectional thermostatic regulation of heating and cooling, a hygrometer-controlled device for humidifying or dehumidifying the atmosphere, and a sensing flow-meter which variably regulates the circulation of air. If we now intercouple each of these separately controlled subsystems with information feedback loops which permit each device to evaluate its own function in relation to the ongoing functions of each of the other component devices, and if we provide each subsystem with a representation of some optimal output for the total system, the contributory functions of each of the participating subsystems can covariably modulate to attain this optimum total system output (see the accompanying figure). A similar construct has been developed for the on-line management of a variable-expenditure fuel system for ballistic missiles.

A more recent dimension of life-sciences research which holds significance for the human-factors engineer is that of neuro-engineering. The principal focus of this area is on the application of physical-science theory and technology to assist, improve, or replace biological and psychological functions essential to living organisms. In this pursuit, the behavioral and biological scientists intervene in the "normal" behavioral functions of their system components, the living organism, to improve its efficiency in much the same way that the physical scientist modifies and upgrades the performance efficiency of his system component, the machine. Included in this neuro-engineering area would be (1) the activity of the prosthetics design engineer, who is concerned with the replacement of both the sensory and motor control of lost behavioral capabilities, as well as the improvement of faulty behavioral functions, and (2) that of the neuropsychologist, the physiologist, and the biochemist, who are concerned with maximizing the behavioral efficiency of the organism's sensory acuities, cognitive functioning, and motor responses through techniques such as: intensive responsive conditioning, the developing of relatively unused sensory intake channels (e.g., tactile), and the extending of sensory, cognitive, and motor thresholds and asymptotes chemically with psychopharmacological agents, and even the modulating of sensory and motor activity through controlled electro-stimulation of the cortex and deeper brain regions.



A SCHEMATIC CLIMATE-CONTROL ANALOGUE OF THE
THERMAL HOMEOSTATIC REGULATION SYSTEM
FOUND IN MAMMALIAN ORGANISMS

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