**Human Systems Integration**

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**Introduction**

**How Ergonomics Works**

An introduction should explain the motivation for writing a book; it should identify those previous authors and other individuals who have helped to form the conceptual image for the book and who, through their content and style, have helped to focus this attempt to advance the understanding of our profession – ergonomics, human factors, human factors engineering, or the myriad of other attempts to describe succinctly the most complex and worthwhile profession in the world, and beyond. I will choose “Human Systems Integration”

Over the years I have sought many sources of information about my profession in my various roles as a researcher, teacher, and practitioner. The flagship journals – “Human Factors and Ergonomics” and “Ergonomics” now, after 50 years in the profession, fill my bookshelves. I would like to say that I have read them all, but that would be a stretch; I can say however that I have read most of the abstracts and scanned many of the tables and graphs and read quite a lot of the articles in detail. I believe that I have just described the activities of a typical consumer of information; although I hesitate to use the expression “typical”, knowing what I have learned about human variability. A common consumer of information is attracted by a concept – the title – tries to fit this concept into his or her set of mental models, and then seeks to improve their perceptions through the well documented process of learning. Having read the titles and abstracts of the learned articles, I then turn to the pictures – photographs, tables, charts and graphs – the conclusions come next and then, if I am still interested, I check out the methods and discussion and finally go to the background to see how this article fits into the bigger scheme of things. This ‘bigger scheme of things’ to me must provide a pipeline from some theory to some application in the real world. Sometimes, however, our journal articles are not pipelines, rather they are “stovepipes” – they contain theory (hypotheses, models) without data or application, data without theory or application without either.

My next sources of information, particularly as a teacher, have been the classic textbooks. I have taught general courses using Sanders and McCormick, Bailey, Grandjean, Kroemer, the “Kodak” books by Rodgers, and Konz, and specialist courses out of Chaffin and Astrand and Rohdal. I have also used one of the earliest textbooks in the field – “Ergonomics” by Murrell. These are all outstanding books and well suited to traditional didactic teaching, where one addresses in turn such things as anthropometry, biomechanics, work physiology, vision, perception, memory, motor skills, sociology, motivation and so on. Some develop their chapters from outside in, by addressing work place design, manual materials handling, the thermal environment, inspection, assembly, web page design etc. Either way, the material tends to focus on particular areas of human capabilities and limitations or some subdivision of the application. Thus these classic textbooks do their job very well – they teach the building blocks of our profession. It is left up to the user – the practitioner – to put these building blocks together when addressing a particular situation, such as a design problem, accident investigation or legal evaluation or even explaining the many ramifications of, say, human strength or memory. Unfortunately, in my experience, students often discard these wonderful sources, once they leave school and enter the workplace. Students should keep their textbooks, not sell them!

The next kinds of material that researchers, teachers and practitioners find useful are the handbooks that have proliferated over the past decades. Those by Salvendy, Karwowski, Corlett and Stanton are particularly notable in that they attempt to cover broad spectra of our profession, with very readable and well organized chapters by contributors with specialized knowledge of particular aspects of human characteristics, behavior, performance or preference, or particular application experience. These collected works are generally not well suited as course textbooks, because of their size and cost and their sometimes too great specialization. They are well suited as reference books and provide excellent descriptions of the theory and applications of the profession. They should be on the shelves of all teachers and practitioners, and not gather dust.

Perhaps the most useful material for practitioners is contained in the books generally classified as “design guides”. Authors such as Tillman, Tillman and Woodson (Human Engineering Guide to Equipment Design), and Boff come to mind. These books attempt, very successfully, to consolidate the theories into “how to” rules, along with supporting data, such as reach curves, font sizes and symbol design. Supporting these design guides, other textbooks, handbooks and design guides address specialized areas of our profession. These sport such titles as “Situation Awareness”, Workplace Design”, “Accident Investigation”, “Human Computer Interaction” and so on. These attempt to consolidate the theory, technique sets or application domains, and provide very useful sources for either specialized courses or researchers and practitioners in specialized areas.

Finally there are “outside – in” books. These are the ones that are scenario oriented and which backtrack into the human physiology or psychology that underpin the reasons for human or system failure. Naturally they generally present the sometimes biased opinion that the human operator would not have failed if the designer of the system had had at least an introductory course in ergonomics or human factors. Perhaps the best known books of this kind are “Set Phasers on Stun” by Steve Casey and the books by Donald Norman: “User Centered System Design”, “The Psychology of Everyday Things” and its second title “The Design of Everyday Things”, “Turn Signals are the Facial Expressions of Automobiles” and “Things that Make us Smart”. Steve Casey focuses on big catastrophes with often, but not always simple causes, like Three Mile Island, Bhopal, Salyut, Exxon Valdez, X-Ray machines and ‘that new-fangled technology – radar’ which could have prevented the US fleet from running aground. Donald Norman addresses the myriad of small design shortcomings that pervade our technology centric society, like ‘which way should a door open’.

The style of Casey and Norman is instructive. It is both informative and entertaining; it links practice to underlying theory, often in a single sentence or paragraph. Both authors are, sometimes unfairly, critical of designers. While they recognize that design in the real world is often a compromise with constraints of cost and time and other performance requirements, they emphasize the common fact that the problem in question could have been prevented with knowledge that was currently available. Norman is credited with the origination of the expression “human or user centered design”, however this has always been the cry of our profession. The relatively recent, optimistic movement towards “universal design” unfortunately does not recognize the constraints of real world design. Norman’s books are pipelines that go both ways – from theory to practice and from practice to theory. These books can be used as texts, but they require a very different way of teaching; they are not linear, rather they branch around complex concepts and attempt to articulate the causal links in a spatial way, albeit through linear text. Stephan Konz attempts to apply ergonomics theory to textbook design itself, to address the challenges of complexity and readability through the media of integrated text, diagrams, tables, descriptive inserts and examples. The relatively recent developments of concept mapping and web based hypertext provide an alternative, powerful alternative to linear text that comprehends the challenges of complexity. These techniques have great potential in the areas of ergonomics and human factors research, teaching and practice. Web design provides an extremely rich environment, but sometimes there is just too much information; one should be careful what one asks for in terms of search terms.

Over the past few years I have also attempted to describe ‘how ergonomics works’ through a series of articles in the HFES journal “Ergonomics in Design”. These articles are grouped under an umbrella column entitled “The Laws and Rules of Ergonomics in Design”. Each article selects a particular law from either basic science or from ergonomics / human factors. Parenthetically I would venture the opinion that most of these laws were not invented by ergonomists; rather we take our theories from other professions, such as physics, biology, psychology, sociology, medicine and engineering and adapt them to our own needs. For example, I have addressed Newton’s Laws, Fitts’ Law and Murphy’s Law with applications to our profession in such areas as stopping a truck, assembling Barbie Doll clothes and airport security. I have attempted to mimic Norman and Casey by using real world examples as a way of backing into theory. I have also attempted to be both informative and entertaining, because ergonomics really can be very dry. This collection of articles is now available in book form – “Ergonomics in Design.”

Throughout my career in ergonomics I have had many opportunities to apply my knowledge of human characteristics, capabilities and limitations to real world problems, such as mass transit railway design, promotion systems, tax forms, retail establishments, cars, manufacturing processes, instructions and warnings. I have also been involved in projects that address how to prevent airplanes from flying into mountains and cars from hitting each other. Perhaps my greatest challenge was as program manager for the General Motors “ACCESS Car.” This was a concept that was aimed at transportation for the elderly; it addressed physical, cognitive, social and operational ‘access.’ Whereas the inputs to the design included such human centered information as anthropometry, biomechanics, vision, attention, motor skills, learning and social needs, the outputs were recommendations for the design of seats, seat belts, displays, foot pedals, trunks, turn signals, owners’ manuals, roadway design, emergency response systems, neighborhood cars and “rideshare” systems. A common theme throughout all these design experiences was that no aspect of the problem could be resolved by knowledge of a single human capability or limitation, although all problems had to be addressed eventually by combinations of single design specifications. Give the engineer a number! This requirement highlights the fundamental challenge of ergonomics and human factors. People vary; there is variation between people in shape and size and strength and stamina and skill and sophistication, and of course age; there is also variation within people over time - people become fatigued and distracted, they also learn. “Give the engineer a number!” But which number? I used to argue that a prerequisite for all ergonomics / human factors courses should be a course in descriptive and analytic statistics and investigation / experiment design. I have softened a little now – I believe that these quantitative subjects may be a co-requisite – it is possible to back into statistics and probability through ergonomics. “Give the engineer a number;” which number? The fifth percentile is no use; it is only meaningful in particular contexts and the data don’t exist outside the relatively simple area of anthropometry and even there once one gets beyond a single dimension one gets lost very quickly – particularly with the compromise between fit and reach.

One way of dealing with this problem is to avoid the responsibilities of design. We should excel in the role of “ergo-cop”. This is of course a euphemism for “usability specialist.” Let the engineer (hardware or software or organizationware) design something, get a bunch of strangers to check it out and then go back to the engineer and tell him or her that his or her “baby is ugly.” No wonder our profession gets a bad name. But what number should we give the engineer up front?

This book attempts to explain the theory and practice of ergonomics through the medium of case studies and scenarios of varying degrees of complexity. First it addresses systems theory as it is affected by the inclusion of the human subsystem and the inevitable consequences of variation, both in design inputs and process outcomes. This approach to design will use the medium of grammar to articulate the communications between users, designers and their advisors, including ergonomists, as a design passes through its life cycle of requirements, specifications, concepts, implementations, outcomes, evaluations and continuous improvement.

As noted earlier, ergonomics is not one-dimensional. Users bring physical, sensory, motor, cognitive and social characteristics to the same table. Vehicle drivers, assembly line workers and operators of remote controlled devices all have bodies, brains and brothers to contend with, and the eventual system failure in a particular context may result from any one of many vulnerabilities. However, when we break down this complexity into its contributory parts and the particular design opportunities we usually have to address individual dimensions, albeit with their interactions. Therefore the book addresses scenarios that can be decomposed into predominantly physical, informational or social dimensions and their corresponding human attributes. This will enable the ergonomist to attempt to “give the engineer a number” that can be used to accommodate independently but interactively human size, strength, stamina, skill, senses and stupidity.

This book is the first of a two part sequence. It focusses on systems theory with examples thrown in where appropriate. A second book will be bottom up. It will back in to ergonomics and systems theory from case examples.

Chapter 1

# Measurement, Models and the Ergonomics of Aging

# Introduction

This paper addresses some of the technical challenges of measurement and modeling of the aging process and some design opportunities based on experience in the automobile industry. Measurement of aging is addressed by assessment of records for particular well-defined activities, such as athletic events, rather than sample averages. Modeling employs regression methods to describe the aging process and additional effects of sub system deterioration. The design process uses a case study in which some two hundred features, related to physical, cognitive and psychosocial ACCESS to transportation, were addressed. The data for this study are publicly available from the World Masters Athletes website <http://www.world-masters-athletics.org/> and analysis of contemporary vehicles that contain many of the features identified during a two years study of the needs of older drivers. (The GM ACCESS Car)

# Measurement and analysis

Methods for measurement and analysis of aging come in different forms with different levels of reliability, validity and generalizability. There is no shortage of anecdotal evidence of great feats of old people. At the other end of the spectrum there are voluminous statistics related to morbidity and mortality. In between, the literature contains many reports of surveys and formal performance studies of cohorts of older people. The discussions hover between emphases of older human capabilities and their limitations.

# Modeling

Models of aging typically show an accelerating performance deterioration curve, much like the Weibul equipment wearout curves. Indeed this is a good model of the human reliability process as affected by aging and associated component deterioration (cancer, arthritis, obesity, neurological deterioration). As with physical systems, human systems are sometimes subject to significant acute incidents (fractures, strokes, heart attacks) that are followed by recovery at varying rates. Parametric performance studies of physical, sensory and cognitive capabilities commonly make use of the familiar Normal Distribution for comparison purposes. A shortcoming of such studies is that the results may be simple artifacts of the study sample. A second shortcoming is that for one reason or another the data may not be Normally distributed; rather it may be more appropriate to use distributions that have skewness (positive or negative shape parameters) such as the Gamma or Gumbel. The major challenge to modeling is to distinguish between aging per se and the associated sub system failures and deterioration due to injury, illness or simple disuse.

**Medicine**

The overt purpose of (geriatric) medicine is to assess, treat and manage those illnesses and acute incidents that are associated with aging, but which are not necessarily a result of aging per se. Typically geriatrics deals with the confluence of multiple, often functionally inter-related disorders – such as osteoarthritis and obesity or diabetes and amputation. The late Charles Sheffield wrote plausible science fiction related to aging and concluded that even an infinite amount of money, spent on medical and engineering interventions, could not prolong life indefinitely, although he did articulate the vision of cryogenics. Contemporary medicine for aging populations is dominated by pharmaceutical interventions and organ replacement and is responsible for the prolonging of life through intervention in disease processes. However, physical, mental and social activity in the preventive mode and rehabilitation in the reactive mode remain the essential components, genetics aside, of longevity for most individuals.

# Design

The design approach to aging has two facets – engineering and organizational. The engineering philosophy is to replace (automation) or assist human functions. In the case of transportation systems we address ease of entry and egress, accessibility of controls and seat belts and the design of information interfaces, both with the vehicle itself and the outside world, to accommodate the limited sensory, perceptual and cognitive functions of elderly people. Driver communication systems now extend to external support as well as the traditional within vehicle displays. In the broader context, engineering also addresses supplementation devices such as eyeglasses and hearing aids, powered wheel chairs and kitchen aids. The proliferation of remote control devices may be a boon for the arthritic but a barrier for the cognitively challenged. Self-driving cars are a technical possibility but an organizational nightmare.

# Organizational Design

Organizational design addresses the psychosocial, operational and economic limitations of older people. Social security and Medicare are a start and prescription drug subsidies are essential if older people are to reap the benefits of the research that their tax dollars subsidized. The private sector also sees an organizational opportunity through the construction of comprehensive habitats away from the challenges of roads with 18 wheelers. On a smaller scale there are local “agent-broker” transportation systems for the elderly, and organizations such as AARP aggressively sponsor political and functional interventions on behalf of the elderly. At the other end of the spectrum the World and National Senior Games Associations sponsor athletic competitions among older age cohorts. These competitions cover most of the events of the Olympic Games, but fall short of some of the recently popular “Extreme Games.” Community organizations, which prefer “senior” to “old”, sponsor many physical and social activities at the local level. In other cultures, the extended family fulfills many of these psychological, social and economic support roles.

**Ergonomics Analysis**

So what then is the role of ergonomics in aging? We carry out measurement and analysis, we develop models and we prescribe interventions for individuals and populations. There is merit in formalizing the measurement process, much like the developmental psychologists assess progress at the other end of life. Broad based test batteries, such as the “available motions inventory” have merit as an indicator of functional age. Similar functional, sensory and cognitive tests, such as tests of situation awareness and workload, may also be adapted for older cohorts.

# Modeling

Models of aging lack a “gold (or silver?) standard”. However, the World Masters Athletes <http://www.world-masters-athletics.org> publishes statistics on a wide variety of track, field and road running events in 5-year age groups between 40 and 100. Many athletic events use these records to create a ratio with actual performance measures as a form of handicapping. Such a broad based physical performance battery, which involves strength, stamina and skill, offers a “pure” model of aging with minimal contamination by illness or lack of motivation. This concept may be usefully applied to other aspects of human functional performance, wherever standardizing task demands can be achieved (chess, scrabble?) The variability associated with such records may be modeled by the Extreme Value (Gumbel) distribution, which reflects their inherent skewness. Regression models may be applied to the general aging variables together with elements related to particular system shortcomings, due to disease or other individual bodily system functional deficiency.

# Interventions

Ergonomics intervention may be offered at the population and the personal levels. Such interventions may involve design of hardware, information systems (often software), medication (the usual prerogative of medical “ergonomists”), humanware (selection, training, rehabilitation and assignment) and organizational design. At the population level, the design basis must comprehend the age effect per se, very wide variability and bodily system functional deviations. At the individual level, a rating in comparison with the record will indicate the amount of accommodation (handicap) needed in the design

**Human Performance Data**

The decline in human performance capabilities may be demonstrated using published data from the World Masters Athletes Organization (formerly WAVA – World Association of Veteran Athletes), experience from a major automobile industry project related to the design of transportation systems for elderly users and experience in the physical rehabilitation of elderly patients. An example of the WMA data for the men’s Ten Thousand Kilometers run is shown in Figure 1. Note that a quadratic regression provides a good fit to the data.



# Figure 1 World Masters Athletics records for the 10 kilometer race

**A Design Case Study**

The General Motors ACCESS car program involved studies by many universities, a series of customer clinics with a wide variety of vehicles, and the design and evaluation of some 200 features. The features were classified into physical, informational and psycho-socio-economic. The entry egress features of interest were related to the design of door openings, including step over and head clearance, seat height and profile, obstructions and the availability of support devices, such as grab handles, seat backs, instrument panels and steering wheels. Similar consideration was given to stowage, for large and small articles, both within the vehicle interior and the trunk. Seat design and seat comfort faced the inevitable discussion of the differences between “comfort” and “discomfort”; on balance however the older drivers preferred and performed better with firmer seats with less contouring. Access to restraint systems was also a concern with the placement of the seat belts and the fastening mechanisms. Also the particular fragility / vulnerability of older people to air bags was and remains a concern.

At the informational level there was polarization between the demand of many, usually younger customers for features of all varieties to enhance their driving and peripheral experience, and the requirement of older people for simplicity. Much of this debate revolved around access to a hierarchy of features and interface design. The vehicle system information displays pursued the classical sequence of: tell the driver about the existence of a deviation from normal, indicate the seriousness of the deviation, indicate the source, communicate what should be done to resolve the problem and indicate the urgency. The vehicle operation information display evidence agreed on the visual needs of older people for size and contrast, but bounced back and forth between the merits of status (“idiot lights”), analog, digital and representational displays. The special needs of older drivers were addressed by the development of an emergency communication system that at the press of a (large) button connected the driver with assistance for medical, vehicle, navigational and security assistance. This system was a prototype for the commonly available driver communication facilities that involve GPS and agent-broker systems.

The agent-broker concept was also applied to the psycho-social-economic aspects of transportation. Ownership of a vehicle has many challenges – purchase, licensing, insurance, driving, maintenance, repair, disposal etc. The provision of mass, small group and personal transport for elderly people required a high level systems approach, that started with analysis of journey type. One outcome of this analysis resulted in the development of a neighborhood car concept that required attention to vehicle design, organizational access and journey management. The design implementation of this analysis resulted in the confinement of small electric or hybrid vehicles to largely self-contained neighborhoods, isolated from the 18 wheelers, frantic commuters and distracted teenagers. The more recent development of widely accessible ride share systems (Uber, Lyft etc.), has developed to address the various requirements of many, including older people.

**Chapter 2**

**Boats, Trains and Planes – Systems and Process Engineering**

**Introduction**

This paper addresses some opportunities for human factors to become involved early in the design cycle. Brief descriptions are given of five case studies in which different human factors approaches and systems engineering tools were applied successfully. The case studies include a mass transit railway, supertankers, cars, car manufacturing and space vehicles. All design processes start with requirements – the customer wants the device or service to fulfill some function. Of course there are conditions associated with the requirements that are articulated in criteria such as quickly, safely and inexpensively. In all cases the measurement and communication of these and other human factors benefits from the design of a common communication currency. The chapter employs frequent but consistent use of “jargon” – requirements, specifications, verbs, adjectives etc. and examples. The reader is encouraged to develop alternative examples to investigate the concepts.

When we discuss human factors it is common to describe a machine, a user, an interface and an environment, in the broadest sense of the words. In systems design we focus on the interfaces with the equipment, tools, environments and organizational structures with due regard to user (and misuser) capabilities and limitations. Human factors usually faces complex “human-machine systems”. For example an operator in the Space Shuttle may be controlling a robotic arm on the end of which is perched another astronaut. A third, tethered astronaut is outside assisting with the placement of a multimillion-dollar piece of hardware on a space telescope. The environment is characterized by minimal gravity, zero air pressure, alternating hot, cold, light and dark. The interface has to deal with the control of a six or seven degrees of freedom “robotic arm” using quite limited camera views and communication facilities while the whole world is watching. Whatever the context the rules are always the same – we must design the tools and tasks so that the users can be successful and safe.

**Visions and Missions**

All good ideas start with visions. “Beam me up Scotty.” Visions are free, but when we translate a vision into a mission we need funding. We also need specific mission requirements that can be measured so that we may know whether or not the mission has been accomplished. Missions usually have constraints – “put a man on the moon before the end of this decade” or “put a group of people on Mars.” Next come the details – the specifications of how, what, when and how much? There may also be a “where” thrown in although usually the “whys” are beyond question. Most complex missions have a way of costing more than the first estimates because as the plans unfold, problems arise due to lack of information or opportunistic subcontractors holding the main organization to ransom. The more successful missions have clear requirements and accurate specifications very early in the design process.

In the 1970s Hong Kong decided to solve its traffic problem – 5 million people all wanting to go to work at the same time. Rickshaws and old busses could not handle the demand, so a mission to build a mass transit railway was born. The mission had requirements – move 1 million people from A to B quickly, safely, comfortably and cheaply. And “oh by the way expect to move 2 million people from A to B to C in a few years time.” The plans involved digging a channel up main street, putting in a tube and then returning main street to its former condition a couple of years later. In the 1980s the oil crisis directed attention to reserves in Arctic Canada, but it was deemed to be unwise to have a ship full of LNG collide with an iceberg or run aground. After considerable human factors, economic and engineering analysis, the plans proved to be untenable. In the 1980s General Motors was feeling the heat from overseas competition and so developed a mission to improve the quality and productivity of their automobiles, and reduce the costs. They embraced many concepts of systems engineering and learned all about “the voice of the customer.” They found that there are many external and internal customers and they learned the language of systems engineering. By 1990 the US unions decided that “ergonomics” would help to reduce the effects of the increasing levels of repetition needed to improve productivity. Work related cumulative trauma disorders began to increase to epidemic proportions. The plans included the creation of the General Motors Manufacturing Ergonomics Laboratory and the development of a plant based “reactive ergonomics program.”

The mission to Mars turned out to be more formidable than the mission to the moon in the 1960s, despite the enormous advances in technology. It may be tolerable to lose a robotic mission, but a manned mission had to have more guarantees. So NASA refocused its attention to Low Earth Orbit and the International Space Station in a hope to answer some of the questions associated with long duration manned space flight. Many people still have a vision of going to Mars and many have laid out elaborate plans, but at the present time there is no mission. All of these case studies confirmed the importance of clear operational definitions in human factors and systems engineering. Unfortunately the evolution of this subject area has resulted in ambiguities. The next few pages outline some definitions that may help to improve the reliability of communication as human factors engineering interacts with the system design process.

**Systems and Processes**

A key concept lies in the definition of what is a “system” and what does a “system” do? A convenient operational description of a “system” is any hardware, software, and naturally occurring or human entity that, by themselves, have no functions. When two or more systems interact, in a physical and organizational context, to achieve an objective then this interaction is called a “process”. Usually the objective or outcome of a “process” is a change in the characteristics of one or more contributing systems. In the case of human factors, one of the contributing “systems” is a human “system”. For example a person may have the characteristic of “being at home”. Only when he interacts with a car and a roadway does he change this location characteristic to “being at work.” During this journey the human subsystem may interact with other systems – such as a coffee cup, a cell phone, a frosty road and another human-vehicle system to engage in a process that results in an accident – characterized by a change in the shape of the vehicle and the owner’s wallet.

Design processes create various human, hardware, information and organizational systems with the purpose of producing a new entity or service. There are multiple purposes of such processes. First the product must meet with customer expectations – this in its broadest sense is called product quality. The next process objective is to be efficient or productive; that is it must achieve its quality objectives with minimal use of consumable resources (systems) such as people, money, materials or time. This last resource “time” often stands out as a key aspect of process design. The customer would like the elapsed time between his want being expressed and fulfilled to be as short as possible. “Time to market” is a key objective of most product design processes. One way of achieving this objective is through the practice of “concurrent engineering” in which phases of the process are implemented in parallel rather than in sequence so that, for example, the demands of manufacturing can be addressed during the product design phase. These process objectives are of particular interest to the eventual paying customer, management and the shareholders. However the unique nature of the human system elements is that they may have their own agendas and objectives. For example employees would like to maximize their own salaries and minimize the risk of accident, both of which may conflict with the other process purposes - such as productivity. A more detailed look at the design process identifies multiple overlapping stages. The term “concurrent” is somewhat optimistic in practice.

Given the vision of putting a man on Mars, there are distinct, but interdependent phases that must be addressed. The first phase is a function identification – launching, navigating, eating - each with their own purposes that are characterized by “quality”, “productivity”, “safety” etc. Next comes the realization of these functions through the design and construction of the appropriate hardware, software, “humanware” and “organizationware”. The process integration phase focuses on interactions, interdependencies and interfaces. Of course the advantages of concurrent engineering are particularly evident here as, for example, the human and hardware systems must be compatible. The penultimate phase of operations design really addresses the time element. In the Mars mission example it is critical that various supplies (food, water, oxygen, shelter etc.) would be on the planet before the humans arrive. Another good example is to be found in automobile production – it is one thing to design and build a car, but to produce 1000 cars a day presents altogether new operational challenges, not the least of which is “just in time” materials delivery. Finally there is operations implementation, which has its own local objectives and its contribution to the next mission through “lessons learned” (feedback).

**The Grammar of Design**

The grammar of design offers a discipline for communication that increases the effectiveness and efficiency of the design process. The first concept is that “processes have requirements” and that requirements relate to the adverbs associated with the process functions (verbs.) The process “verb” may be “transporting” a vehicle and human systems in some context or environment. The purposes or objectives of “transporting” may include speed and safety. They will certainly include “quality” - the payload should arrive at the correct destination. Thus “transporting” may be measured in terms of how “quickly”, safely” and “accurately” – adverbs. It is important to emphasize that quantification of these adverbs is important if the process requirements are to be reliably assessed.

The achievement of these process requirements will depend on the characteristics of the contributing systems. In the above example, if speed were emphasized, then a vehicle with a big engine and a driver with a heavy foot would assure the desired objective. Again, for precise system design it is necessary to quantify the adjectives – “big” and heavy” associated with the system nouns – engine and foot. Otherwise the engineer cannot design the system and the human factors engineer cannot evaluate the quantitative relationships between the system specifications and the process requirements. Give the engineer a number!

**Verification and Validation**

Once the system is built (or modeled) and the process implemented (or modeled) then the human factors engineer is faced with the important task of evaluation. This consists of two sub processes – verification and validation. If the system characteristics have been specified precisely and quantitatively then verification of adherence to these specifications is simply a matter of measurement. On the other hand evaluation of process requirements implies the process of validation, which in turn implies the performance of the interacting systems in a real world context. The key challenge to validation is the inevitable presence of user, context and temporal variability. A precisely specified and constructed car may not “perform” adequately with an inebriated driver in thick fog. Development of the validation process begs the question of “humanware” design – who are the expected user and possible misuser? Validation also may exclude certain contextual conditions such as inebriation, fog, ice or 100mph. The contribution of human factors engineering lies in clear description of usage requirements, user capabilities and limitations, design specifications and evaluation conditions.

**Performance, Behavior and Preference**

Human Factors measures of process requirements may be classified at three levels – performance, behavior and preference. Performance can usually be measured in terms of time and accuracy, given the context. For example running a mile on level ground will differ from the time taken to run the same distance up hill. The accuracy (quantitative deviation from the objective) needed to thread a needle is different from that needed to park a car. Behavior relates to how a task is performed. In cricket it is possible for the bowler to achieve his objective by swing or spin. Behaviors can be categorized and counted. Using the cricket example again, three bouncers gets the bowler suspended; in baseball one beamer gets the pitcher mugged. However these “bench-clearing brawls” (ungentlemanly behaviors) can be modified (despite the preaching of Skinner) by negative feedback – fines. The most elusive measure associated with humans is that of preference. Preferences may be stated and counted, but may not affect behavior or performance. However extraction of the “voice of the customer” or the mechanisms of “usability studies” often resort to the assessment of preferences or subjective judgments of differences. We must be ever vigilant that we do not put too much store in observations elicited by improper application of one of our most widespread techniques – psychophysics. Unfortunately this is often the only technique we have available.

Working in space involves many processes such as staying in one place, moving, eating and assembling. The more complex activity of assembling involves the interaction between multiple human systems, components, robotic arms and communications facilities. The context of microgravity, the vacuum of space, radiation and very high cost presents unique constraints on the process requirements. The interacting tasks of controlling the robotic arm whilst perching exemplify the challenges, especially when the higher-level task of assembling an expensive component may take all day. The adverbs related to this task include carefully, slowly and comfortably. Slowly can be and is defined precisely and carefully is described in terms of deviation from a prescribed, tight trajectory. Comfortably is one of those unfortunate human factors challenges that defy reliable quantification, although it is likely that uncomfortable perching may create a distraction that in turn may compromise carefully.

**Requirements and Specifications**

These process objectives and requirements can only be realized through precise specification of the contributing system characteristics. What kind of restraint design results in comfortable perching? What kind of joy-stick design contributes to the activity of careful control of a heavy payload (crew colleague, components and tools)? What kind of organization of multiple pairs of eyes and brains is conducive to reliable communicating? How much light should be provided, given that the daylight only lasts forty-five minutes up there? How much oxygen should be provided for the strenuous tasks of fighting the resistance of a pressurized space suit? How long should the workday be? Give the engineer a number!

The development of process requirements and design specifications is not simple. It is rarely possible to simply translate empirical data into a number that can be applied to reliable validation. At a simple level, if asked why the height of a door opening is 7 feet, we may waffle about percentiles and allowances for shoes and hats. Similarly we may look at accident statistics on the freeway and determine that 100mph (160 kph) is acceptable for 95% percent of journeys. Or we may state unequivocally that 15 minutes of arc is the design specification for font height on a computer screen. If we don’t give the engineer a number he can’t design or verify. But we all know that the number includes a policy overlay and will usually be modulated by domain experience. Consequently it is essential that requirements and specifications be developed by consensus, with management (or the law) imposing policy, our scientists providing the logic and the data, and the engineers – the eventual users of the standard - providing the domain experience. Of course all standards (requirements and specifications) should be subject to iterative evaluation and an effective technical memory should lead us to convergence. Unfortunately those policy makers often change their minds when faced with tradeoffs.

**The Hong Kong Mass Transit Railway.**

The main performance requirements of this transportation process were to maximize safe throughput of passengers, given the constraints of size, speed and the need to show a profit. Throughput is constrained by spatial capacity and passenger behavior, which in turn is affected by spatial arrangements. The seat design and grab rail specifications were based on anthropometry and human behavior. The approaches used to generate the anthropometry and behavior evidence involved the human factors literature, surveys, analysis and evaluation of performance and behavior in physical mockups. The use of adjustable physical mockups of both the passenger compartment and the operator’s cab proved to be very instructive. In fact there were substantial discrepancies between simple application of anthropometric accommodation principles (5th and 95th percentiles) and the actual behaviors of representative samples of subjects in the physical mockups. An ironical twist in the seating systems development, based on emphatic input from the Hong Kong Fire Department, resulted in the adoption of flat stainless steel bench seats rather than the scalloped aluminum that were first proposed. This resulted in an adaptive rather than constrained seating arrangement. The vertical poles and horizontal grab rails were positioned to allow optimum accessibility, stability and motion, given the wide range in anthropometric characteristics of the expected user population. A horizontal bar reachable by a fifth percentile female would hit a ninety-fifth percentile male on the chin! Compromise!

The operator’s seat design followed from a task analysis that indicated that the operator would have to get in and out of the train every 90 seconds as he checked that the platform was clear prior to starting the train. This resulted in the design of a seat that could be folded back (allowing easy egress in an emergency) or in the down position for the longer, between station, transits. The seat also had a padded front edge to accommodate the preferred lean sitting posture. In these examples, human factors was applied in a somewhat ad hoc way in the very early design stages. The principal “tool” was physical mock-up evaluation.

**Liquefied Natural Gas Transport**

In the early 1980s serious consideration was given to the exploitation of the vast oil and gas reserves in Arctic Canada. The two transportation options were pipelines and large double-hulled ice breaking tankers. Given the cargo and the context, there were substantial safety concerns – a collision or a grounding could result in a cloud of escaped gas descending on a town and then exploding. The preferred analytic approach was to use fault tree analysis – both for the mechanical and electrical systems and the human systems. It should be noted that, unlike military vessels, commercial vessels are designed to be operated with very small crews – thus reducing the human redundancy in case of error. The approach to the assessment of human error was based on the human reliability assessment techniques developed for the nuclear power plant industry at Sandia National Laboratories. A massive (paper) fault tree was developed and assessment of the performance shaping factors indicated that an incapacitated crewmember would be a likely cause of catastrophic failure. Six years later the Exxon Valdez confirmed these findings. Fortunately the LNG project was abandoned for a combination of environmental, engineering, economic and human factors reasons.

**Car and Truck Design**

Car and truck design is a fashion business. Some quip “function before form,” whereas others say “form before function.” This can be translated into preference before performance. There are, however basic functional requirements of capacity, operating, maintaining etc. before aesthetics takes over. Human factors contributions in product design covers the full spectrum of customer needs – from basic physical issues, through sensory and information processing to their requirements for alternative features and styling. Different vehicle types attract different customers and have different uses. Much of this evidence is elicited early in the design process through competitive review, clinics and more precise laboratory investigations, involving simulators of various levels of sophistication. As the design process progresses various iterations of prototypes are assessed using modeling, checklists and “drives” on closed courses and the open road. The formal process is iterative and involves concept evaluation, selection and refinement, through processes of analysis, testing and, eventually, board review.

Quality Function Deployment is a technique that has been applied widely in the automotive industry to translate the voice of the customer into design specifications and on down through the manufacturing, production and distribution processes. Early uses of the technique resulted in vary large and unwieldy matrices that became increasingly less than useful. However the principles are sound and lend themselves well to the discipline of requirements and specifications development. Unfortunately the user (customer) does not always adhere to these grammatical rules of design. The dutiful customer should ask for a vehicle that “goes fast”, “is easy to maintain”, “enhances his social image” and “protects him in the event of an accident.” Instead the customer may stipulate engineering nouns and adjectives such as: 300 horse power, maintenance free, red vehicle with side air bags. This lack of discipline (customers stating specifications rather than requirements) occurs among all the many internal and external customers.

An example of QFD in product design would be to address the operation or driving of the vehicle. One adverb might be top speed and the range of top speeds of competitive vehicles might be available from market research. The engineer would recognize that top speed would be accomplished by, among other things, engine size, which would be described in engineering units of cu ins. The adverb “fast” (speed) is of course affected by more factors than engine size – there is the mass of the car, the gearing ratio, the aerodynamics and the type of fuel etc. Similarly the “safety” requirement might conflict with the “fast” requirement. Thus the task of the human factors engineer becomes more complex in the optimization of often conflicting requirements.

The human factors engineer is a surrogate for the end user. He or she should identify the populations of interest on the dimensions of interest. He should communicate clearly with the design engineer by relating the associations between levels of design specifications (independent variables) and performance outcomes (dependent variables). The relationships are affected by human variability, which can only be reduced by curtailing the “expected user population” by selection or training. There will be many occasions where the relationships are affected by the prevailing conditions and by interactions with other variables; there may also be multiple, sometimes conflicting outcomes. Eventually the designer will have to settle for a single value on each dimension, unless he can design an adjustable feature. The task of the human factors engineer is to communicate the acceptable ranges for each independent variable, given percent accommodation policy, and to articulate the likely sources of interaction.

**Design for Manufacturing and Assembly**

Contemporary vehicles have many more features and components, especially on the engines, than they had a few decades ago. However, the drivers have not changed in stature and so it is not possible to increase the height of the hood. Thus more things have to be compressed into a smaller space, which produces challenges for packaging, assembling and maintenance. Contemporary “design for assembly” approaches use mock ups and computer models to assess these manufacturing challenges. There are also certain well defined, though not always feasible, ground rules for design – such as layered assembly and upward and outward facing fasteners. Given the best possible design, with manufacturability in mind, the ergonomist is next faced with materials delivery and presentation, tools, workplaces and task content. This last challenge of “line balance” attempts to maximize the utilization of every second of the assembly operation. The ergonomist looks for ways of increasing physical (and mental) job variety through team structure, job enlargement and rotation, but may be constrained by seniority agreements and quality concerns.

One fundamental challenge of manufacturing ergonomics lies in the difficulties associated with measuring people in their working environment. These conditions do not lend themselves to the rigorous demands of the experimental laboratory for accuracy, precision, reliability and even sometimes validity. Sample size is also usually restricted. Consequently the thrust of manufacturing ergonomics should be the assessment of the workplace using population data while allowing the eventual individual operator(s) to fine tune the arrangements to suit their particular needs. Systems approaches to workplace and task evaluation using various levels of analytic tools should therefore limit themselves to population data, while leaving room for some flexibility.

Manufacturing ergonomics assessments are applied at all stages of the manufacturing system design and implementation process. These assessments take the form of computer modeling, “wall reviews”, prototype review and “slow build” review in which each motion is evaluated in great detail. This up-front assessment leads to much improved designs of production systems. The practicing manufacturing ergonomist has available a wide variety of analysis tools that range from checklists through integrated analysis methods to digital simulations.

Ultimately any design, design change or operational intervention will be based on a risk- cost – benefit assessment. The solution may be a change in the component (the product engineer’s responsibility), a change in the tool or workplace (the manufacturing engineer’s responsibility, a change in the amount of work in the job cycle or the line rate (the industrial engineer’s responsibility), a change in who does the job (the supervisor’s responsibility with due regard to seniority) or the method by which the job is performed (the operator’s or trainer’s responsibility).

**Opportunities for Intervention**

The application of systems engineering and human factors in car and truck manufacturing addresses the opportunities for change that are presented during each of the product, manufacturing process, production and operations phases. By way of example, rather than use a specialized manufacturing process, one can consider the baggage handling processes at an airport. The first design phase is the product – an item of baggage. There are restrictions on shape, size, weight, materials and content. The handling process design includes consideration of all sub-processes that occur between the parking lot and the aircraft’s hold and back to the parking lot. These sub-processes include mechanical handling and information processing devices, human handling and information processing activities, the design of interfaces and due consideration of the environment. The production system design element takes the problem from the handling of a single item to that of millions of items a year. It requires the coordinated activities of sufficient handling devices, sufficient information processing capacity, sufficient people (with appropriate training) and sufficient numbers of interfaces. Finally, operations management involves a full complement of baggage handlers, maintainers, customer service agents, second level problem solvers and managers all being appropriately selected, trained and assigned to achieve a desired level of customer service. As the overall process moves towards operations there will be increasingly greater levels of scrutiny. Hopefully the baggage and handling systems design issues have been dealt with early in the design process. However unusual, seasonal demands to handle golf clubs, skis, bicycles and fish may expose the shortcomings in design accommodation.

**Walls and the Ergo Cop**

One way of modeling each phase of the process is through the development of physical or computer based “walls” that contain an array of standardized details of the systems and processes as they mature towards implementation. These “walls” provide the media for multidisciplinary teams to comprehensively evaluate each stage of the process so that late developments don’t interfere with the critical path and late changes don’t result in excessive costs.

Manufacturing ergonomics has its own elements on the “walls” Assuming that the product design issues have been addressed on an earlier “wall” the manufacturing ergonomics wall will contain questions that address workplace design issues of fit, reach, targets and task content. At the production level the physical and temporal aspects of an operation will be amalgamated to assure acceptable job cycle workload. Later the operations wall will address individual job and team assignment questions. Finally, the operations output wall will document quality, productivity and health and safety issues associated with each operation.

The practice of manufacturing ergonomics provides important lessons for many other practice domains. The traditional practice of imprecise process requirements and unrealistic design specifications lead to inappropriate designs to be addressed by the “ergo cop”. Eventually battles ensue in the “review boards” that often result in requests for waivers and either a loss of face, or an inflated ego, of the ergonomist. This process is both inefficient for the company and unhealthy for the profession. The ergonomist should participate with engineering, management and the operations / user community in the establishment of clear performance requirements and sufficiently precise design specifications and design implementation. In this way there will be no surprises at the board (performance) reviews.

**Space Vehicles**

The design of space vehicles differs from high volume manufacturing in product cost and product life cycle. The environmental challenges, power requirements and human interactions are unique. The complexity and remoteness of the operations leads to massive information management challenges and costs. The space program is deliberately very visible – the whole world is watching. Finally because of these things, there is relatively limited opportunity for the program to capture sufficient “lessons learned”. Much of the evidence that cannot be based on analysis, must be based on small samples of empirical evidence. Human factors specialists become acutely aware of the challenges of human variability, given the relatively small number of experienced astronauts. Manned exploration missions, for example to Mars, present even greater challenges of evidence from robotic missions.

Over the past two decades NASA has developed extensive statements regarding the human factors issues of manned space flight. These statements are in addition to the extensive medical requirements. The NASA Standard 3000 – the Man- Systems Integration Standard (MSIS) is a compilation of evidence from both the profession of human factors (and other sources) and domain knowledge. Military standards such as Mil Std. 1472 were particularly influential in MSIS development. The basic MSIS standard has been adapted to program specific statements for Space Transportations System (Shuttle) and the International Space Station. These basic and derived standards have, like the programs to which they refer, been subject to hostile attacks in the requests for waivers from engineers, programs and contractors. As the space program matures working groups, tiger teams and review boards all contribute evidence on which the next generation of standards will be based.

A general challenge to human factors is exemplified by the NASA review processes. Almost all human experiences are dogged by individual, contextual and temporal variability. For example an ideal thermal environment is affected by activity, clothing, individual acclimatization / tolerance and duration of exposure. The requirements for strenuous exercise are different from those of reading. Consequently an overly specific statement like 720 F will inevitably be inappropriate much of the time. The challenge to a human factors review panel is to address all the, possibly interacting, criteria in coming up with a decision that the engineer can design to. Clearly adjustability is required, but how much adjustability? Further complications arise because of constraints on design or change. For example a particular intervention may be too costly or not feasible in the time scale of the overall project. The final complication of the review process is that the judges (usually experienced managers) overlay their own experience / prejudice on the decision. The task of the human factors engineer is to apply his / her own principles to the conditions surrounding the review process. It is the responsibility of human factors engineers to be “user friendly” in their own practice. The response: “come back in a year when I have done a comprehensive study” is only occasionally warranted. Similarly the answer 720 F because the textbook says so is equally naïve.

The human factors community at NASA makes extensive use of digital modeling in the design, evaluation and real-time mission support phases. The primary contractors – Boeing - made extensive use of anthropomorphic modeling during the early design phases of the International Space Station. Currently the Interior Volume Control Working Group uses models of the ISS interior, together with anthropomorphic models to evaluate additions and changes such as sleep quarters, the galley, exercise equipment and protruding racks that interfere spatially and temporally with routine and emergency activities. The application of digital human modeling in the evaluation of the conditions of work in an assembly task was shown to be more precise than, faster and far less expensive than the alternative of a full blown trial in the Neutral Buoyancy Laboratory. Modeling was particularly useful in the iterative design and analysis cycle of the crew quarters rack which provides facilities for sleep, computer workstation storage and privacy.

Lighting models, using the Lawrence Berkeley Laboratories “Radiance” software, are critical to operations, given the changes from extreme brightness to complete darkness every 45 minutes. Differing viewing points for crewmembers and cameras, shadows and glare compound the difficulties. Just in time modeling and prediction of lighting conditions are invaluable to many Extra Vehicular Activity operations. Exterior robotic operations in the rapidly changing day / night cycles make use of both human vision and camera vision for both training and real time activities. These models are particularly useful to aid decision making when contingencies change the time line and hence the lighting conditions for particular activities.

Although there are very few crewmembers, the multiple demands on their time and the many resource constraints, such as equipment, power, materials and lighting, make activity scheduling a very difficult challenge. The difficulty is compounded by sparse and imprecise evidence regarding the duration of human activities in the micro gravity environment and the ever-present challenge of human variability. The problem is being addressed by enhanced data collection approaches and a range of complex and simple scheduling models. The crew work day on the International Space Station is broken up into three main categories – work (including scheduled science investigations, assembly, maintenance, planning and communications), sustaining activities (sleep, exercise, eating and personal time) and responding to contingencies (such as caution and warning signals). The considerable spatial restrictions of the ISS complicate work activities through stowage constraints and spatio – temporal interference. The personal preferences of individual crew members in the highly congested conditions sometimes results in excessive times being spent in finding tools and materials. The crew workday is categorized in detail, however the variability of times of activities within categories is not well understood. Consequently steps are being taken to collect better data and develop simulations of activities on a daily, weekly and mission basis. These models show not only the occasions when the schedule is overbooked but also how different priorities of activities can be used to accommodate this overbooking – such as sacrificing sleep or personal time.

**Global Integration**

Human Factors and Systems Engineering are essential to effective and efficient design. However all designs of processes and contributing systems are complicated by change and human, situational and temporal variability. A major thrust over the past decade has been attention to common processes of both the design activity itself and the resulting product and manufacturing processes. Unfortunately times and best practices change, so the processes must be flexible to assess and accommodate these changes. These challenges are particularly evident in international operations, where economies of common processes often conflict with different national practices that have been established over many years. Of particular value in the human factors area is the establishment of a common communication currency that enables comparisons to be made between widely differing alternative and conditions and which resolve the ubiquitous importance weighting problems.

Global integration efforts are often the source of conflict between the efficiencies of common processes and the perception of what are best practices. “Not invented here” is often an underlying motive. The challenges of competition in the automotive industry, coupled with the explosion of computing and telecommunication facilities have combined to fuel the fires of globalization. Manufacturing organizations seek out high quality, but lower cost labor markets. Also it is not efficient to have an engineering design center in every country – why develop essentially the same product separately in multiple markets? But engineers worldwide are conservative and resistant to imposed change. In these cases there is no substitute (other than dictatorship) for extensive face-to-face interactions among the design teams, including the human factors engineers.

The International Space Station faces similar challenges. The program has very important political underpinnings, the costs are extremely high and national identities need to be clear. And there are other constraints – only three crew members at a time, relatively few modules and only occasional opportunities to visit. The management of such a program is not limited to the handful of astronauts and cosmonauts; there are very large support staffs in operations, engineering, medicine and science management. The ISS is at once a miracle of systems and safety engineering and at the same time a management nightmare.

**Changes**

The mechanisms of dealing with change are described in different organizations as request for waivers, change requests or engineering change orders. In many cases these requests are appropriate, albeit due sometimes to poor planning or unclear requirements and specifications statements earlier in the process. Often however they are seen as frivolous – made only to accommodate the failure of a supplier to be able to deliver on earlier agreements. Where waivers are processed on an individual basis, they may not comprehend the implications on other aspects of the process or the trickle down effects to other subsystems. Cost is a common reason for change and the systems engineer and the human factors engineer must work with the managerial accounting community to establish a common basis for the rational processing of waiver requests.

Human Factors cannot be practiced without engineering – the people who design the systems – and management – the people who make the policies. Sometimes policies are imposed from elsewhere – through technical standards, government regulations or labor agreements. Some human factors practitioners feel that it is their duty to convey policy, especially where engineering and management do not have the appropriate information to decide on policy. On occasion, human factors specialists may substitute dogma for policy. The notorious 5th percentile is a prime example. It is a useful concept, often with good rationale, but it is widely misunderstood and often inappropriately applied.

A major problem is that someone who represents the 5th percentile on one measure is unlikely to hold that relative position on another; furthermore, when accommodation is based on multiple dimensions then it may be difficult to define who or what is a 5th percentile. Monte Carlo simulation methods may be applied to somewhat relieve this problem. Another difficulty is that the implications of a design decision may be more or less important. Thus in the case of a highly sensitive design decision it may be appropriate to accommodate the 1st percentile. On other occasions, design for the average may be an adequate approach, given that the dimension in question is not related to an important outcome. An example of a highly sensitive design decision would be the walking speed of old people crossing a busy road.

**Outcome and Design Scales – Common Currencies**

Human Factors engineers are made aware of the processes and theoretical underpinnings of scaling methods from their earliest training in the statistical methods applied in the broad context of human variability. Scaling systems abound – percentages and Yes / No are separated by Lickert type scales of varying degrees of resolution. A prerequisite of any scale is the establishment of anchors for both end points and intermediate thresholds. Fuzzy classification reflects reality but is often a practical inconvenience. Appropriate resolution is always needed. The zero to ten scale is probably the most universally familiar one and has stood the test of time. It usually has adequate resolution and can easily be linked to a response categorization.

Given this ten-point scale it is relatively easy to visualize a nonlinear mapping function that covers the full range of outcomes from ideal to unacceptable. Examples include lighting, noise, temperature, spatial and force scales of design specification ranges. It is also possible to comprehend single and complex variables, although, for engineering design purposes the evaluation will ultimately have to identify individual variables for change. Where the relationships are not monotonic, as in the choice of an optimal temperature, then it is convenient to use two scales – one for hot, the other for cold. There may also be multiple outcomes – some of which might be conflicting. For example a spatial scale related to controls, such as vehicle pedals, may have movement time and inadvertent actuation conflicts. Such conflicts point towards the importance of consensus processes in the establishment of mapping statements and cut offs. The reality of human variability is such that a single mapping function will never be precisely “right.” Again the inclusion of human population accommodation policy in the consensus decision is essential to assure “buy-in” of all concerned as the design process develops.

Later, a 0, 1, 2, 3 outcome scale that mapped from measures of the physical or informational context to levels of stress on the operator, was developed for work analysis worksheets which provided sufficient resolution and with a small amount of practice became easy to use and consistent.

**Consensus**

The development of human factors design standards is best pursued through a consensus process, using the common currency described earlier. The credo that standards should be data driven is over simplistic. Policy, scientific logic, technical feasibility and experience must all contribute to the establishment of a standard. It is also essential that representatives of the customers – internal or external – who will have to apply or be affected by the standard should be involved. In this way up front agreement in both the principles and the values related to the standard will help to assure “buy-in” and less demand for waivers. Human Factors standards are also iterative in that they should be verified, validated and evaluated as the project or program evolves. An clear example lies in the establishment of speed limits for different road conditions.

Design tradeoffs should be made with a full global view of all the relevant information, preferably with a common communication currency. The choice of cut off points on individual variables can be used to assign explicit weightings. A broad range would imply wide tolerance (less importance) and a narrow range greater importance. The common currency outcome prediction scale facilitates the process of amalgamation. At the simplest level a count of the number of variables in each of the outcome ranges produces an index or profile that reflect the general nature of the problem. The count can also be used as a decision aid – for example decision policies could be “no reds” or not more than “5 yellows.”

Addition (as opposed to counting) is rarely justified, although this is the preferred method for some checklists. However the case for multiplication in the amalgamation process may be justified where interactions are likely. Such situations are best handled by two-dimensional matrices using the same common currency described here. The special case of interactions between basic variables and time may also be approached in this way. This big picture decision aid can be used to indicate before and after change situations, comparisons between alternatives or progress of a project through the design process.

The common currency scale can be viewed as an estimate of the “probability of failure on a single transaction”. For example the probability of “failure to accommodate” of a 12 inch wide seat would be of the order of 0.7. Similarly the probability of failure of a 2mm high font, given an elderly reader population could be 0.99. At the other extreme, the probability of failure of a 24 inch diameter escape hatch might be 0.05.

**Decisions**

The decision process must also involve benefit of the transaction, the number of transactions per unit time, the number of people affected and the various costs of failure. To complete the assessment an evaluation must be made of the costs, benefits and probabilities of alternative designs and outcomes. Where possible, objective evidence (including data) should contribute to the probability and costs / benefits and exposure estimations. Where individual, personal decisions are made then subjective probability and cost estimates may be sufficient – this is of course the basis of most naturalistic decision-making.

The hypothetical example of our choices of transport to work – car, bus or tank – can be used to illustrate the quantum decision process. Assuming a decision horizon – a day, year or project lifetime – all measures can be reduced to base ten arithmetic. In the case of choice of transportation mode based on cost and safety then the analysis shows that we should ride the bus. However, if we are the president of a country in political turmoil then we may wish to revise our probability, exposure, cost and outcome estimates and at least buy an armored car. This quantum arithmetic approach is appropriate for a cursory analysis and exploration of the sensitivity of the different elements of the decision to changes. Greater resolution may be obtained by including multipliers and decimal components, while still adhering to the basic decision logic. However in this case it may be appropriate to use some computational aid.

**Conclusions**

It is important to reiterate that it is the role of management or governments to communicate policy, given human factors evidence of outcome likelihood and effect. The role of consensus in the establishment of design standards was also addressed. In this respect it is important to address the realities of false consensus and the sometimes inappropriate or overly weighted influence of experts. The opinion of experts should always be weighted heavily, but only in the area of their expertise. A better approach is to use independent and interdependent “voting” processes, with sufficient allowance for discussion as the standard or decision scenario is developed.

The design of boats, trains, cars and space vehicles as most other human factors opportunities necessarily involves teams of one kind or another. Generally the teams consist of an exhaustive and exclusive “set” of people regarding technical and domain knowledge. Individual team members may have discrepant objectives. Team dynamics create challenges to both the effectiveness (accuracy) and efficiency (speed) of standard, risk and design decisions. Greater effectiveness and efficiency can be achieved through the application of common currency and clear visual aids to comparison, tradeoff and decision-making.

Even the decision processes common in contemporary design projects face the challenges of over / under reliance on expertise. On occasion the efforts to substitute process for expertise may also be counterproductive. Overly enthusiastic attention to “process” can be cumbersome, where simple experience may be sufficient. One hundred years ago craftsmen built outstanding automobiles, slowly. Nowadays, common processes result in the high volume production of automobiles. Hospitals used to be run by medical experts, now the processes of HMOs have diverted the purpose to a profit rather than caring motive. Soccer is essentially a game of experts, football has experts that are bound by processes. Music was once the realm of experts, now it is relegated to simplistic marketing processes. We went to the moon on the backs of experts; processes will get us to Mars.

Human factors is alive and well early in many design processes. The appropriate place for human factors is as a branch of engineering, not as an after the event“ergocop” in safety or consumer protection functions. Human factors is rightly a component of systems engineering, it can contribute important knowledge and tools both to the designs themselves and to the design processes. One important contribution is the establishment of a common currency for communication of human factors implications of design.

**Chapter 3**

**Buddies**

This article is about system behavior and performance involving two or more people, along with a discussion about some human frailties and their effects on buddy process outcomes such as effectiveness, efficiency and safety.

# SCUBA

Recently I took some lessons in SCUBA diving and took a trip to the Gulf of Mexico to view the wonders of the deep. Much of the SCUBA training, after you have learned how to breath, involves development of the buddy system, in which two divers pair up and perform many routine tasks together, provide for mutual surveillance and enable a rapid response in the case of an emergency. Essential communication is effected by a well-defined set of hand signals, such as thumbs up and down. A most important component of the SCUBA equipment is the alternate regulator connection from each system that can be used to supply air to a buddy in case it is needed. Shortly after taking my training I had dinner with a research colleague who was an avid SCUBA diver. Two weeks later I heard that she had drowned in an accident in which her regulator had become entangled in kelp and was dragged from her mouth. Her buddy was also a very experienced SCUBA instructor, but on this occasion, when the divers were engulfed in dense foliage, the system didn’t work. All complex systems consist of people, technology, processes, and unchangeable environmental, operational and temporal contexts. SCUBA is no exception, sometime the context wins.

# Truck Driving

Many years ago I looked out of my window across the road in Wellman Croft and saw a delivery van backing up. Behind the van was a little girl who had fallen off her bicycle and become entangled as she tried to stand up. I ran out of the house and was fortunate enough to attract the attention of the driver before he ran over the girl. Even more years ago, I used to talk to my uncle about his job as long distance lorry (truck) driver. In those days the British trucking industry was nationalized and one of the requirements was that all trucks should have a driver and a mate to deal with maneuvering in close quarters and to allow rest for the driver on long journeys. The ‘mate’ was required to get out of the cab and assist in all backing maneuvers. Nowadays a single driver is the norm although some companies supply extra mirrors so that the driver can see the area immediately behind the truck. Modern technology provides video and other exotic electronic (auto)buddies to facilitate the backing up process. “Beep, beep, beep”. Another recent pressure that may encourage companies to adopt two person truck crews is the reduction in the number of hours that an individual driver can drive. The advent of GPS makes enforcement of such systems much more feasible. Will the trucking industry become obsolete with the advent of drones, along with their contextual conundrums? Even drones need human managers, sitting in a little office watching a bunch of monitors.

**Manual Materials Handling**

Jumping forward some 40 years I became involved in the legislative controversy regarding the weight of a load that could be lifted by a single person. OSHA and NIOSH aspired to set standards that were effective, efficient and safe. Their principal challenge, as in all standards setting, was that of human, operational and contextual variability. Where should the line be drawn? The NIOSH lift equation is a brilliant, robust and (almost) comprehensive tool, that is quite easy to use. The trucking industry in the United States was adamantly against lowering the maximum weight, as this would require them to employ two people for each vehicle, which would greatly affect labor costs. Many objects require more than one person to lift. We have all moved heavy furniture at home and had to navigate around corners, through doors, and up and down steps and stairs. Building sites, domestic appliance wholesalers and retailers, forestry, agriculture and nursing homes all require more than one person to lift objects, if you can call granddad an object. Some objects have better handles than others, some do not have an equal weight distribution and some have awkward shapes. The lifting and carrying process timing is very critical and it is always important that the two buddies lift together and that the buddy walking forward does not push the buddy, at the other end, who is usually walking backwards, too quickly down the steps.

# Confined Space and Skilled Trades

Many construction and maintenance tasks involve skilled trades operators working in confined spaces or in situations where there may be a risk of falls, electrocution, toxic fumes or mechanical entrapment. In many of these situations devices and procedures such as safety harnesses and “lock out tag out” are required to prevent the inadvertent release of energy. These mechanisms plus the proximity of vigilant buddies can go a long way towards the prevention of accidents or to provide a quick response to a potentially dangerous situation. But sometimes these processes may be inconvenient and slow down the operation, so operators, with their buddy’s compliance, may circumvent the safeguards. A common feature of these buddy systems is that seniority plays a role in the (union) team decision-making, and this is where some problems may arise. “Votes equal opinion times salary.”

# Aircraft Cockpits

The complexity of aircraft cockpits is such that, at certain times of the flight, the workload is too great for a single pilot. Until a few years ago large airliners had two pilots and an engineer, but modern technology has reduced the need for the engineer. Very long duration flights may require another increase in the crew size, perhaps with teams that alternate between flying and resting. The duties of the crew-members are very refined and formal interactions (crew resource management) are required in many situations such as takeoff and landing. In mid flight, routine interactions are required to check for alertness, especially in highly automated cockpits. Even this buddy system has been known to fail as in the case of the NW 263 flight out of Detroit in 1993, where a checklist procedure failed catastrophically. Another cause of failure that has been cited is due to the fact that flight crews consist of a commander and a less senior pilot; which can result in inappropriate overrides, especially in cultures where seniority is perceived to be sacrosanct.

# Games

Baseball consists of a dynamically changing set of buddy teams. The pitcher and catcher conspire to assess strategy, but it is the pitcher’s responsibility to implement the strategy and the catcher’s job to compensate for pitcher error. The runner on first base collaborates with his coach and the runner on second. The outfielder collaborates with the basemen and a triple play is a festival of buddies. It is even rumored that the umpire may occasionally communicate covertly with the catcher in the discrimination between balls and strikes.

Doubles play at tennis, badminton and racquetball involves close collaboration between buddies. In two person team games, allocation of responsibilities changes frequently due to the rules of the game and situational expediency. Because such games are usually competitive, the final result of the game can strain the buddy relationships. Partner bridge and whist are complex games in which both formal (bidding and play sequence) and informal (nods and winks) communications are used to plan strategies. In another gaming circumstance each of a pair of “buddies” can choose to be cooperative or competitive to optimize their own personal outcome – this is situation is described as the “prisoner’s dilemma.” John Nash became famous for his exploration of competition and collaboration in economic games.

A simple Venn diagram can be used to describe the behavior of buddy teams. The buddies A and B, act as a team for those activities (AB) that they have in common. However A and B each have other lives - A and not B and B and not A, that may distract them from their primary responsibilities as buddies. Indeed these “other lives” may create such a pull as to result in the total dislocation of the buddy system. Continuing the metaphor, the compatibility, selection and training of the buddies may be such as to create considerable adhesion or in other cases repulsion. It pays to choose your buddy wisely.

**Reliability Estimates**

Bob went SCUBA diving 20 times and recorded the air pressure in his tank after each dive. Note that the air remaining in a tank is supposed to be enough to get you and your buddy back to the surface in a controlled manner. On 4 occasions, the air remaining in Bob’s tank was below the 500 psi safety margin. Therefore the average probability of “failure” is calculated as 4 / 20 = 0.2. As this is a sample of Bob’s habitual behavior, we estimate the 95% confidence limits of this point estimate by using the Normal approximation to the Binomial Distribution as: 0.2 ± 1.96 √(0.2\*0.8 / 20) = (0.375, 0.0245). In other words there is a chance that Bob will run out of air as many as 7 times out of 20 dives, or perhaps not at all. As we collect more data we can be more precise regarding Bob’s reliability as a diving buddy. In general terms we denote the probability of system success as Ps and of system failure as Qs = 1 – Ps. For convenience we can call Ps the reliability of the system. SCUBA diving failures are due to bad planning, bad behavior or, occasionally, bad luck.

# Buddy Theory

The behavior and performance of two person teams can be described by reference to Boolean logic, probability and reliability theory, with the complication of human idiosyncrasies of strategic allocation of function, inconsistencies and various levels of interdependence.

If two buddies (Bob and Ann) are carrying a large delicate showcase up the stairs and one buddy drops his or her end then the showcase falls and breaks. This is because the buddies are working in series and the reliability of the system is only as good as the weakest link. In algebraic terms:

Ps = Pa \* Pb = (1-Qa)(1-Qb)

Put another way Qs= 1 – Ps = 1 – Pa \* Pb,

where Qs is the probability of serial buddy system failure.

If Ann’s chance of dropping her end is Qa = 0.2 and Bob’s is Qb = 0.1 (based on observation of many previous furniture moving experiences) then the chance of the load being dropped is:

Qs =1 – 0.8 \* 0.9 = 0.28 or about once every three times.

so perhaps they should give up for the day and go SCUBA diving.

We can assume that the SCUBA alternate air source is a simple parallel or redundant system. If Bob runs out of air, he grabs Ann’s spare line and they move together slowly to the surface, with the admonishment that next time they should show greater buddiness by more closely monitoring the air pressure in each other’s tanks.

The reliability of a parallel system like this, where Qb = 0.1 and Qa = 0.2 is calculated as:

Ps = 1 – Qs = 1 – Qa \* Qb = 1 – 0.1 \* 0.2 = 1 – 0.02 = 0.98

This is much better than the serial reliability of carrying heavy things upstairs, even though the individual buddies had the same reliability. But is a 2/100 chance of failure a good bet where the outcome may be catastrophic?

# Outcomes and Contexts

Fortunately or unfortunately, as the case may be, all failures are not created equal. A system failure may vary from a minor inconvenience or delay to a catastrophic loss of life. Also, all benefits of reliable systems are not the same – getting to work on time by driving quickly and increasing the probability of system failure (getting a ticket or wrecking the car) may be perceived as being a fair trade. The systems analyst must therefore address the cost and benefit tradeoffs of subsystem failure and success if a rational conclusion is to be drawn.

The outcome may also be affected by the context. Missing an easy volley at match point in a tennis match may be more serious than a similar failure earlier in the game. Redundancies in complex systems also provide for “safety nets” for certain failure modes. In SCUBA if both buddies are low on air it may still be possible to carry out an emergency ascent, which results in various degrees of the bends rather than drowning. A pilot or co pilot may catch a mistake made by his buddy in time to avoid a serious failure. Dropping a heavy piece of furniture on a bare toe is likely to be more painful than if you were wearing sturdy shoes as a form of parallel subsystem redundancy.

# More Complex Systems

When we look at the truck drivers, scuba divers, flight crews or lock out tag out the processes may involve both parallel and serial activities each of which have their own intrinsic reliability and various contexts and outcomes. For example in SCUBA diving the buddies must be swimming close enough to share an air supply, in the airplane cockpit the co pilot must complete his own series of checks independently before he collaborates with the captain on a joint activity and in lock out tag out both workers must collaborate in the main process before reverting to other parallel and serial roles. In truck driving the buddy may wish to sleep after a long driving stint; this then reduced the reliability of the temporary system to a single point failure.

The reliability of serial systems can be improved by the different system elements having their own parallel redundancy. Great strides in SCUBA safety were made when the alternate air supply became standard equipment. Before this time the emergency system was stressed by buddies having to share a single air supply – you really have to trust your panicking buddy to return your mouthpiece when you are 100 feet under water. Conversely the reliability of parallel systems deteriorates when the parallel systems have their own serial vulnerabilities. For example in the aircraft cockpit, if each of the buddies has to perform a long series of independent activities before combining on a joint system check the very vulnerable short term memory may reduce overall system reliability.

The US constitution suggests that all men are created equal and the democratic voting process underscores this where all votes carry the same weight, providing the voter is deemed legitimate by the managers of the vote before or after the event. In reality, buddy systems often ignore this mandate through the development of dominance and unwritten rules. In fact large organizations generally rely on hierarchical dominance, euphemistically called leadership. Votes equal opinion times salary. Majority voting and dominance complicate the analysis of system reliability and sometimes it is expedient for democracy to give way to dominance and the unequal division of labor. This is where groups, which consist of independent but interacting individuals give way to teams which consist of interdependent and interacting individuals.

A familiar characteristic of human buddies is that they vary in their reliability in different contexts and over time. SCUBA buddies, manual materials handlers and airline crews get better with practice, but deteriorate with fatigue. Buddies may behave and perform differently when under contextual stress. Flight crew simulator training deliberately addresses rare, but potentially serious contexts.

Unequal buddy teams are the norm. If the buddy can’t swim fast enough in SCUBA he had better not run out of air. In doubles tennis, the opponents will exploit the weaker player. In truck safety the vigilant eyes of the passenger may not compensate for the slow brake foot of the driver. In the aircraft cockpit seniority may be a double-edged sword. Don’t assume that your buddy has switched off the circuit breaker before you remove the cover of an electrical outlet. Inequality among buddies and their assignments generally leads to the reduction of parallel redundancy and therefore a reduction in system reliability.

Another look at Bob and Ann can shed some light on this matter. Suppose that Bob and Ann go for a bicycle ride in the mountains – they have created a serial dependency – the reliability of the system (getting home before dark) is only as good as the slowest rider. When they get home they start to move furniture so Bob who is stronger than Ann takes the heavy end. Unfortunately as they were going up the stairs the piece of furniture hit a light fixture and broke it, so off they went to the hardware store to get a replacement. There are now contextual and time problems – it is dark, light is needed to do the job and the circuit breaker puts out all the lights in the area. Should they dispense with lockout – tag out or go back to the hardware store to buy flashlight batteries. Dominance rules and they arrive at a false consensus – Ann will go for the batteries, meanwhile Bob will get the job started without turning off the breakers. Ann has a flat tire and the whole buddy system reliability goes downhill rapidly. The system reliability analysis demonstrates a whole sequence of independent, interdependent and sequentially dependent activities.

# Analysis Tools

In practice even two person buddy systems can get very complicated when there are many parallel and serial subsystems. Fortunately there are well-established methods that enable us to analyze the complex probabilities of system reliability or failure. First it is appropriate to use some flavor of Failure Modes and Effects Analysis. This process consists of examining all the components and activities in the system to identify the context, cause, probability and outcome of any possible failure. It is usual to use charting methods, block diagrams and logical arguments to break down the complex system. A simpler version of FMEA is the “Five Whys” method. This consists of asking a sequence of “why did or how could this happen” questions. For example in the case of truck driving the first question could be “”why did the truck run off the road” to which the possible answers could be “because the brakes failed” or “because the driver went to sleep”. The analyst would delve into these separate failures by asking such questions as “why did the driver fall asleep?” The response that it was because his buddy was not vigilant in his surveillance duties could lead to many other questions.

These qualitative methods have been formalized through the development of fault tree analysis, which consists of a tree structure of parallel and serial logic gates that carry the analysis from somewhat quantifiable base event probabilities to a particular conclusion or outcome. Contemporary software tools such as FAULTREASEC allow the rapid construction and revision of large logical trees and the calculation of the overall system failure probability. But even these powerful systems are themselves only as reliable as the particular model and the available data.

# Cooperation and Competition

In practice there is a continuum from completely cooperative to completely competitive. It is probably as important to choose your enemies, as it is your buddies. In a simple competitive two person zero sum game one wins and the other loses, over a long series of games:

Pa = 1 – Pb or Pa + Pb = 1 = Ps

In simple parallel or serial cooperative systems if both buddies are completely reliable

Ps = Pa \* Pa = 1 – (1 - Qa)(1 – Qb)

# Choose your Buddies

It is not always possible to choose your buddies. Sometimes buddy choice is serendipitous. Your best SCUBA buddy is the nearest one with an air supply. Commercial airplane flight decks with their seniority and choice systems mix buddies all the time. Bridge players do better with their preferred buddies. Always lift things with someone your own size otherwise you may get the heavy end. Always put two people in a truck.

**Chapter 4**

**Why did the Chicken cross the Road?**

Why did the chicken cross the road? To get to the other side! Or so the old joke goes. Why did the self-drive car crash? Because it was too late seeing the chicken and it did not know that this was a common chicken crossing area and it was late at night, raining and slippery and the tires were worn and the driver / monitor was in a hurry to get home, under stimulated, drunk, on pain killers, fatigued, complacent, inexperienced or maybe asleep. Furthermore the vehicle was last year’s model without the updated sensor technology or software and anyway, the driver was baffled by the interfaces with this new technology. A Fault Tree Analysis (Peacock, 1982) would put all these conditions together and conclude that the chicken or driver should have stayed at home.

Another model, SHEL (Edwards,1964), of system behavior and system failure would describe interfaces, interactions, interruptions, interferences, interdependencies and integration within and among people (and chickens), technology, processes and contexts. An expansion of the SHEL model adds energy, information, space, time and purpose. That said, the transition to self-driving cars, supported by ever increasing and improved technology, will take a long time. This transition period will inevitably involve interactions among the self-driving cars and conventional vehicles. The only constants will be human and situational variability. The $64,000 (or greater) question is when, probabilistically and politically, the failure rate of self-driving cars will be demonstrated to be lower than the failure rate of conventional vehicles. The lawmakers will have a field day developing constraints and conditions for this newfangled technology, including segregation and driver / monitor training and certification.

Systems designers would realize that the many and various stakeholders in this complex system - drivers, passengers, chickens or other pedestrians, road builders, traffic managers, emergency services, vehicle designers etc. might have different and perhaps conflicting priorities related to system (and process) design purposes and outcomes. The E4S4 model summarizes these (arguably exhaustive and largely mutually exclusive) expectancies and outcomes: Effectiveness, Efficiency, Ease of use, Esthetic appeal, Safety, Security, Satisfaction and Sustainability, which may include both reliability and resilience (Peacock, 2004). For example, the driver may have wanted to get to his destination (effectiveness), quickly (efficiency) and safely while riding in his fancy new automated car (esthetic appeal). The emergency services would be out of business if the system didn’t fail from time to time. And the vehicle manufacturers would soon go out of business (sustainability) if there were too many failures that they couldn’t blame on the drivers. It remains to be seen when the lawyers will focus on the designers rather than the drivers / monitors of these non-segregated vehicles and routes.

Pavlov (1927) had something to say about this situation having focused on salivating dogs rather than jay walking chickens. Pavlov suggested that if the experimenter rang a bell at the same time as providing food, soon the dog would learn to respond (by salivating) to the sound of the bell (an alternative stimulus) in the absence of the food. Dogs, but maybe not chickens, can learn to put two and two together, all they need to get to Carnegie Hall is practice, practice, practice (often attributed to Jack Benny). Chickens, on the other hand, can run, perhaps in random directions, with their heads cut off; there are various peripheral and spinal connections that make this possible! Franciscus Donders in 1869 demonstrated that there is a delay (reaction time) in response to a stimulus. Other researchers have shown that (choice) reaction time is affected by the complexity (number of choices) of a signal. Koster and Peacock (1971) determined that this response was further delayed when the signal of interest was preceded by an intense signal - psychological refractoriness. Sometime later Peacock (1972) determined that if there was too much time between the stimulus and the response then there was the opportunity for interference in the retention of the first stimulus; furthermore this (retroactive) interference could also be complicated by proactive interference, especially from intense or otherwise interesting stimuli. These observations are all well and good in the reductionist, controlled, laboratory context. But can a chicken pay attention to the noise or sight of the rapidly approaching car, perhaps based on practice, and take timely evasive action? Or go to the crosswalk? People, like chickens are subject to distraction; from time to time they do not pay attention to important signals. Sometimes they are in a hurry.

A key to all this behavior, especially in the case of people, is the innate and acquired ability to pay attention, perceive, think and anticipate, to prepare for any one of various actions ahead of time and then (re)act in a timely manner. In other words we learn from experience or, better still, learn by being taught, having had a similar transferable experience, reading a book, searching the internet or simply thinking about it. The processes of anticipation, attention and perception presuppose a more or less well developed mental model (framework) that is used to explore and simulate information regarding the sources and effects of various external or internal inputs over time, various model parameters and various outcomes. Sometimes the desirability of a particular outcome outweighs the risk of failure, with catastrophic consequences. Sometimes there are just too many factors related to the decision (to cross or wait) that the poor chicken becomes overwhelmed and just “goes for it”. The Bayesian, (Bayes, 1763), community has much to say on this problem, although the human capacity for forgetting makes them generally sub-Baysian. Another problem for the chicken, people with chicken brains and even ordinary people is this word “various.” The earlier described complex systems model - people, technology, procedures, contexts and their interfaces, interactions, interruptions, interferences, interdependencies and integration - is incredibly complicated by variability within and among all these components. Furthermore, these situations are replicated all over the world (places), all through the day and night (times) and involve millions of people and transactions. No wonder people have accidents from time to time or are blamed for causing accidents, especially those playing chicken with the traffic. As suggested earlier, this probabilistic problem will be interpreted politically.

The matter of interest here is the viability of self-driving cars (primary technology) without the concomitant design, integration and otherwise management of all the supporting technology (including roadways), contexts (weather, traffic, pedestrians), procedures (drive on the right, keep a safe spacing, obey traffic signs and signals etc.) and the selection, training and assignment of all the primary, secondary and tertiary stakeholders. The solutions are technical, economic, political, legal and probabilistic. Segregation is or is not an option? Are self-driving cars safer statistically than conventionally driven cars? The lawyers are happy to assign blame and sue errant drivers. But who will they sue when the automated system fails, albeit less frequently? The driver / monitor, the traffic management, the designer of automation, the company that designed the vehicles or the traffic managers that permit the integration of automated vehicles. Of course the lawyers will find a way and the self-driving car manufacturers have deep pockets, albeit full of equally cunning lawyers.

So we are back to probability and statistics, perhaps even Bayesian models if the lawyers can estimate the likelihood of a particular event given the existence of other (also probabilistic) evidence. The juries may not have studied Bayesian convergence and so may revert to simpler statements of likelihood and the assignment of blame when the system fails, depending of course on who suffered the unwanted outcome and who is lined up to defend the failed system components. The applied psychologist or human factors / ergonomics practitioner or researcher may again fall into the trap of reductionist research and analysis. The astute safety practitioner will apply the 5 Whys, and end up with 5 to the nth power explanations. Meanwhile, in the absence of latter day Luddites, technology will develop until the automatic driving machine brains have learned, not only to learn from past experience and selectively take in (perceive) relevant and timely information but also to anticipate and make (probabilistically) sound decisions, just like or event better than drivers. Unfortunately, chickens will continue to cross the road out of habit and get to the other side, until that unfeeling automatic car decides to sacrifice the chicken as braking hard is more dangerous (to the car occupants rather than to the chicken).

This was a very brief discussion of human cognition, attention, behavior and performance; the challenges of automation and chickens would not be complete without some case studies to explore the underlying theories:

1. The first situation is a crossroads consisting of two three lane divided highways with sidewalks on both sides. It is six o’clock in the evening and going dark. The roads are full of tired and impatient drivers and pedestrians on their way home from work. It is raining cats and dogs and beginning to freeze. Fifty percent of the cars and large trucks have various generations of self-drive technology. The traffic lights have failed and a lone policeman has stepped into the breach. The automated vehicles do not comprehend the subtleties of the policeman’s glances, nods and hand waving. Half the automated vehicles resort to manual control. The other half make a mess of the intersection, blocking the way for the automated emergency vehicle. Meanwhile the early nightly news drone hovers to capture the details of the carnage.

2. The next situation has a genius seventeen year old riding in his parent’s automated car. Now this seventeen year old has spent 90% of his waking time playing video games, that are filled with exciting system failures, and has become immune to the realities of mass and acceleration. He (auto)pilots his way onto the freeway and joins the fast track. He decides to take over from the automation, with disastrous consequences.

3. A third scenario involves grandma, who uses her newfangled golf cart sized technology to go shopping, just along the street. At the same time the automated garbage collection truck is performing its start - stop regime in the neighborhood and cannot tell the difference between grandma in her private pod and the garbage bin.

These examples are offered to explore the limitations of technology and its applications, especially where it interacts with people of different abilities and motives, in different contexts.

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**Chapter 5**

**Death and Taxes**

There are two certainties in life – death and taxes. This article is also about natural laws – aging and gravity, and man-made laws and ‘ergonomic’ dogma. They all apply to everybody. We are not very good at these challenges but valid ergonomics intervention can help to analyze the problems and lighten the load.

**Aging**

The general problem of aging is that many human systems and sub systems show a functional decline and, to make matters worse, these systems often interact to compound the resultant performance problems. Sehl and Yates (2001) carried out substantial research on individual biological system decline rates. Over the years 40 to 70 our musculo-skeletal, endocrine, cardio vascular systems etc. decline at an average (linear) rate of about 2% - 3% per year, the exact rate being somewhat influenced by nurture. Peacock (2016) reported on the use of athletic records to delineate the boundaries of aging, and noted that when the age range is extended to 100 a nonlinear decline is observed. Nurture is also a big player in tooth decay and a massive industry has grown to prop up or replace our pearly whites. Joint replacement is now commonplace, as also are hearts, blood vessels, lungs and skin. The declines in our sensory systems are legendary and eye and ear doctors apply very sophisticated technology to counter this deterioration. Our cognitive systems – attention, perception, memory, decision making, and learning have no such prosthetic solutions (as yet), although smart phones offer a plethora of (sometimes) easily accessible, situationally pertinent information to reduce our mental workload. The Internet has an enormous fund of information, much more than any individual will ever use or need. However technology aimed at the general (above average) public can often bring its own barriers and hazards to the less gifted often older users. Information on the Internet is not always easy to access or use, and sometimes it may even be “fake”. The confluence of physical and cognitive decline often gives rise to a decline in our social interaction capabilities that are offset somewhat by combinations of community and family interventions. The only reliable recourse is to exercise our bodies and minds if we wish to reduce the rate of inevitable decline. Unfortunately, disease processes associated with aging can hasten system deterioration and hence compromise performance capability.

One general response to the [gradual] decline associated with aging is to [gradually or abruptly] change our behaviors. We reduce our performance goals and are happy when we continue to achieve success. We give up running because our knees hurt and we ask our grandchildren to help us thread our sewing needles. Our roles as parent and protector are reversed as we age.

**Taxes**

Less than 50% of the US population develop and submit their own tax returns. Furthermore a majority of tax returns, even those completed by specialists, have errors of one kind or another (Peacock et al, 1993). These authors conducted a study in which the format of both the tax forms and the instructions were rationalized according to general ergonomics principles – larger spaces for entries and rearranged instructions for easier search and links to entries. These alternatives were presented to subjects with varying levels of experience – from novices to experienced tax accountants. Completion times and errors were recorded for returns of various complexities. One finding was that the effects of form and instruction (interface) changes were minimal among the experienced tax preparers. The implication is of course that it is the cognitive challenge of the tax laws that is the main culprit and that improvements in interface design can only go so far in improving performance among less practiced individuals.

The dual purposes of display design are to extract and communicate situationally pertinent system data and, where possible, to present abstractions, combinations and derivations of the raw data in order to reduce the cognitive load. These so called composite displays can enhance attention, reduce memory load and guide decision making. For example in aviation displays one can automatically derive density altitude by combining pressure and temperature information. Fuel consumption displays can be converted to predict vehicle range, given assumptions about future driving behavior. In the tax return situation the use of a computer program can prevent calculation errors, particularly those errors that are induced by frequent page turning and cross referencing during the hectic hours of April 14th. The computer can also check the validity of raw data entries by flagging unlikely values such as an extra zero here or there.

But even with all these packaged computer programs for tax return preparation, the portion of tax returns completed by individuals has not increased substantially and the number of errors remains high. The culprit is still the ever increasing complexity and loop holes in the tax laws which are accompanied by the inevitable cry for tax law reform (the cognitive challenge). Aviation displays have progressed from the traditional “six pack” to an integrated glass cockpit which provides a more holistic view of the many variables associated with flying in the context of unforgiving gravity, weather and traffic congestion. As with tax returns the opportunity for error is a function of complexity but, in flying, the outcome may hurt more than your pocketbook.

**Are you sure that what you just said is true?**

The time honored process of measuring human performance and its modifiers, such as the physical and cognitive effects of aging and the relationship between performance and income tax form design, is to obtain a random bunch of subjects and assign them to the different categories identified as independent variables of interest. Then run the experiment, analyze the data and make wild generalizations and extrapolations about the differences and associations that are attributable to cohorts or formats of interest. Research trained ergonomists are sometimes cautious about the last part, but many ergonomics practitioners may forget all about experimental design, assumptions of normality, randomization, personal biases etc. and they often choose convenient subject samples of insufficient size. Their conclusions may not be “true.” Common causes of untrue conclusions are to be found in the concepts of construct, sample and contextual validity. Generalizations about aging are mired in a mess of individual and situational variability. The tax laws continue to outpace most of the user population and the skies are becoming as congested as the roads. Complexity rules!

It is well known (that’s a dangerous statement) that aging effects can be offset by exercise. Sages may point out that it is not the aging process per se that is affected, rather it is the effect on concomitant factors such as disease or disuse / abuse atrophy that allows performance levels to be above (or below) the observed “population averages” for that age cohort. Examples include the ability to walk upstairs (which is affected by one’s history of exercise and eating) or hear conversations in a busy restaurant (following a career in a stamping plant). Filling out the EZ tax form, when you no longer have dependents, mortgages, second jobs, second homes and multiple investments, indicates a natural adaptation to the cognitive demands. Hardly a day goes by without an advertisement in the mailbox offering a “free” lunch in return for long term tax and money management advice. The aviation industry is swamped by great gadgetry that addresses many of the separate challenges of flying, (autopilot, ADSB, synthetic vision, highways in the sky etc.) but cannot deal with situational complexity. Fortunately one manufacturer now offers a parachute with its smaller products. I suggest that we should invest in parachute technology for the commercial and private Unmanned Aerial Systems of the near future.

**Aging, Gravity, Taxes and Ergonomic Dogma**

Aging, gravity and taxes are inevitable hurdles for all people. Ergonomic dogma should not add to the challenges. Ergonomic dogma suggests that we should reduce the physical and cognitive demands faced by older people (of all ages) by design to assure both immediate and continued success. On the other hand the conventional wisdom and research data of geriatricians indicates that longer term success will be assured by continuing exposure to physical and cognitive demands, albeit with the aid of “parachutes” – that is to rely on individual’s ability to learn from experience.

The most basic of “physical ergonomic inventions” - the chair, the wheel and the engine all have their place. They are highlights of contemporary society that are accompanied by a “parachute” – medicine that remedies the human effects of abuses of these devices. Unfortunately the long term effects on the environment have no equivalent parachute. Or at least none that appears to be generally acceptable. The chair, the wheel and the engine are less used in primitive societies, but unfortunately their success, as measured by longevity, is hampered by more fundamental challenges – diseases, which are preventable and curable by the appropriate deployment of modern medical knowledge. This deployment can be helped by ergonomic analysis of the process. The iatrogenic effects of contemporary ergonomics – disuse atrophy in a general sense – are due to ergonomists paying lip service to issues of short term comfort, convenience and productivity without due regard to longer term.

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**Chapter 6**

**Facilitator Design**

**Background**

This is not about the Hippocratic Oath (first do no harm); rather it is about the hypocrisy of engineers, scientists and operations managers in their attempts to patch the interfaces between their designs and the end users. These patches are euphemistically called facilitators and cover a spectrum of devices such as labels, warnings, instructions, procedures and a plethora of other so called job aids. Modern computing technology has now made available the rich medium of augmented reality to facilitate the activities of the human operator.

**A facilitator is a temporary device used to supplement the user’s knowledge or current situation awareness to ensure an accurate and timely transaction.**

For example, a label on a switch that says on/off obviates the need for the operator to know which way to move the switch; after using the switch a few times the user no longer needs the label. Warning signs on the edge of the Grand Canyon caution the adventuresome tourist to “Be careful.” Labels on food and drugs present a frequent challenge to manufacturers who have to strike a delicate balance between advertising their product and avoiding the consequences of misuse. An augmented reality example is the yellow line on the computer screen to mark the ten yards needed for a first down in football and the chains which are the (10)yardstick. In this example, the facilitator is used regularly, because the human judgment of the 10 yards is unreliable. On the International Space Station the crew members have to perform many complex system and payload tasks, and respond to contingencies which may escalate into emergencies. The complexity of these tasks is addressed by extensive training and the even more extensive use of facilitators. The usage and utility of facilitators (such as procedures) depends on the degree and currency of training at the knowledge, rule or skill level (Rasmussen, 1987 – *Cognitive Control and Human Error Mechanisms* in *New Technology and Human Error* edited by J, Rasmussen, K. Duncan and J. Leplat). At Christmas time, parents are often faced with the dreaded messages “some assembly required” and “read me first.” Mothers do as they are advised; fathers, who know about these things, put the instructions on one side.

The key, as with medicine, to good facilitator design is to “first do no harm.” Harm in this context includes inaccurate, cumbersome and untimely advice. However this raises another common human factors engineering dilemma – the speed-accuracy tradeoff. Commonly instruction and procedure designers err on the side of accuracy, by expanding detail, and sacrifice speed. Conversely, label and warning designers often favor speed (or space conservation) in their use of acronyms and symbology, and may sacrifice accuracy, and, because of the subsequent need for recovery, ultimately they may also sacrifice time. Perhaps the greatest mistake made by designers is the pseudo sacred cow of standardization. There are two fundamental reasons why standardization is not universally useful in facilitator design. First, not all problems are alike and second, not all users are alike. Trying to fit a medical emergency procedure into the same format as a hardware maintenance or assembly procedure begs the question of the level of training and knowledge of the user. Also the obsession of many organizations with technical jargon and acronyms often overestimates the knowledge of the non specialist user. A prime example of this issue is with the international crews on board the ISS, whose language differences impair the effectiveness of acronyms. On the other hand, certain conventions and forms of standardization have their place – a prime example being the familiar “Windows” interface.

**The Human Factors Approach**

The human factors engineering community approaches this challenge of the bridge between engineering or operational designs and the user in a number of ways. The first level is through the design of the permanent displays and controls that are normally essential for successfully carrying out a transaction or procedure. The second step is to carry out a task analysis that addresses the sequences of information and actions that comprise the transaction, including the human and system contributions. The third step is to assess the conditions and context of the transaction(s). The fourth step addresses the knowledge and skills of the intended user – it should be noted here that users’ capabilities change with practice and may fluctuate with the conditions under which a particular transaction takes place. The final analytical step is to evaluate expected use and possible misuse of the interface or procedure. This step should involve formal “usability testing,” in which users of varying degrees of knowledge, skill and experience perform representative tasks, under a variety of conditions and contexts with a candidate set of facilitators. Facilitators should first be designed with due regard to the expected users, possible misuses and likely conditions, and should then be subject to formal evaluation.

These analytical activities lead to the design of facilitators to fill the knowledge and skill gaps. Because conditions and users vary, it is necessary to include flexibility in facilitator design, while remembering the important rule: “first do no harm.” In the context of facilitator (e.g. procedure) design, ‘harm’ includes both inappropriate action as a result of the design, with various possibilities of outcome from minor inconvenience to catastrophe, and unnecessary delays in the transaction caused by the verbatim following of the procedure. It should be noted that errors in the use of facilitators (procedures) commonly cost recovery time, which in turn may lead to catastrophe in a time constrained condition, lack of productivity or simply frustration in “being treated like a child.” Unfortunately these possible outcomes are affected in their likelihood by the particular user, conditions and contexts, thus making evaluation a probabilistic process at best.

**Some Cases**

In case the reader is skeptical about this discussion he should consider the NW255 accident at Detroit Metro Airport in 1987:

*About 2046 eastern daylight time on August 16, 1987, Northwest Airlines, Inc., flight 255 crashed shortly after taking off from runway 3 center at the Detroit Metropolitan Wayne County Airport, Romulus, Michigan. Flight 255, a McDonnell Douglas DC-9-82, U.S. Registry*

*N312RC, was a regularly scheduled passenger flight and was en route to Phoenix, Arizona, with 149 passengers and 6 crewmembers.*

*Of the persons on board flight 255, 148 passengers and 6 crewmembers were killed; 1 passenger, a 4-year-old child, was injured seriously. On the ground, two persons were killed, one person was injured seriously, and four persons suffered minor injuries.*

*The National Transportation Safety Board determines that the probable cause of the accident was the flightcrew's failure to use the taxi checklist to ensure that the flaps and slats were extended for takeoff. Contributing to the accident was the absence of electrical power to the*

*airplane takeoff warning system which thus did not warn the flightcrew that the airplane was not configured properly for takeoff. The reason for the absence of electrical power could not be determined.*

In this instance, the use of a checklist – a facilitator – was complicated by the crewmembers’ considerable familiarity with the procedure, a failed warning system (another facilitator) and the unforgiving context.

Closer to the interest of space human factors are the comments from an astronaut:

*The biggest issue with all of the Payload experiments from a Human Factors perspective is that the procedures are too lengthy and are not clear (they read more like an airplane checklist as opposed to furniture assembly). The crewmember thinks they need to use fewer words and more line diagrams/drawings. They perceived this as a common problem for all payload procedures during training and on-orbit. The procedures typically resulted in very slow and inefficient operations (ex. was 20 pages telling how to remove a screw.). They mentioned that they did comment about this in other briefings also. They stated that someone should take ownership of this issue and coordinate with all payload developers to simplify their procedures.*

*A lot of time and productivity is lost when the crew has to follow airplane checklist-style procedures (e.g. Medical, Payloads, and IFM.)This style of procedure writing increases the chance of errors. Simple, clear, line drawings with a few words are best for efficient procedures.*

*But the biggest issue with Payloads is that too many acronyms in a multi-lingual environment will cause confusion among the international crewmembers. It was not a problem of inaccurate/incomplete acronyms, but that there were “way too many” acronyms used for the hardware. They suggested that it should be stressed to the engineers to not use acronyms if at all possible and to spell out a name that describes what the hardware/system is and “stick with it”.*

**Previous Work**

Bailey (1982) – *Human Performance Engineering: A Guide for System Designers (Prentice Hall)* - presented an extensive discussion of facilitators, including their role in supporting human performance, selection of facilitators, the design of instructions (procedures) and other performance aids. Facilitator designers who heed Bailey’s advice and rules of thumb will go a long way towards achieving acceptable facilitators, but it is clear that many designers do not consider this advice or use their own flawed common sense to supplement their designs with facilitators. There are many other examples of “good” labels, warnings and instructions, often stimulated by “failure to warn” law suits. An extensive bibliography of research in this area is contained in Miller, Lehto and Frantz (1990) – *Instructions and Warnings- An Annotated Bibliography.* The American National Standards Institution (ANSI) and the International Standards Office (ISO) both offer extensive guidance on instructions, warnings, and labeling, usually in domain specific contexts.

<http://www.ansi.org/>

<http://www.iso.ch/iso/en/ISOOnline.openerpage>

NASA Standard 3000 (6.4.3.3.4) states simply that “Warning labels shall be provided where potentials are hazardous to crewmembers.”

Despite this extensive activity, facilitators (labels, warnings, instructions and procedures) continue to be a major source of system failure, inefficiencies and personal frustration in many domains.

**Research, Measurement and Analysis**

Whereas there are many “rules of thumb” for facilitator design there is no robust theory of the pervasive role that they play in everyday life and particularly in technical areas. Such a theory must address level of complexity, outcome / recovery importance, human and contextual variability, including learning, and the speed-accuracy tradeoff. Measurement of the use and utility of facilitators must consider the human capabilities to learn and forget. Analysis of facilitators requires tools that can be used both by researchers and designers to evaluate the effectiveness of alternative ways of aiding human performance.

Another research opportunity lies in understanding the relative roles and interactions among of system designs, human learning and facilitators. For example facilitators can become crutches that interfere with knowledge or skill acquisition and result in human performance shortcomings in the absence or other deficiencies of the facilitator. Reliance on contemporary vehicle navigation technology is a case in point.

**Modeling and Development**

A simple model of a facilitator places it between the varying demands of a system design and the varying capabilities of the human operator, with the purpose of assuring that the human capabilities will not fall short of system demands. Such a model although conceptually meaningful fails to capture the specific form and content of a facilitator, given the environment of complexity and variability.

**Requirements and Design**

The literature cited earlier presents many considerations, guidelines and standards for the design of facilitators, but these are rarely supported by clear system performance requirements. Consequently many facilitators are designed as an afterthought and are refined iteratively following untoward incidents or user comments. Most facilitators are static in nature and do not address the changing needs of users as they become more familiar with system behavior. There is a need therefore to develop facilitator performance requirements and detailed system and facilitator design specifications to assure safe and productive human performance.

**Implementation and Evaluation**

All system design processes should require the integrated design of facilitators along with formal assessment of expected human performance and performance variability. The changing role of facilitators should be evaluated as the system is validated in an analog or operational context. Formal guidelines and evaluation protocols are needed for the implementation of facilitators.

**Integration**

Facilitator design needs to be formalized and integrated into the system design process. This integration requires answers to the research, modeling, design and evaluation questions described in the previous paragraphs.

**Opportunities for Focus**

There are many opportunities in which facilitators play a key role in system effectiveness and efficiency. The first area is in the management of its complex activities and its notorious reliance on acronyms, despite the often observed speed accuracy tradeoff. As in aeronautics, space operations rely heavily on procedures and esoteric jargon for its vehicle operations. Assembly and maintenance of space vehicles is engulfed in labels, acronyms, instructions and procedures all of which contribute to the possibility of catastrophic system failure, inefficiencies and inconvenience. Space vehicle payloads are notorious for their use of cumbersome and inconsistent procedures. Finally the medical treatment procedures, full of jargon in English and Russian, and supported by minimal training, are a time bomb waiting to explode.

**Chapter 7**

## **How long does it take to stop a truck? – Newtonian Moments**

## **Newton’s Laws (Hibbler, 1983)**

1. A particle, originally at rest, or moving in a straight line with constant velocity, will remain in this state providing the particle is not subjected to an unbalanced force.

2. A particle acted upon by an unbalanced force, F, experiences an acceleration, a, that has the same direction as the force and a magnitude that is directly proportional to the force.

# If F is applied to a particle of mass m this law may be expressed mathematically as F=ma

3. For every force acting on a particle, the particle exerts an equal, opposite and collinear reactive force.

## **Rugby and Needles**

Picture this. In rugby union football the number 9 player (the scrum half) is usually small and the number 8 player (the loose forward) is generally big. One cold day about 50 years ago a small number 9 put the ball into the scrum, which wheeled (rotated) right, and ran round to the back to pick up the ball. He pretended to throw the ball towards his colleague (number 10), but then quickly turned to sneak around the “blind side” of the scrum. Now as the scrum had rotated the number 8 of the defending side was hidden from the eagle eye of the referee, who was watching the scrum half; the number 8 was therefore able to stand up and break a little too quickly from the scrum. The small number 9 ran nimbly but the tall number 8 stuck out his stiff left arm and caught the small number 9 around the neck. Now the small number 9’s legs kept running, but his upper body did not, so he fell on his back with a hard thud. This small particle, mass m1, originally moving at a constant velocity v1 (or perhaps accelerating a little) was met by a large particle, mass m2, and history is blurred by posttraumatic amnesia. The pertinent law here is that of the conservation of linear momentum m1v1 = m2v2.

The small particle was a slow learner and often lacked situational awareness. A short time later, while playing “touch rugby” he made a feint to the right, side stepped back to the left and was free and clear until he ran into the goal post. This equal and opposite force led to an even more traumatic demonstration of Newton’s Laws. After stitching up his split lip, the ER nurse instructed him to drop his trousers for a tetanus injection. If any of you know how to insert a sharp object through skin, subcutaneous tissue and a couple of inches of gluteus maximus you will realize that it is important to impose a high velocity on the small needle in order to minimize the pain. But the nurse, who was a professional colleague of this captive patient, at the Birmingham Accident Hospital, deliberately ignored her physics lessons.

**Moments**

Newton’s findings were pretty important, but as these examples show there are complications that have to be dealt with by other mechanical principles. For the tall number 8 to put the impudent number 9 on his back, he had to impart a turning moment to the small particle by aiming the stiff arm some distance from the small particle’s center of mass. Many sports injuries are caused by a combination of Newton’s laws and the mechanical advantages offered by moment arms. Some, like skiing into a tree or heading a soccer ball are direct examples of Newton’s principles. Games played with racquets and bats and feet and hands make great use of moments. How can a pitcher throw a ball at 100 mph? How can a golfer hit a drive over 300 yards? Long before Newton – a few hundred years BC to be exact – Archimedes was relaxing in his bathtub, thinking about how to move the earth. Being an empiricist, he suggested getting a very long piece of wood, anchoring it under the earth and over the moon and then getting his buddy Phidippedes to run along the lever until his weight was sufficient to move the earth. Archimedes discovered that a moment is calculated by multiplying the force by the length of the lever arm, but would Phidippedes have been weightless when he got to the end of the lever?

## **Friction**

Another mechanical principle that was demonstrated by the needle incident is that of friction, which is helpful in stopping things. The amount of frictional resistance to motion depends on two things. First there are the characteristics of the two surfaces. The coefficient of friction, µ, takes on a value between 0 and 1 or a little more if we introduce adhesion into the discussion. Also there are the normal forces (N) applied to the objects in question. Thus the limiting static frictional force, F <= µN, Now ice has a pretty low value – the coefficient of friction between metal ice skates and ice is about 0.04, whereas that between two pieces of wood is about 0.5. If we rub two pieces of aluminum together we may see coefficients as high as 1.5. I suspect that the frictional resistance to a needle penetrating soft tissues is somewhat higher! Slips and falls, because of low friction surfaces, cause very many accidents. Trips and falls, on the other hand are caused by large moments.

## **Fork Trucks**

So how long does it take to stop a forklift truck and how far will the truck have traveled before it stops? Well first of all, the driver has to be able to recognize that it would be wise to stop. This decision is hampered somewhat by high loads or broad “masts” while the driver is going forward, and the reliance on peripheral vision while driving backwards. This visual part of the story is sometimes amplified by poor factory layout and lighting and the fact that most fork truck drivers have high seniority (age) and often deteriorating eyesight (driving the trucks is a desirable job when compared with working on the line). The next part of the reaction process is moving a heavy boot to the right pedal (unless a rocker pedal is installed). Then Newton and friction and a few other mechanical and fluid principles take over. The floor may be composed of oil soaked wooden blocks – a coefficient of friction between 0.1 and 0.3 between this floor and the solid rubber wheel. But fork trucks, especially loaded ones, have a big N – the normal force that is a sum of the mass of the vehicle and load, and the effect of gravity. Now we come to the important issue – the brakes. When the driver puts his foot on the brake pedal, brake fluid is compressed in a cylinder which in turn pushes a high friction pad or shoe onto a shiny metal brake drum, which is directly connected to the wheels. The effectiveness of this truck stopping system is related to the surface area of the contact between the brake pads and the drum and the amount of normal force that can be generated by the hydraulic braking system. The matter of rolling resistance complicates the discussion somewhat.

There are three more factors that compound this problem of stopping a fork truck. First there are the mass and speed of the truck. Of course there are speed limits and governors but those are for the other guys. We now have to move into part 2 of Hibbler’s book – Engineering Mechanics – Dynamics. So this big vehicle is trucking along at 8 to 10 miles per hour and we encounter linear momentum, which is defined as the mass (m) of the vehicle times its velocity (v). We also have to consider impulse, impact, deformation, elasticity and restitution – mechanical and financial! Now the brakes really have to work – assuming the vehicle doesn’t skid on the slippery floor - they have to overcome this combined effect of mass and velocity. And the law of conservation of momentum suggests that the small mass and velocity of the unwary pedestrian who just stepped into the isle way is not going to help much – it’s back to number 9 versus number 8 on the rugby field only more so. The second factor is when the floor slopes and this mess of mass is moving with increasing momentum downhill. The third factor is more insidious and controversial. Suppose instead of carrying the load on the forks, the truck is towing a train of trolleys, all loaded with heavy components. So the normal force over the fork truck’s wheels is reduced, thus reducing the frictional effect, while the mass of the material in the trolleys is increasing the momentum, and the brakes of the fork truck were not designed to deal with this double whammy. The result is that the truck will take a little longer to stop and travel a little further in the process, which is just fine, providing it does not meet Newton standing in the way with a small mass.

**Newton the Astronaut**

Sir Isaac Newton, who lived between 1642 and 1727, was an astronaut. He must have been because his laws work when there is not much gravity and not much friction due to the drag of the atmosphere. Up there about 240 miles above the earth’s surface the velocities and the masses are quite big. The International Space Station is trucking along at about 17,500 miles per hour and the driver of the Space Shuttle or Soyuz is trying to catch up and dock the two vehicles together. Now this is all right if the driver can see where he is going and has practiced a bit in the simulators back at the Johnson Space Center, but when Progress comes along, the cosmonaut in charge of docking, like our fork truck driver, may not have a very good view. Another space job is to stick a remote controlled multi-jointed arm out and catch a satellite that weighs quite a few tons on earth and will do funny things if it gets an off center Newtonian nudge. Remember the number 8 who caught the number 9 some distance from his center of mass? Once one of these satellites is spinning it takes a well-trained rodeo star to rope it in – that’s why they put the Johnson Space Center down in Texas.

Just recently we were asked to advise on the location of handles on large pieces of equipment that had to be manipulated in and around the International Space Station. Just imagine a Newtonian nudge with a good lever arm setting a large rack careering around the confined interior of an ISS module. Now these astronauts are quick learners and it is a joy to see how they maneuver large objects around the ISS interior with a little push of a foot here and a little pull of a spare hand there. The trick is to get all the handles and restraints in the right places to allow maximum accessibility, stability and mobility – this is where biomechanical analyses and models come into play (and intelligent astronauts.)

## **Newton and NIOSH**

Back down on earth we have manual materials handling, bad backs, NIOSH, OSHA, insurance and politics. In the middle of this mess we have the industrial ergonomist. The consumer wants to send big parcels through the mail or its commercial competitors; household appliances and furniture are, for functional reasons, big and heavy; buildings are built of big components; batches of produce on the farms and in the food and drinks industry are somewhat heavy. And speed (v) is always a priority because time (t) costs money ($). The first job of Newton the ergonomist is to reduce the mass of objects whenever possible and the next job is to reduce the lifting moment arm; when things get moving, velocity (acceleration and jerk) is often bad and friction can be useful, especially between feet and floors. When we put all these Newtonian nuggets together we realize that the delicate junctions between tendons and ligaments and bones and muscles line up to see whose turn it is to fail when the foot of a manual materials handler slips and a jerk runs through a mass of moments to be stopped by failure of the weakest link in the biomechanical chain.

## **Conclusions**

This mechanics stuff that Newton started is fun. Engineers use it to design machines. Biomechanists use it to develop analytic models. Ergonomists can apply it to games, to syringes, to vehicles, manual materials handling, assembly operations, and to space operations. But for ergonomists to be able to win the confidence of their engineering customers, it is important that they learn something of the language and principles.

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**Chapter 8**

**LETSGOLOOKATAJOB - Task Analysis**

**Introduction**

This article is about physical and cognitive task analysis and some of the requirements for the application of these tools to analysis and intervention decisions in a wide variety of human tasks. There are many variants on the theme and descriptors such as “job evaluation” or “work study” (Konz and Johnson, 2000, Wilson and Corlett, 1990), but they all converge from different viewpoints on the central ingredient of human factors and ergonomics – the analysis of human characteristics, behavior and performance for the purpose of product, system and process design.

“LETSGOLOOKATAJOB”, said Richard Cobb, the UAW ergonomics monitor at a vehicle assembly plant, early one morning in the summer of 1985.

“Sounds like a good idea”, I said. “The ergonomics profession has developed dozens of task analysis methods over the years and I have one for Physical Work Stress Analysis that I developed 10 years ago in Hong Kong.”

“We won’t need any pencil and paper and the guys on the line don’t like video cameras, checklists, clip boards and stop watches,” said Richard, “LETSGOLOOKATSOMEJOBS.”

**Physical Work Stress Index**

The Physical Work Stress Index (Chen et. al, 1989) was developed at the University of Hong Kong in the mid 1970s to examine the activities of workers in the booming electronics, textiles and plastics industries. It was based on the concept of activity sampling (Hansen,1960). Random samples were taken of the spatial, force and environmental contexts of tasks on a common ordinal scale. The first spatial factor was the location of the person – a score of 0 was recorded if he remained in the same place and a higher score was given depending on the distance from the previous location. The base posture – standing, sitting, stooping / squatting and, lying were also recorded. A “box” was visualized in front of the operator and a score of 0 was recorded if the operator’s right / left hand was inside the box, with higher scores if the hands were at the edge of the box, outside the box or outside the box in two dimensions. A similar approach was used for load (force) and thermal environment. The index was computed by adding the differences between successive sampling intervals and then computing a weighted sum of these summed differences over the separate independent parameters. It was argued that if these factors did not change very much then the operator would have an undesirable high static load. On the other hand if these factors changed frequently the operator would have an equally undesirable high dynamic load. The optimal physical workload was somewhere in between. This method was applied to a wide variety of jobs over a dozen or so years and validated by comparison with physiological measures.

**Mixing Chalk and Cheese**

The experience highlighted two major challenges for task analysis. The first is how to account for multiple qualitatively different but interacting factors and how to amalgamate these observations to create an index that accurately describes the situation. The second challenge is even more fundamental – what to observe – there are many ways of viewing a task. In the physical contexts described above the focus was on the readily observable postures and physical activities of the operator. However, the purpose of task analysis is usually to identify what the engineer or manager can change to achieve some outcome such as product quality, productivity, health and safety or job satisfaction. Consequently, a task analyst, interested in human error and product quality could focus on motor or decision behavior. A productivity engineer might wish to look at non value added movements – like lifting and carrying. An analyst interested in health and safety might look at joint angles and movements or even only at medical reports by department. Other observers may look at the task itself or the task outcomes, such as critical incidents or “human errors”, and not the human operator. Consequently, task analysis tools must be developed with some [design] purpose in mind. As there will never be enough human factors experts to go around, one of our jobs is to develop task analysis tools that can be used effectively and efficiently by the engineers and operations specialists who have a direct responsibility for design or intervention.

Generally speaking our customers are only interested in what we call “main effects” and sometimes even these [customer] responsibilities may be spread over many different specialists. For example in the case of the NIOSH lift equation the product engineer is responsible for object weight, the manufacturing engineer for horizontal distance and the operations engineer for frequencies and durations.

**A Domain Focus**

When I toured the vehicle assembly plant with Richard Cobb, he automatically went to what were known to be problem jobs, because they generally had a history of injury or illness or were staffed by operators with lower seniority, although sometimes job choice was affected by factors that were not immediately obvious, like who was working in the same area, who the supervisor was or how close the job was to the cafeteria. He was about to demonstrate the relative importance of domain knowledge as compared with checklists. The first job was a rear axle install which required the [new] operator to choose the correct component, then pick it up with an articulating arm, before chasing the car down the line to install it; he appeared to be incapable of keeping up with the line, but a more experienced operator on the second shift had no trouble. A big part of the problem turned out to be the location of the manifest on the next car and the operator’s eyesight. Moving to the front axle install job, I was horrified to see the operator using his thigh as a mallet and to hear that he had a cumulative injury called “flat muscle” caused by nerve damage. In this case the problem turned out to be because the operator picked up two axels (right and left side) and did not have a hand free for the mallet that was provided. An operator on the sealer line had a similar damage to her lower leg caused by leaning on the sill while she used the sealer wand on a joint in the middle of the floor of the car. The second shift operator, a much smaller person, attacked the job “face on” to avoid leaning on the sill. A job in the body shop required the operator to stand / walk in a side pit while manipulating a large spot welding tool supported by a balancer. The issues here were inertia and fine motor skill, compounded by a very unfriendly environment. The battery install job again showed a difference between operators - the use of an articulating arm caused the first shift operator to take much longer to do the job than a bigger and stronger second shift operator, who tied the assist to a pillar and handled the battery like a basket-ball. Another second shift operator could attach a large, multiterminal, electrical connector under the dashboard without looking, whereas the first shift operator had to go through all sorts of contortions to be able to see what he was doing. Similar vision and reach problems with the intermediate steering shaft, spare wheel, brake booster and windshield wiper motor were because these units were placed way out of the reach of a normal sized person and the fasteners were not oriented for easy visual and physical access.

“Try this job for a while” said Richard. All I had to do was attach a piece of trim around the door pillar with hand gun and half a dozen sharp screws that drilled holes into the sheet metal; the floor was littered with thrown away screws, from a not very sharp batch and the operator complained of a painful wrist. Two jobs down another piece of trim was attached with a plastic snap followed by attachment of the rubber weather strip around the door, all the operator had to do was to use his hand to hammer the parts on as the use of a mallet might have damaged the surface. “Watch out!” said Richard as we walked to the final assembly line and a fork truck came racing round a corner. “These truck drivers can’t see where they are going and, because they are self-paced they try to hurry up and finish their job quota early. So stay inside the yellow line, or else you may have to develop a checklist for fork truck drivers from your hospital bed.” How was I going to develop a task analysis checklist that could address all these qualitatively different situations?

**Generic and Pragmatic Approaches**

But, despite this early training, I was undaunted by the challenge of developing a generic checklist that could be used to guide task analysis on the very wide variety of jobs in a vehicle assembly plant. So in 1990 I made a list of about 130 quantitative yes/no ergonomics questions that would cover every possible kind of manual assembly work – similar to the American Bureau of Shipping method of habitability assessment. (ABS, 2001) The head of the manufacturing engineering department said, politely “there is no way that you are going to get anybody to fill out that Ph. D dissertation.” So along came some colleagues: Paul Amman, Al McCarty, Ed Mohr, John Hill, Bruce Hancock and Bob Fox, who, collectively, had a zillion years’ experience in manufacturing, and we started again. Al introduced me to the pragmatic, domain focused, “McCarty’s rules”, aimed largely at the vehicle design engineer. These included simple advice like “Don’t use drill drive screws”, “Put connecters and fasteners where the operator will be able to see, reach and access them easily.” “Don’t require the operator to push more than 6 pounds (that was a biggie!),” “Limit option choice,” “Replace fork trucks with tuggers.” And so on.

Paul Amman, was not much for task analysis checklists either. He knew from experience that there was always more going on in a plant than meets the eye. One day, we were trying out a checklist to analyze some work at the end of a press line. My observations and the results of the checklist assessment indicated that the three guys were working very hard; Paul noted that there were really five guys assigned to the job and they rotated around a “newspaper” job. On another occasion, we noted that two assembly line operators seemed to be getting in each other’s way, until Paul pointed out that one of the operators was working up the line. Paul also pointed out wear patterns around workplaces and improvised staging areas or padding, which are not usually addressed in a formal task analysis, but these may be key ingredients in job acceptability and performance.

But the product and manufacturing engineers were not completely happy with these totally pragmatic, “expert” approaches. What they wanted was a process for analyzing the whole vehicle design and manufacturing process as it moved through the development cycle and process review “gates” (boards), and on to the factory floor. This process was to be aimed at removing the big problems in the product design phase and successively eliminating latent manufacturing and production problems as early as possible, so that the eventual analysis by a newly designed shop floor checklist would have nothing left to catch. This was achieved by developing a sequence of task analysis tools consisting of short sets of generic questions, related to variables that engineers could change, such as spatial layout, force, target size and frequency, which were supplemented in a hierarchical way by more detailed task analysis tools or in depth investigations where needed.

The expansion of physical ergonomics over the past two decades has led to a very large number and wide variety of similar task analysis checklists and worksheets. These all attempt to assess the characteristics of existing or future jobs with the intention of predicting the likelihood of work related musculoskeletal disorders. Some focus on sitting, some on lifting, others on the environment or overhead work, and the majority on repetitive hand work. (Peacock and Orr, 2001) They all face the challenges of scope, focus, depth of inquiry, data capture and amalgamation, decision implications, and linkage to the solution domain.

**Amalgamation and Indices**

The implementation of this process forced attention on how to amalgamate measurements from qualitatively different and often interacting and interdependent factors. There are three plausible approaches – adding, counting and multiplying (non-linearities and exponents are less user friendly). It is possible to simply weight and add up the scores, which may be valid if the importance weightings are reliably established and the scores are mapped to a common currency. However “adding” a force score to a moment arm score to a repetition score does not have much validity. The next, less mathematically demanding approach is to simply count the numbers of good, bad and ugly problems as identified by a checklist that reliably assigned qualitatively different measures of the job into green, yellow and red; the resolution of this approach sometimes resulted in an unclear prioritization and required that the scale was expanded with words such as good, acceptable, marginal, unacceptable and unthinkable, each with well-defined mappings from the measurement scales. A final amalgamation approach was adopted by the NIOSH lifting equation. (Waters, Putz-Anderson and Garg, 1994) This requires the mapping of the measurement scales by [linear] transformations into multipliers on a continuous scale from 0 to 1 with certain boundary conditions. These multipliers are applied to a “load constant” to create a recommended limit, which is then divided into the actual load to create a “lift index.” This discounting approach is easily appreciated by users with various backgrounds; however, it demands careful attention to the mapping of individual stressors, otherwise it rapidly converges to an asymptotically near zero value as more multipliers are applied.

The interactions between temporal and other physical factors always presents a challenge in task analysis. Basic relationships such as repetitions per minute or pounds lifted per day have familiar physical interpretations. On the other hand pounds per vertical foot per hour per degree Fahrenheit may have physiological stress and perceived strain implications, but the analytic interpretation of this high order interaction would require a nomogram of an overly complex form. Thus the temporal factors of repetition, frequency and duration are best incorporated into low order models.

**Cognitive Task Analysis**

The examples given in the forgoing description of task analysis draw attention to the, sometimes incompatible, operator view of the human factors analyst and the design needs of the engineering customer. Just as the physical domain deals with human capabilities and energy demands, the cognitive domain deals with human information processing and external informational demands along with time and context. The world of cognitive task analysis has addressed these challenges with gusto and has produced a plethora of devices (tools) that address the operator on one hand and the changeable features of the domain on the other. (Gawron, 2000, Charlton and O’Brien, 2002) Many of these tools are based on well-established basic relationships such as the Hicks – Hyman law, which addresses the amount of information to be processed in a decision task, Fitts law, which addresses the effects of task difficulty constraints on motor activity, de Jong’s law (among others) which addresses the complicating factor of learning, and multiple resource theory.

Basic cognitive task analysis approaches first address the domain of interest, the tasks required of the operator and the information content of these tasks. Next, the process addresses the serial, parallel and interdependent cognitive resources used by the operator for each task stage. The analysis then links the task stage demands and the limitations of the required cognitive resources, in light of the training and experience of the operator. The effects of context are superimposed on the model with regard to their potential effects on task difficulty or operator performance capability. Finally, temporal effects, such as vigilance and fatigue on the one hand and learning and anticipation on the other, complete the analytic framework. As with physical task analysis, the context and motivations of the operator may introduce issues that are beyond the scope of the formal tools.

The [not so simple] task of flying an airplane is a common target domain for these applications as at certain task stages there are considerable information processing demands and a very unforgiving physical and temporal context. (Hayashi, 2003) Similar complex cognitive tasks are found in process industry (such as petrochemicals, electricity distribution and nuclear power), military operations, medicine and transport management. Less exotic tasks are found in telemarketing, service interfaces and driving. There are three basic approaches to cognitive task analysis. First, one can analyze the task itself for its informational content and operator demands. Second, one can ask the operator what he is doing because watching people think by the assessment of eye movements and brain activity are not yet subject friendly processes. Third, one can observe how well the operator performs by comparison with an ideal (Baysian) operator who makes full and timely use of all information that is available, however uncertain. Indirect methods use secondary task performance fluctuation as a measure of primary task demand.

**A Memory Model**

Around 1970 I became interested in why people forgot things, having observed that retention and consolidation of information was key to all kinds of human performance.(*memorito ergo sum*) So I developed MIRC – a memory involvement recording chart, which addressed the sensory and informational characteristics of the item to be remembered, potentially interfering information occurring before and after the presentation of the item of interest, and how the resulting decision or control action was implemented. (Peacock, 1972) I tried this model out on a wide variety of sensory – motor tasks and other tasks, like medical diagnosis, that were primarily cognitive. (Peacock, 1974). I came to the conclusion that activity (proactive and reactive) rather than retention time (decay) *per se* was a great source of interference and that “similar” information had a greater propensity for interference than dissimilar information, e.g. different sensory modality. It appeared that “negative interference” occurred in literal retention, but that “positive interference” was a necessary part of semantic retention or consolidation. My earlier hopes for a Baysian model went out of the window early on, simply because I observed that people are very “sub Baysian” in their use of information – they forget! (Edwards, 1968). I also noted that this “interference” could be negative or positive – sometimes people were actually able to amalgamate (consolidate) information to converge on a useful decision or action – like putting a series of words together to make a sentence or even a book! The (cognitive) task analysis challenge remained and has since been addressed both by people focused researchers and by task focused designers.

**Information Systems and Concept Mapping**

The rapid expansion of computers over the past three decades has created a massive industry that addresses information system design and the human access to and use of these enormous resources. How does an expert approach complexity? And how do ordinary people find their way through a forest of menus, icons, buttons, pictures, banners and text? Again the designers of these systems resort to task analysis and have developed a theory of “Questioning” to assess behaviors of users faced with large amounts of data and too little time. (Lauer, Peacock, and Jacobs, 1992) The familiar “systems analysis” process resorts to network diagrams and concept maps to conveniently assess the flow and interrelationships of information. The question generation and categorization indicates a novel way of assessing how people formulate inquiries about complexity that is much more complex that the traditional linear checklist. These concepts have been amplified in recent years by a growing interest in concept mapping – a network diagramming technique with hyperlinks to multimedia sources. (Peacock, Shaffer and Zelik, 2003)

Nowhere is there greater complexity than in the audit process in which accountants search through financial and activity records to analyze the behavior of an organization. (Lauer and Peacock, 1993) Sometimes their enquiries are deliberately made more difficult to hide improprieties. There is merit in human factors practitioners looking at the ways that other professionals analyze complexity. Human Factors engineers have addressed complexity in systematic ways for many years and incorporated the additional issue of probability. Techniques such as event or fault tree analysis are extremely powerful, both for accident reconstruction and for prediction. (Peacock, 1982)

**Car Driving**

The familiar car driving tasks require attention to the changing outside world of roads and traffic, supplementary attention to secondary sources within the vehicle and attention to higher order tasks such as route planning, entertainment and the ubiquitous cell phone. Sometimes backseat drivers provide useful redundancy for over stressed resources. The motor demands, particularly with automatic transmission and a few years of practice are generally less of a limiting resource for the primary task, unless they are distracted by other task demands, such as tuning the radio. The contextual and temporal demands of driving are both very varied and very interactive. Driving in the fog at night on icy roads allows little spare capacity for entertainment for all but the young. Similarly the idiosyncratic behavior of other motorists at intersections may greatly increase the time pressure for information capture, decision making and motor response.

Formal task analysts in the car driving context, apart from researchers, include the other drivers, backseat drivers, the highway patrol and the driving instructor. The first three groups generally rely on unsystematic activity by behavior and performance sampling, often with relevance but usually with bias. The driving instructor on the other hand addresses and sometimes manipulates the external task demands in a systematic way, by imposing different workloads, contexts, temporal demands and risks. The instructor observes particular behaviors, such as the use of eyes, hands and feet as well as higher level outcomes such as positioning and speed control. Verbal protocol assessment may supplement the information available to the instructor, regarding the driver’s perceptions, knowledge, situational awareness and plans.

The task analysis work sheet used by the instructor generally involves sets of independent questions related to particular task phases, such as parking, merging or emergency maneuvers. Usually these assessments are on a pass fail scale, although Lickert scales, and interpretive comments may be used by instructors with greater analytic bent. It is unusual for driving instructors to use systematic workload demand assessment devices such as the anchored Cooper Harper rating scales (Gawron, 2000). Eventually the report by the instructor may be detailed towards particular areas of improvement, perhaps smattered with appropriate praise for good behavior. At the end of the course however, the instructor is required to give an overall pass/fail recommendation, amalgamated from his task analysis charts. I once knew an engineering professor who refused to give partial credit in his exams on the grounds that bridge builders and circuit designers must get it all right. Human Factors professors and driving instructors are sometimes a little more lenient in their application of task analysis.

**Situational Awareness**

Situational awareness is simply [self] task analysis with a mental clipboard. Situational awareness analyzers however use an electronic clipboard to record and dissect what is going on inside a person’s head and what can be done to the array of displays and controls to help this activity, or reduce the likelihood that the activity will result in error. One problem arises when the analyst is in too much of a hurry to turn to page two of the checklist of things that need attention. Another arises when the list of things needing attention is too long. The third is when attention is paid to the wrong information sources. The domain centric approach to task analysis employed by Richard Cobb in the car plant is an important complement to situational awareness task analysis tools.

**LETSGOLOOKATAJOB**

Physical and cognitive task analysis addresses task demands, context, human behavior, human performance, time issues and outcomes. Some approaches analyze what is happening to the human operator, whereas others focus on what can be changed in the task, context or time. Amalgamation of multiple aspects of the analysis is always a challenge, but this is necessary when an overall decision has to be made, either with regard to the task or the individual. On the other hand, decomposition and weighting are usually necessary to direct the analysts towards the profitable areas for change. Formal task analysis is the bread and butter of both physical and cognitive ergonomists, but domain experience is necessary to really comprehend what is going on.

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**Chapter 9**

**Little Boxes**

This article contains a discussion of the attempts over the years to describe the human and system outcomes of lifting and to present guidelines for what manual materials handling processes are effective, efficient and safe.

In 1972, I was asked a common, but impossible, question, which I answered with the best tools that I had at my disposal at the time. The context was the prospective purchase of a new container on wheels for employees of the British postal services. The container was to be used at postal distribution centers and on railway platforms and was something like the ones used nowadays at airports to move luggage from the planes to the claims, but it would have to be moved by man power, not tractor power. The question was to measure the, sometimes conflicting, outcomes of effectiveness, efficiency and safety of the new container in comparison with the old standard one. Now the astute reader will note that there is no such thing as an ergonomic thing – we can only assess the outcomes associated with the expected use and foreseeable misuse of things by people. And we must also assume or describe what kind of people we are talking about.

My initial approach was to measure the spatial dimensions of the box on wheels – the height of the floor, width / length depending on which way you are looking at it and the depth / width that constituted the maximum horizontal reach. The next step involved the creation of a load for the container. This begged the question of weight, size, shape and variety of the boxes typically handled by postal workers. This is where high technology got its chance to shine. Computer cards came in boxes of standard sizes and by binding sets of boxes together it was possible to obtain larger boxes of incrementally different sizes, shapes and weights. So we manufactured a set of these boxes just enough to fill the container. But how full is full? This question addressed the maximum height of the parcels in the container and the location and dimensions of the stack on the ground.

The next step was to design a set of tasks, typical of those carried out with the container – these included: pulling and pushing while unloaded; loading, pulling and pushing while loaded and then unloading. Preliminary behavioral analysis of the loading and unloading processes indicated that different people used different methods – the tall ones kept their feet anchored and twisted and the small ones took a step while the intermediate ones did an old fashioned waltz – you can’t fit all human behaviors into a standard “box.”

The gold standard in those days was work physiology – the number of kilocalories consumed per minute. And the official postal standard was 6 kilocalories per minute, which was the average energy expenditure of a postman walking at 3 miles per hour carrying a 35 pound postbag full of letters. The technology at my disposal was not too high tech by contemporary standards – I opted to use a Kofrani-Michaelis gas meter and oxygen analyzer. This involved the subjects biting a rubber valve (like a snorkel, but with inspiration and expiration valves) and a nose clip, having them breath out through the meter and collecting a sample of the expired air for analysis of its oxygen content, with due regard to standard temperature and pressure.

The next challenge was the experimental design, procedures and subject recruitment. We obtained a sample of 16 men, between 20 and 50 something and it’s a good job we didn’t have the IRB to contend with. A couple of the subjects couldn’t attach themselves to the bite bar on the valve due to a history of inattention to dental hygiene, and the can of chewing tobacco in one old subject’s top shirt pocket turned out to be a pacemaker! The procedure of loading and unloading and pushing and pulling up and down the 20 yard laboratory floor required that the subjects had to occasionally remove their mouth piece to spit. The experimental design presented a common problem, found in many ergonomics investigations – order and carry over effects. It was logistically cumbersome to arrange the condition of pushing an unloaded container immediately after loading it; furthermore the demanding physiological load of pushing a loaded container carried over to the following unload condition. Consequently the arrangement of the primary variables – subjects, conditions, and order - into their experimental boxes presented an interesting challenge in counterbalancing and calculating the error variance in a mixed effects model.

The bottom line, given that each subject took about two hours to complete all the experimental tasks – “at a rate at which they felt they could work all day” was that the average energy expenditure was 6 kilocalories per minute! This number has to be contrasted with the 12 to 15 kilocalories per minute experienced by agricultural workers and materials handlers in some third world, sometimes calorie deprived, countries and the 3 kilocalories per minute recommended by NIOSH in the calorie rich United States.

The next box in the story is of a different kind. It is a virtual “box” placed 30 inches of the ground, whose top is 50 inches off the ground, a width 30 inches and a depth 20 inches. These numbers are derived from anthropometry, with due deference to the practical attractiveness of round, memorable numbers. It also benefited from the simple instruction by Henry Ford many decades ago to “bring the work to the worker.” This imaginary “box” is placed directly in front of the standing operator as a guideline for the assessment of the biomechanics and physiology of manual materials handling tasks. It is the basis of the Physical Work Stress Index developed at the University of Hong Kong in the mid 1970s and further developed and published at the University of Oklahoma in the mid 1980s (Chen and Peacock, 1988). In the mid 1990s it became the basis of the General Motors assessment method for manufacturing processes. It should be noted that by this time various people and organizations had begun to fuss about cutting off the corners to change the box into a wedge or to create many little sub boxes.

The Physical Work Stress Index assessed tasks on an ordinal scale with regard to the location of the operators’ hands – in the box, at the edge of the box, outside the box or outside the box in two or more dimensions. The interacting load was also measured on another scale of round numbers – less than 10, 20, 30 or 40 pounds, with > 40 being out of the question for repetitive jobs. The next step in the analysis process is to apply random activity sampling, throughout the shift or day, with a frequency dependent on the desired resolution of the assessment process – typically an average of about 10 observations per hour should suffice. Sedentary workers spend most of their days with their hands inside the box and with a very light (< 10 pounds) load – they suffer from a very high static loading. Active manual materials handlers have their hands inside and outside the box, with variable loads – they end up the day with a very high dynamic (physiological) load. Analysis on the static – dynamic scale is carried out by subtracting the score for each variable (location / posture / hand position and load) at one sampling interval from that of the previous sample and then summing these differences.

Automobile manufacturing and assembly involves a lot of non value added work – materials handling. This involves trucks and trolleys, warehouses, containers, racks, fork trucks, conveyors and lifting aids with people interspersed where the automation is not up to the task. The trick is to manage the material so that it flows at a maximum rate from its point of production to its placement on the vehicle. This so called just in time delivery process also minimizes the amount of space needed to store materials at strategic places along the route. Often these processes are dependent on the flexibility of people at key points, but human centered design principles address the process from the point of view of human pulling, pushing, lifting, carrying, holding and searching. Here again the box concept comes into play, this time with a greater number of zones, typically 10 inch cubes, that are assigned particular weights (in 10 lb increments) and frequencies (in lifts per hour increments), based on the principles of biomechanics, physiology and psychophysics. The resulting charts are easily used by manufacturing and materials engineers to manage the layout, container design and operations associated with materials handling.

The National Institute of Occupational Safety and Health (NIOSH) created a committee during the 1970s and ‘80s to develop a more sophisticated tool for the assessment and design of manual materials handling tasks. (CDC.GOV/ NIOSH, 1994) The resulting NIOSH Lift Equation and its limits and recommendations have enjoyed worldwide success over the past two decades, mainly due to its plausibility with regard to the description of “good and bad jobs” and the ease of use following the development of manual and computer interfaces. But it has also attracted a lot of, mostly unfair, criticism, largely because of its probabilistic nature (people vary) and its unfortunate link to the contentious area of work standards that have for centuries separated management and labor. Various authors (Silverstein, Marras) have converted the principles of the NIOSH Lift Equation, supplemented by additional anthropometric, biomechanical, physiological, psychophysical and epidemiological evidence, to a set of cubical boxes, dispersed around the operator. An understanding of moments is sufficient to populate these boxes with generally acceptable numbers that describe the location and load, but the really contentious issue is frequency. This is because the only possible ways of dealing with frequency are to modify the line rate – reduce the throughput – or to vary the number of people, which has implications for labor and floor space costs.

The package transportation industry is intimately concerned with the movement of boxes and they have made great strides with the introduction of automation, but perhaps the most visible challenge of boxes is in airline luggage management, because Joe passenger wants to take his golf clubs and the kitchen sink. The general principle of if you want to take it you can lift it on and off the scales and conveyors helps to some extent, but the individual passenger only moves a small number of boxes and the now ubiquitous wheel has reduced the carrying chores. But what goes on behind the check in lines and baggage claims is another story, now further complicated by the added security inspections. “Please check your luggage tag as many bags look alike.”

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# Chapter 10

# Nobody is Normal: Human Factors Measurement and Design Policy

# Variability – we can’t avoid it

We are surrounded by variability, but this chapter will be limited to the topic of human variability. The empirical observation of variability can, fortunately, be described by probability theory and statistics. These mathematical tools allow us not only to describe human variability but they also provide the mechanism for making decisions about people and for designing the world in which people exist. Coincidentally, people with no knowledge of these useful tools also deal intuitively with human variability and exploit it. When we speak to a large audience, we use a sound level such that all can hear – “can those in the back hear me?” Conversely, in a crowded room we lower our voices so that only those in the immediate circle can gain the advantage of our insights. Exploiters of variability include the gamblers, the game players and the politicians. When these people harness the power of probability theory they get an advantage over those who limit their observations to subjective probability. We – human factors engineers and ergonomists – come armed with these tools – that is why we are useful. Those “Johnny-come-latelys” who limit their observations in a reactive way, solely to the “voice of the customer,” are doomed to an eternity of feedback control or tampering (Deming, 1982).

# Probability

Variability comes in all sorts of shapes and sizes. Forbes, Evans, Hastings and Peacock (2000) describe some 40 statistical distributions, many of which can be brought to bear on the analysis of human variability. One distribution – the Normal Distribution or “bell curve”– stands out as the most widely applied tool. Many people blame Gauss for developing this theory, but the real culprit was the father of probability – a Frenchman named de Moivre, in 1773. Gauss simply used the ideas to explain how the universe works.

The practice of ergonomics / human factors requires a sound knowledge of probability and statistics plus knowledge of the domain in which you are practicing – Deming calls this “profound knowledge.” Best practices in Ergonomics / Human Factors involve teams of HFE and domain specialists.

# Correlation

The example given above – the heights of people – is the unfortunate example that almost everyone knows about. They know that a 5th percentile person is taller than 5% of the population and go on to extrapolate that they are also stronger, have better eyesight and are more intelligent than 5% of the population. What gobbledygook! But don’t laugh – the clothing industry has been making such assumptions for years about the various shapes and sizes of people. And they sometimes get away with the assumption. Why? Because many human variables are correlated – that is taller people are usually heavier and have longer legs than smaller people. The problem with this correlation thing is that we need another pot full of statistics to describe it, again based on that pervasive Normal Distribution. Suffice it to say that correlation may be perfect and positive, perfect and negative and all shades in between. When we measure people, stature (height) is highly correlated with leg length, but less correlated with back length, girth or weight or strength or stamina or memory or vison or age or political party. You get the idea.

We can measure people on thousands of dimensions that are more or less positively or negatively correlated. These similarities and differences have genetic and environmental causes. What is particularly striking about genetic factors is that we have more similarities than differences as a race. We are not like apes or aphids or apples. Most people can sleep on a standard size bed, eat a standard size big burger, read the standard font on a newspaper, drive a standard car or carry a standard size suitcase. One size fits all? Well it depends how precise you want to be or how important it is that the glass slipper fits only one princess. Given our genetic underpinnings, opportunity and practice allow us to adapt to our environment. Expertise is determined by dedicated practice. Unfortunately age and disease fight our attempts to exaggerate our differences. But to get back to the central thesis of this article, subjective and objective measurement of people can be made on thousands of dimensions and, given sufficient resolution of our measures, we can articulate substantial variability on each dimension. Furthermore these measures are not necessarily correlated.

Say we are a 95th percentile height, 70th percentile weight, 80th percentile strength, 90th percentile stamina, 30th percentile dexterity, 50th percentile sociability, 40th percentile at swimming, 10th percentile at singing and so on. What is the probability that we will find someone else just like us? Fat chance. But with all this genetic stuff pushing through we are likely to be more like our parents on many dimensions than our overseas pen pals.

By now we have established pretty convincingly that people are not alike. We have explained why these differences occur and how probability and statistics can be used to describe the variability. No two persons are alike ergo nobody can be Normal.

# Design

Now to the challenges of design to accommodate this variability. The challenge hit me between the eyes (almost literally) when I contributed the ergonomics input to the design of the Hong Kong Mass Transit Railway. Assuming that 2 million people have ridden the train each day over the past twenty years I feel that I have contributed substantially to the comfort, convenience and safety of a lot of people – I leave it to the reader to do the arithmetic. One challenge was a decision regarding the height of a horizontal grab rail to be used by passengers as they moved up and down the train. Of course we should take the comfortable upward reach of the 5th percentile Chinese female (98% of the Hong Kong population is Chinese and their stature, due to genetic and dietary factors is less than Westerners or Northern Chinese.) So I arrived at a number that hit a fiftieth percentile male on the chin or thereabouts. I had discovered the ergonomics challenge of conflicting criteria! Compromise! The reader is invited to travel to Hong Kong to assess the utility of the final design decision.

The reader is referred back to the diagram earlier in this article, specifically to the value of X. Suppose our job is to design the instructions related to income tax forms. We hope that most citizens will be able to read and understand them. Question: citizens must be members of the human race, can tax lawyers be citizens? So the well intentioned advisor to the IRS persuades the government to make a law that the instructions must be written at a 8th grade reading level – we will assume that this X represents the 5th percentile tax paying adult. This is a pretty difficult task because the cognitive content of the tax laws is determined by these tax lawyers and the instructions only represent the interface. So the result is that 50% of the tax paying public make use of a professional service. Great interface? Don’t blame the interface – it is the system designed by tax lawyers itself that discriminates.

# Conflicting criteria

Now for an example of conflicting criteria. Suppose we work as an ergonomist for one of those parcel distribution companies. Our job is to answer the question: how many (few) young, strong, students does it take to move N parcels, with an average weight of P pounds from A to B in an ideally designed “ergonomic” (I hate that word) workplace, in order to fulfill the company’s promise of next day delivery? One more thing: without hurting these young, strong students. Fortunately we have a wealth of industrial engineering knowledge and the NIOSH lift equation. If we pay our workers enough money they will work very hard and we can set the value of X – the work rate - very high. Another way of looking at it is that we can call x the materials handling capability of the population and we can set the X selection screen to say the 75th percentile parcel handling capability – young strong. Looking at it from the safety perspective we know that as the demands on the body increase there will be two outcomes – first we will get a training effect – the bodies will become stronger but not younger. The second effect of increasing the demands is that a greater proportion of the population will break. The NIOSH Lift equation lift index is a surrogate for the probability of breaking. (I don’t want to get into a lengthy discussion of how good a surrogate it is – it’s probably as good as a test of reading level in the tax form example.) So, back to the design question. We have done our best at work place design; we have controlled the mean parcel weight by economic and physical restrictions; we have selected our worker population perhaps with the help of the union; we are left with the design dimension (X) of parcels per person per hour over a ten hour day. Our conflicting criteria are productivity and safety – both having probabilistic underpinnings. . Set X high and we get great productivity and a high incidence of injuries and vice versa. What are we to do? Well we are not alone – this question has been debated in the highest circles in the land and was resolved at least temporarily by a 5 to 4 vote in the US Supreme Court. Productivity rules OK! Ergonomics is junk science. (But by the way don’t hurt anyone.)

# Ergonomics, variability and policy

These two examples – tax instructions and parcel handling rate – highlight the fundamental separation of human factors engineering and policy. The human factors engineer can measure human capabilities and limitations on thousands of dimensions. It is up to the policy makers – management, government, and union negotiators etc. to draw the lines in the sand. Its just like traffic speed limits and blood alcohol levels. We are working on a probabilistic continuum that is based on human characteristics, behavior and performance measures. So where does this leave our sacred 5th percentile female or even our 95% confidence limits. These are policy concepts; they are human factors dogma; they are convenient; they are useful; they may be used as the basis of rules; rules are meant to be broken, laws are meant to be interpreted, or negotiated. Human factors engineers are good at measuring, they should also help management and the legislature with the evidence of human variability that is the basis of policy. Nobody is Normal. People vary. Ergonomists by whatever name have job security because of it. But human variability is our Achilles heel.

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**Chapter 11**

**Cell Phones and Carpal Tunnel Syndrome: Ergonomics Decision Analysis**

No this article is not about cell phones causing carpal tunnel syndrome, nor is it really about cell phones or carpal tunnel syndrome. Rather it uses these two lightning rods to address the compromises that face the human factors practitioner and the realities of risks and benefits. The second part of the article describes a method for making decisions in ergonomics applications.

**Risk and Benefit**

The safety and risk community use data to assess the probabilities and consequences of system failure, particularly with those systems that involve human beings as controllers or simply as participants in hazardous operations. For example when we drive to work we rarely think about the fact that some 40,000 people a year die on the roads of the United States. We are more likely to think about our contribution to and benefit from the Gross National Product, which usually necessitates us driving to or for work. We may recognize that drivers who are incapacitated by alcohol or drugs cause some 20,000 fatalities on the roads. But even that sobering figure and the severe penalties that are in place to address DUI, do not stop a very large number of people from using their cars to provide access to recreation involving alcohol, nor does it prevent many people from using cold and allergy medicine, or more powerful prescription drugs that may interfere with driving or driving when they are tired or in very hazardous conditions. At a more spectacular level the data tells us that 2 out of 113 Space Shuttles have failed catastrophically, which, if you wish to put 95% confidence limits on the probability of failure, the relevant statistic of the order of 1 in 30; of course those responsible for the space program will be quick to point out that the these statistics are invalid, because the Shuttle is not a member of a large homogenous fleet for which component failure rates are known and that significant changes have been made to the engineering and managerial issues related to known failure causes - O rings, debris and tiles. The astronauts are still enthusiastic to fly because in their minds and those of the Space Program management and many of the US population, the benefits of human space flight outweigh the enormous risks involved.

The business and operations research communities have long been interested in cost – benefit analysis. (Clemen, 1991), Their examples and mathematical models show us that decisions under uncertainty often involve multiple variables and multiple criteria, which have to be weighted and optimized in the process of business decisions. Psychologists who investigate human decisions and choice (Hogarth, 1983) also point out that human beings (managers, engineers, doctors, juries, generals) rarely reach the lofty ideals embodied in Bayes Theorem (1863) in that they rarely use all the data that is available. Even sophisticated consumers, like you and I, are usually subBaysian when it comes to buying the more expensive model of car, computer, cell phone or camera. In the laboratory, cognitive psychologists can easily demonstrate the fallibilities of operational memory when the subjects are faced with time or other psychological / social stress. (Gonzales, 2004)

**Cell Phones and Driver Distraction**

Strayer and Drews (2004) quantified the decrement in human driving performance as affected by the secondary task of having a cell phone conversation. They produced numbers like an 18% increase in driver response delays and a doubling of rear end collisions (in a driving simulator). They also pointed out that the effect on younger drivers is to make them perform as if they were old. Like most good human factors researchers these authors reported averages and standard errors – the chances are that those with average responses would have survived, which leaves a whole bunch of accidents waiting to happen in the right hand tail of what is probably a positively skewed response time distribution. These issues of driver distraction have been around for decades. Years ago car radios were the target of the safety advocates. From the late 1980s to today the car companies conducted extensive research on driver distraction with in vehicle navigation systems, mobile phones and head up displays. Many of these studies showed that, although the driver visual and motor resources may be aided by such things as hands free operation and better (often bigger) display features, the issue of cognitive capture remains the premier challenge. During the GM ACCESS car study I remember one old lady taking almost a minute to fathom out how to tune the radio while she was traveling at 45 mph. I was also very active in the assessment of the physical and content characteristics of head up displays, which in the simulator sometimes had similar cognitive capture difficulties. On another occasion I had the opportunity to evaluate whether or not it would be safe to drive a car equipped with a video player that projected into a small mirror next to the rear view mirror. I remember watching “Top Gun” and that, although I was attuned to time sharing between the movie and the road ahead, the extended headway between my car and the one in front was typical of many (but not all) cell phone users on our roads today.

This brings me to my main point. It was possible for me to drive without incident while watching a movie. Also, the vast majority of cell phone uses in cars do not result in accidents, even under heavy traffic conditions. This is due to what used to be called “spare mental capacity”, with a bit of probability thrown in. Speaking on the phone, even in a car, is perceived by some 80 million cell phone users in this country as being a reasonable thing to do and most of the time they survive the experience and feel that the conversation, like drinking (a little or a lot?) was of a level of benefit that greatly outweighed the risks. Meanwhile our profession offers (even with excellent data) the simple statistic that response times are increased by 18%.

# Carpal Tunnel Syndrome

In the early 1980s and throughout the 1990s I was involved in manufacturing and office ergonomics. Work related musculo-skeletal disorders, including carpal tunnel syndrome rose to national prominence in epidemic proportions, fueled by contentious debate between labor and business and between the two main political parties. Early attempts to push the problem under the table were soundly defeated when it was realized that on many occasions these disorders were real, even though very variable in their levels of pain, debilitation and reporting. However, nobody caught carpal tunnel syndrome by assembling one car a fortnight, cutting up one turkey a year, taking one geriatric patient to the toilet once a day or entering one page of data an hour into a computer. Meanwhile, management and one of our parent professions – industrial engineering – were pressured by the competitive economic climate to improve productivity. So now automobile assemblers may face one car every 40 seconds, typists one page a minute, turkey carvers one bird every few seconds and nursing homes are like an ice hockey rink.

Students of human factors / ergonomics will also realize that this mess of force, posture, repetition and politics was complicated by the ever present problem of human variability. Just like cell phone users and accidents, not all assemblers or disassemblers caught carpal tunnel syndrome. The benefits of work and competitively priced products greatly outweigh the prevalence of work related musculo skeletal disorders, to managers, consumers, shareholders, unions and workers, unless you are one of the unfortunate ones. The reader is also invited to consider the repetitive work involved in building the pyramids and the Burmese railroad as described by the movies: “The Ten Commandments” and “The Bridge over the River Kwai”. Closer to home there are the self-inflicted stresses commonly experienced by athletes, for whom the reward is worth the pain.

# Production with Protection

We may debate the gross accident, fatality and injury statistics. We can also pick the low hanging fruit - drunk drivers and drivers who cause accidents by cell phone use should be punished, but the cell phone will not go away. Similarly, the demand for cheap meat and cars, affordable extended care, and computer-centered work will not go away, so we will continue to face the physical and political problems of work related musculo skeletal disorders, at least until the automation utopia arrives. Human factors engineers / ergonomists will always find themselves wandering in the middle of a mess of variability. Some of our profession veer toward the side of protection. They say, “Ban cell phones from cars” and “Slow down the line rate”. Meanwhile, those that pay our salaries – the consumers and managers (academics aside) say, “If you want to get at my cell phone, you’ll have to go through me first” or “Productivity provides profit, which makes us all happy” (except of course for those relative few who die in car accidents or can’t sleep at night because of carpal tunnel syndrome.) Now the academics may be politically neutral and simply report prevalence, associations and sometimes solutions. Or they may consider that our profession is a humane profession largely driven towards health and safety. It wouldn’t be the first time that academics showed their social conscience, but some academics work on nuclear weapons and other killing machines. Is science and policy really an oxymoron? Policy cannot do without science, but science alone does not dictate policy.

**Cell Phones and Carpal Tunnel Syndrome**

It makes no sense to discuss risk outside the context of benefit. Space flight is risky, but who wouldn’t wish to walk on Mars? Cell phones in cars are risky; they are very useful when you have a flat tire or someone runs into you. When you are lost, forgot to pick up the children from day care, are late for an appointment or can’t wait to relay the latest office gossip, who wouldn’t be tempted to a brief conversation while driving. Until the mental workload puts you in a fix. Also repetitive work is useful, productivity is good and if you can find a more efficient way than the production line (or work cell) then you will be a hero; I’ll not hold my breath!

Somehow the human factors engineer / ergonomist must assess the triple whammy of costs, benefits and human variability and provide the customer with usable advice, not just statistics and rhetoric. You may argue that Strayer and Drews’ number of 18% is both statistically and operationally significant. But just look around you while driving along the highway. The NIOSH / BLS findings on work related musculo skeletal disorders are pretty convincing, but so is the trade deficit. As in the forensic branch of our profession, we must give both sides of the aisle unbiased science and go further – give them a number that accepts that risk and benefit go hand in hand

**Ergonomics Decision Analysis (EDAN)**

A missing element in many ergonomics processes is a formal tool to support design or intervention decisions that are often made on only a limited assessment of all the implications.

The concept of risk is widely developed in the safety world. In the United Kingdom, criteria have been established to define regions of acceptability, tolerability and unacceptability in terms of number of fatalities per year. Negligible risk is considered to be at a level of 1 in 10 million. The borderline into the tolerable region starts at 1 in 1 million and into the unacceptable region at 1 in 10,000. A distinction is made between the risk to the general public and to workers employed in hazardous industry, in which case the borderline between tolerability and unacceptability is 1 in 1000. The tolerability region is further defined as that region where the benefits may be judged to outweigh the risks. The risk calculator (Raafat, 1995) takes into account outcomes of lesser severity than fatalities and includes quantitative concepts of exposure in the denominator of the equation.

In the USA, the National Association of Manufacturers has strongly supported the Regulatory Improvement Act of 1998, which aims at laws (particularly environmental laws) that “are based on sound science and focus on the comparatively higher risks to society.” The recommended process includes:

1. Scientifically sound risk analysis
2. Risk based prioritization
3. Benefit cost analysis
4. Flexible efficient, cost effective risk management
5. Public participation in all phases of the process

A fundamental issue in the assessment of risk is uncertainty. Many hazard sources are innocuous at low exposure levels but lethal at high levels. Such sources include physical energy such as heat, sound, light or force, and exposure to chemical and biological stressors. In many cases there are direct tradeoffs between the risk of harm to people, equipment or the environment and the benefits to society or a subsection of society. An intuitively clear example is traffic speed - there are benefits of completing a journey quickly, but the risk and severity of accidents increase with speed. A second issue with risk on a particular dimension is that sometimes the effects (benefits or risks) are not monotonic in relation to hazard intensity. Sometimes too little is as harmful as too much, as in the case of heat. The same problem occurs with physical work. Biological systems thrive on (mechanical) stress, without it bodily systems atrophy as commonly seen after bed rest or space flight. It is generally understood that underuse is a primary risk source for ill health. On the other hand over use is a common risk for athletes and production line workers.

A second complication of risk analysis is the inherent variation among people in their response to hazardous sources. People are also capable of adapting to increasing levels of stress, given gradual increase in exposure. These sources of variability confound the issue of risk analysis. They beg the question ***“what proportion of the population should be accommodated or protected?***” Clearly the answer to this question must factor in an assessment of the possible severity of the outcome and the acceptability of selection strategies to remove vulnerable individuals from exposure. In the case of driving, selection is accepted at both ends of the age spectrum, although not always without a challenge. In unionised industry, seniority based job choice is a prime method of self selection. In the area of recreation self selection is the primary method of hazard avoidance and, in general employment, given a healthy economy, personal choice of job is widely used, although here again there may be a tradeoff between personal benefit (wages) and risk.

An appropriate decision tool must comprehend all the relevant aspects, including both the positive and negative outcomes and the costs of analyses and alternative designs or interventions. It must also address the short and long term implications. The decisions must also be made in light of the broader relevance of the situation, such as the cost of a design or intervention alternative when compared to the value of the functional process. Again a traffic control example is pertinent where the design alternatives for an intersection may range from a yield sign to an overpass, depending on traffic density.

The proposed model is comprehensive and accommodates the errors that accompany many outcome and cost estimates. It addresses the nonlinearities of human judgment by the application of fundamental psychophysical principles. An elementary mathematical process involving exponents (Tables 1, 2) is used to allow the model to be applied manually. Alternatively, more complex model elements can be applied through a spreadsheet. Units are chosen to facilitate estimation and meaningfulness of the quantities involved in the model.

Table 1. The relationships between decimal values and base 10 logarithmic exponents:

**Numerical Value** **Base10 Logarithm Exponent**

0.000001 -6

0.00001 -5

0.0001 -4

0.001 -3

0.01 -2

0.1 -1

1 0

10 1

100 2

1,000 3

10,000 4

100,000 5

1,000,000 6

10,000,000 7

Table 2 Basic mathematical relationships used for convenience in the manual method:

*log101 = 0, log1010 = 1, log10100 = 2, log101000 = 3 etc.*

*101\*102\*103 = 101+2+3 = 106*

*or 10 \* 100 \* 1000 = 1,000,000*

*104 / 102 = 104-2 =102*

*or 10,000 / 100 = 100*

*101+102+103 = 103(approx)*

*or 10 + 100 + 1000 = 1,110 = 1000 (in quantum / rounded terms)*

The decision model elements and ranges (Table 3) have been chosen to cover most practical purposes but expansion is possible, should the situation warrant it. Although it is understood that there are non-financial elements of outcomes, it is convenient for the purposes of this model to reduce outcome assessment to a dollar equivalent of the daily availability of employees or systems. The purpose of this assumption is to obtain common currency measures for the comparison of outcomes and design interventions and to address the wide-ranging variability of severity of outcomes. The time unit of a day is used because of its universality.

The data capture process requires the estimation of the expected value of each element by an individual analyst or, preferably, by a consensus of experts. The latter approach is more likely to produce a more stable estimate. Another benefit is that consensus can be used to account for multiple sources of costs, benefits and other factors affecting system performance. Given these expected values, high and low estimates are identified as those values above and below the expected value respectively.

**Table 3 Ranges of Benefits and Risks for Model Components**

**Model Element** **Units Exponent Range**

Functional Process Value $ per day 0 to 7

Additional Process Value $ per day 0 to 7

Personal Benefit $ per day 0 to

Probability of Failure F/Transaction -6 to 0

**Exposure:**

Iterations (per person) I/day -3 to 5

Replications Number 0 to 6

**Costs of Adverse Outcome ($/day):**

Environmental $ 0 to 7

Human $ -3 to 5

System Down Time $ -2 to 5

Other Economic Costs $ 0 to 7

**Cost of Intervention:**

Additional Manpower $ 0 to 4

Additional System Costs $ 0 to 6

Repair/Replacement Time $ -2 to 6

**Table 4. Calculation of sums, products and ratios:**

Process Value = Total revenue + Additional revenue generated by the intervention

Risk of Failure = Probability of Failure x Number of Iterations x Number of Replications

Cost of Failure = Environmental + Human + System + Other

Cost of (Additional) Design / Intervention = Human + Design + Repair

Tolerance Ratio = Cost of Failure / Value of Process

Intervention Ratio = Cost of Failure / Cost of Intervention

Relevance Ratio = Cost of Intervention / Value of Process

Intervene if: Tolerance Ratio > 0.1

Relevance Ratio < 0.1

Intervention Ratio >1.0

**Expected Costs / Benefits**

Expected Failure Cost = Risk of Failure x Cost of Failure

Design / Intervention Costs (Benefits) =

Expected Failure Cost (Avoidance) + Additional Process Value - Cost of Design / Intervention

**Example 1 - Road Accidents (Statistics from Barfield and Dingus 1998)**

1. The perceived value of driving = annual cost of car + fuel + extras divided by the annual mileage - (7000+500+2000) / 10,000 = (approx.) $1 per mile
2. The annual fatality rate on the roads in the US is about 45,000 with 5.4 non-fatal accidents and 28 million vehicles damaged
3. There are about 193 million registered vehicles, including commercial
4. The average annual mileage is about 10,000 for passenger vehicles, commercial vehicles average about 60,000 miles per year
5. There are therefore about 1,930,000,000,000 miles driven per year
6. There is about 1 accident per 100,000 miles driven
7. There is about 1 fatality per 25,000,000 miles driven
8. The average vehicle can be expected to be involved in about 1.1 crashes during an operational lifetime of 13 years
9. The estimated annual economic cost of road accidents is $137.5 billion
10. The average cost per crash is about $8,600
11. The monetary value of each vehicle crash is about $7,200
12. A device that would avoid all crashes would be worth about $7,200
13. A device that would avoid 25% of crashes would be worth about $1,800 per vehicle

**Example 2 - Heavy Manufacturing (hypothetical numbers)**

Value of process 5,000,000 items per year sell for $5,000 each

Annual revenue = 25,000,000,000

Average wage + benefits rate = $20 per hour at 10 hours per day @ 200 days per year = $40,000

Daily cost of labor = $200

100,000 employees

Annual labor cost = $4,000,000,000

Annual materials cost = $10,000,000,000

Annual Plant Cost $5,000,000,000

All other costs $3,000,000,000

Margin = $3,000,000,000 = 12% revenue

2,000 hours per employee per year, 3 fatalities per year

10,000 lost day cases per year = 10 per 100 employees per 2000 hours

Average lost days per case = 2

Days lost per year = 20,000

Simple cost of days lost = $4,000,000 = 4% revenue

Medical Costs $100 per day = $2,000,000 = 2% revenue

Replacement employee cost = $4,000,000 = 4% revenue

Intervention by hiring additional 10,000 employees (10%) - @ Annual Cost of 400,000,000

Half the injury rate 5,000 lost day cases per year, 10,000 lost days per year

Simple cost of days lost = $2,000,000

Medical costs = $1,000,000

Replacement employee cost = $2,000,000

Intervention by automation - double the plant cost, half the labor cost

Plant cost =$10,000,000,000

New Labor cost = $2,000,000,000

Half the Injury Rate = 5,000 lost day cases per year, 10,000 lost days per year

Simple Cost of Days Lost = $2,000,000

Medical costs = $1,000,000

Replacement employee cost = $2,000,000

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**Chapter 12**

**Scenario Analysis**

The ergonomics researcher, professional or practitioner is often faced with complex situations and has to decide on an approach to the problem including consideration of:

1. What are the important problems? What are the purposes of the investigation?
   1. Are there problems of system effectiveness?
   2. Are there efficiency, productivity or cost implications?
   3. Are there health and safety problems? What are the probabilities of “human error or failure”? What are the implications or consequences of system failure? Are the effects acute or long term?
   4. Are there issues of human preference? Opinion?
   5. Are there individual and social issues involved?
2. What data or evidence are needed?
   1. Does accurate, reliable and valid data / evidence already exist?
   2. Are there any existing design guidelines or standards that are not being applied?
   3. Can data be obtained by simple observation or questioning of those involved?
   4. Should a formal survey or observational approach be used?
   5. Can physical mockups, modeling or simulation be used?
   6. Can the investigation be carried out in the laboratory? In a simulator, or in the field?
   7. Is a formal controlled experiment needed? What about sample selection and size? What about experimental design? What about confounding? What about subject selection?
   8. Is there need for a multi-pronged approach to the collection of evidence?
   9. How long will it take to collect the data? How much will data collection cost?
   10. What equipment and methods should be used?
   11. Are there any human subject and institutional review board issues with your proposed approach?
3. Which measurement and analysis tools should be used?
   1. What tools should be used to collect, process and analyze the data?
   2. Are the approaches validated and calibrated?
   3. Is significance of differences or associations important?
4. What designs or changes are indicated?
   1. Do the suggested designs or changes include hardware, software or operations?
   2. Are user selection and training needed?
   3. Will facilitators help? – Instructions, warnings, labels, checklists, procedures, tutorials, augmented reality?
   4. Will the changes require careful implementation, persuasion and monitoring?
5. How should the changes be justified and communicated?
   1. What effects will the changes be expected to have?
   2. How long will it be before the changes have a detectable / useful effect?
6. How should the effects of human variability be assessed and communicated?
   1. To whom should the results be presented?
   2. How should the results of the investigation be communicated? – Presentation, report, process requirements, system design specifications, guidelines, standards.
   3. How should graphs, tables, diagrams, photographs, statistics, verbal arguments, demonstrations be used?
   4. Are the results of the investigation suitable for publication in academic, professional or trade literature? Are the results proprietary? Could the results be used in court cases?
7. How should the effects of the changes be evaluated?
   1. Is there a plan for monitoring the implementation and effects of the changes?
   2. Will these evaluations be specific to the particular situation or will they have general applications?

**Analysis**

Analysis is a very broad term encompassing many qualitative and quantitative techniques from description, arithmetic and geometry to more abstract algebra, trigonometry and calculus. Selection from this full spectrum of methods may be applied to ergonomics assessment of human characteristics and capabilities and limitations in behavior, performance and preference in any context. Because of human and contextual variability statistical methods are used widely in ergonomics. In the present context of Human System Integration, however, two checklist methods are described which can be applied either qualitatively or quantitatively and be supported where justified by more detailed methods.

**Convenient Definitions**

A system is an object, person or entity that can be described by a noun and qualified (or quantified) by an adjective; a process or activity is an interaction among systems that is described by a verb and qualified (quantified) by an adverb. Under this definition, a system itself is inert, until it interacts with one or more other systems to perform a process. A process has some explicit (or implicit) purpose or outcome that is a change of state (adjectives) of the contributing systems. A process takes place in a context (environment), such as place, time, or weather that is not changeable but which may affect the outcome of the process. The outcomes of a process result in a change of state of the contributing systems. An example would be a driver (or supervisor) in a car driving on a road. The outcome is a change in the location of both car and driver, a consumption of time and fuel and harm to the environment.

Thus we have the model:

* Systems (Nouns and Adjectives) combine as Processes (Verbs and Adverbs) to produce Outcomes (Changes to system features / adjectives)
* Systems have Specifications (adjectives) which can be verified. Processes have Requirements (adverbs) which can be Validated
* The Systems, Processes and Outcomes may be affected by Context / Physical or Operational Environment

The entities involved in the process of driving include the driver, the vehicle, the roadway and the environmental and operational context. Although most drivers have passed a competency test there remains considerable variability in the capabilities, limitations, motivations and behaviors of this very large cohort related to age , experience and physical, sensory and behavioral shortcomings.. Similarly, although vehicles are required to pass a roadworthiness test, they also exhibit considerable variability in size, power, maintenance, color etc. Despite the efforts of the local and federal authorities roads vary considerable in their capacities and state of maintenance. The driving environment between hot summer days and cold icy winters with rain and fog occurring from time to time. Also the amount of congestion and average speed on a particular road may also vary considerably. For most journeys the drivers wish (their purpose) to arrive at their destination safely and quickly (or quickly and safely).

**Purpose or Outcome** **- E4S4 model:**

* Effectiveness - The process outcome meets or deviates from the intended or desired outcome
* Efficiency - The process consumes an optimal amount of resources such as energy, manpower, money or time
* Ease of use - The process is compatible with the characteristics, capabilities, limitations of the (human) contributors
* Elegance - The non-human entities and activities are compatible with the desires of the human contributor
* Safety and Health - The process does not result in an unwanted outcome
* Security - The process is not subject to malicious input by a third (human) party
* Satisfaction - The outcomes of the process satisfy the requirements of all stakeholders
* Sustainability:

Reliability - The process continues or repeats over time with the same predictable outcomes

Resilience - The process is robust in that it is not affected by uncontrollable contextual or environmental factors

**Example: A Fast Food Restaurant (E4S4)**

* Effectiveness - The primary purpose of a meal is to satisfy the requirements of an individual for calories and various nutrients. Whereas fast food restaurants may satisfy these basic requirements as well or better than more expensive restaurants, a meal may also involve other personal, social or business purposes, in which case the ambience and food preparation and presentation may also contribute to effectiveness.
* Efficiency - Efficiency may be measured from the viewpoint of the customer, cook, server or company in terms of costs, prices and profits. Time may be of the essence, for all of these stakeholders; this may be estimated or measured by the number of service stations and queue length in a fast food restaurant. The owner may have overhead costs, such as manpower, air conditioning, maintenance etc.
* Ease of use - The limitation of menu items and pictorial displays in fast food restaurants make choice and oaring of food simple. Also the item packaging and transport of the meal on a tray enable the customer to manage delivery usually without the assistance of a waiter. Eating without utensils is facilitated by meal design and presentation. Residue return by the (cooperative) customer to the convenient bin is also made easy by appropriate hardware and location design.
* Elegance - Elegance is an elusive concept and particularly subjective. However the owners of fast food restaurants go to considerable lengths to make their establishments and food presentations attractive. Furthermore the ambience is within the expectation of the patrons.
* Safety and health - Primary components of food preparation are cutting and cooking, both involving safety hazards. Lack of cleanliness and contamination may also be health hazards. Such hazards are mitigated by equipment, workplace and tool design. Selection and training of employees and warnings to customers are also designed to mitigate health and safety hazards.
* Security - Malicious interference in the restaurant industry by dissatisfied stakeholders and opportunistic third parties is a possibility, although remote in practice. However all large organizations take steps to identify possible hazards such as through the use of security cameras and trained and vigilant management. For example, establishments that serve alcohol usually have procedural practices to discourage unruly behavior.
* Satisfaction - Fast food restaurants have multiple stakeholders – the customers, servers, preparers, managers, owners, shareholders etc. The issue therefore is one of optimization with due regard to the management of expectancies.
* Sustainability
  + Reliability - Given the experience in the industry leading to the equipment, workplace and procedures design and continuous improvement, fast food establishments are generally seen to meet the reliability requirements as indicated by their continued operational success and demand
  + Resilience - The hardware and operations design and employee selection, training and oversight are such that contextual challenges, such as inclement weather are usually well managed. Even such contextual problems as power outage or equipment failure may be mitigated by the availability of redundant facilities.

**A Process may also be analyzed, described or evaluated by the six Us model:**

* Utility - Is the process useful?
* User and Misuser - Who are the intended and expected users and misusers, what are their capabilities and limitations?
* Usage and Misusage - How do the entities (including human contributors) initiate, carry out and monitor the activities?
* Utilization - How often and for how long does the process take place?
* Usability - Are the non-human entities and context compatible with the capabilities, limitations and expectancies of the human users?
* User error - What is the potential for error by knowledgeable and skilled, or unknowledgeable or unskilled users?

**Example: Flight booking**

* Utility - The need for effective and efficient long distance travel for both business and leisure is such that flying is widely considered to be an essential mode. This considerable demand for services requires effective and efficient booking services for both routine and problematic situations. The routine services can be met most of the time by automated websites, sometimes with the availability of a telephone or chat feature.
* User and Misuser - Customer variability in terms of air travel experience and journey choice and complexity are such that even the most meticulous designed systems and interfaces are sometimes beyond the knowledge and skills of less experienced and capable travelers. Because web sites differ, customers may be unfamiliar with those of airlines that they use infrequently and may be subject to carry over effects between their use of different sites. Misuse in this context is usually due to inexperience rather than malice.
* Usage and Misusage - The transport reservation interface may reside on various technology platforms – such as lap top computers, tablets or cell phones. The conditions of use may also vary in terms of user experience and urgency and context, such as quiet home or busy workplace. Even familiar users may fail if their choice of medium is a cell phone while driving.
* Utilization - For some the process is frequent an quick, given the complexity and context of the booking. For other users the frequency of use may be occasional and time consuming. As with users and usage, utilization is subject to considerable variation - from daily to annually.
* Usability - User experience, training and knowledge may go a long way to mitigating the shortcomings and idiosyncrasies of the interface. However, most large organizations now benefit from records of customer errors and help center experience. Again most, at least, large organizations pay dedicated attention to the evaluation of user interfaces, errors and comments in their continuous improvement processes.
* User error - Errors may result in minor inconvenience or catastrophic failure. They may be due to an unfamiliarity with the aviation context or the booking process. The errors may be due to misunderstanding of the underlying process or the meaning of a particular link or button. Errors may be due to perception of the feature or to a forgetting of a previous choice or input.

There are tombs written on these subjects of systems engineering, usability and user error, but missing a connection in Detroit or Bangkok can be challenging, whether due to the user or “the system”.

These examples generally involve qualitative analysis which may be sufficient for many situations. However the requirement to “give the engineer a number” should not be forgotten. Where process shortcomings are detected, either at the design or implementation stage, it behooves the analyst to be specific regarding the form and likely cause of an error. It is usually the province of an engineer (hardware or software) to design a system. In practice the ergonomics analyst works (or should work) in collaboration with the engineering designer.

The reader is invited to consider some of the following scenarios using the E4S4 and the 6 Us analysis tools:

1. The observations of air traffic control and the communications from the pilot of a small airplane indicated that he was acting irrationally shortly before the plane crashed. The pilot was relatively inexperienced and was not trained to fly at night or over open water using his instruments. You have been asked to comment on the possibility that hypoxia was a leading factor in the accident. Describe how you would prepare for your presentation to the board of enquiry, which may include members not familiar with physiology?
2. You are SCUBA diving at a depth of about 90 feet in relatively warm water in the Caribbean. You notice that a relatively inexperienced pair of divers appear to be in difficulties and are repeatedly looking at their pressure and depth gauges and dive computer. Given that you have a PADI instructors certification how would you assess the possible causes of the problem and what information would you seek and what advice / instructions would you give? What are the implications of alternative responses to the problem? How would you evaluate alternative equipment designs and training to prevent such incidents?
3. You are a newly hired ergonomist in a large gas and oil company that produces, transports, stores, processes and distributes products under pressure. You have been given the task of reviewing the instrumentation used throughout the processes in order to reduce the probability of human error by the process controllers. How would you use your knowledge of the gas laws (Charles Law, Boyles Law etc.) to recommend changes in display design? What help would you seek from experienced chemical engineers?
4. You have been asked by a university vice president for facilities to advise on the seating design for a new basketball stadium donated by a rich alumnus. How would you address the challenge of human variability in your recommendations? What criteria would you use in the evaluation of alternative designs? What recommendations would you give and how would you justify them?
5. You have been asked to design a seat for a new fork truck, which is to be used to move materials in and out of trucks parked at the loading bay, to temporary storage areas and then to sites of operations throughout a large manufacturing plant. How would you address this task and evaluate the appropriateness of alternative designs?
6. You have been engaged by a commuter airline to investigate the numerous complaints about seats. How would you approach your task? An approach proposed by the CEO is to provide adjustable seating and to charge a premium for people who take up more space. How would you implement this approach?
7. A major league baseball club is planning to address the challenge of soaring salaries by opening its batting cages for the general public to pay to participate in a new game – hitting baseballs for distance with different implements and different ball speeds – from 0 to 100 mph. What factors would affect the distances achieved? How would you design an investigation to evaluate the effects of equipment design, ball speed and individual differences?
8. A major league football club is interested in alternative biomechanical strategies for their defensive linemen. They have engaged you to develop a computer based model of the locations, directions and sizes of the forces involved, including issues of friction, but excluding holding and tripping. How would you go about this task?
9. OSHA has engaged you as a consultant to evaluate and modify the NIOSH lift equation for application to single lifts. Their objective is to account for all possible factors associated with acute injuries to people in the warehousing and construction industries. What biomechanical factors would you consider important? How would you develop a model of injury likelihood? How would you validate this model empirically?
10. You have been engaged to investigate an epidemic of bad backs in a large data processing facility. The union leadership has offered the opinion that all the desks and chairs should be replaced by adjustable units, based on a numerical fitting matrix. The union membership would rather just have the adjustable chairs. Management is prepared to pay for either new chairs or new desks, but not both. How would you approach this problem? How would you plan an evaluation of the effects of the changes? How would you justify your findings to the scientific community?
11. A non union precision, labor intensive manufacturing facility is being pressured to reduce costs and increase productivity, while maintaining its historic high quality standards. The management approach is to introduce a team structure along typical Japanese lines. What would you expect to be the long-term outcome of this situation? How would you monitor the effects of the changes?
12. A colleague with a business school background has asked you to explain the Hawthorn effect to a professional seminar for accountants. You may expect that they had all taken an organizational behavior class. How would you communicate to your audience that the causal factors for individual and group behavior may not necessarily be related to their organizational design strategies?
13. When you get into a rental car you have various expectancies regarding the locations and direction of operation of the secondary controls such as climate control, entertainment systems, seats and windows. These expectancies are based on basic spatial relationships and your experience with other vehicles and control operations. How would you address the designers of future cars, the marketing departments and their managers regarding the importance, or otherwise of standardized control locations and operations. What kind of arguments against your ideas do you expect to face? How would you deal with these arguments?
14. When you want to increase the flow of water from a tap you turn it counter clockwise. When you want to increase the volume of your radio you turn it clockwise. How would you investigate and design an electronic interface for the control of the temperature of a shower (assuming that you could be sure that you would not electrocute the subjects during your usability trials.)
15. One difficult job for an astronaut is the control of a six-degree of freedom robotic arm. This involves the use of two controls – one for pitch, yaw and roll and the other for the three translation axes. The astronaut also makes use of multiple cameras, with similar controls, but which, because some are mounted on the arm and some are on fixed stations, provide different views of the scene at different times of an operation. How would you apply your knowledge of expectancy and compatability to the design of controls and training methods?
16. Foundry workers are required to clean out hot furnaces. Time is of the essence as the costs of shutting down and starting up the furnaces in terms of productivity are very high. Consequently, management would like to get the maintenance operators into the furnaces as quickly as possible after shut down. Describe your approach to data collection, analysis and intervention, including personal protective equipment and administrative controls. How would you explain heat stress to the workers and managers?
17. You have been engaged by the Army to acclimatize the infantry for very physically demanding work in a desert war zone. How would you assess the effects of alternative and complementary intervention approaches?
18. You have been engaged by a local school board in Texas to investigate the dangers of starting aggressive football training on July the first. How would you assess the physiological effects of alternative training, monitoring and intervention strategies?
19. You have been asked by the government to develop easy to use rules for manual materials handling in large hardware stores that can be easily implemented assessed and understood, similar to traffic control rules. How would you research the background to this task? How would you quantify, implement, enforce and evaluate the rules?
20. The biggest challenge to ergonomists is human variability. Individuals vary on many dimensions and most tasks involve many human attributes. How can you justify simple 5th percentile type rules? What other forms of rules could be developed and applied so that the majority of the population could be productive and safe in their work?
21. Many ergonomics situations involve tradeoffs between productivity and safety. These issues are notoriously contentious. How would you develop and implement a rule based approach to the challenges of baggage handling at airports or in nursing homes.
22. You have been engaged by the Department of Homeland Security to design the jobs of inspectors who have to screen thousands of people a day with the challenge of identifying a few terrorists. The Department is increasingly sensitive to the problems of false accusations. Given that all physical avenues (lighting, image enhancement, training, etc.) to improved detection have been exhausted, what organizational strategies could be applied to improve inspector performance?
23. Car driving is becoming increasingly complex with fast speeds, traffic congestion, complex vehicle features and increasing numbers of non-driving tasks led by the ubiquitous cell phone. Given that driver performance is related to distraction levels but that the effects of distraction are situationally specific and often of little importance, how would you use laboratory, simulator and field methods to develop guidelines for driver attentional management?
24. You have been asked by a major wine producing company to plan an evaluation of wine tasting methods in a task that compares home produced wines with imported wines. The plan is to have large groups of volunteers assemble on Friday evenings for three-hour wine tasting sessions. Given that wine can be assessed by sight, smell and taste you are expected to distinguish between the roles of these senses and the possible interaction effects. You are also required to produce and evaluate criteria for measuring individual differences in wine tasting behavior and performance. Finally, you are expected to assess the likely order effect in performance and time into session, assuming of course that designated drivers accompany all participants.
25. People come in all shapes and sizes and clothes manufacturers address these challenges by discrete sizing systems, sometimes with a little bit of adjustability. Fine tuning is carried out on the sewing machine and if all else fails sartorial license rules. Given the advent of whole body scanning techniques there is a wealth of new information that could be brought to bear on clothing design. Devise a field fitting method for men’s suits using whole body scanning and while you wait sizing and adjustability.
26. Common experience demonstrates that individuals familiar to the observer can be recognized under limited lighting and exposure duration conditions, especially if movement information is added to shape and size. Identify a set of features that are likely contributors to this shape recognition task and develop a laboratory experiment and computer based method to test your hypotheses.
27. Sheldon developed an easy to understand method of somatotyping that has become less popular in modern times. Devise an experiment involving both anthropometric measurement and subjective perception to evaluate Sheldon’s model.
28. Contemporary advertisers highlight key features and associations of products, such as cars, to inflate customer’s general impression of the product. A challenge to such processes is that in reality the products do not differ a great deal objectively on these dimensions. Devise a field experiment to investigate the halo effect in car purchase behavior.
29. Multiple choice or “objective “ tests are used widely in education and professional certification examinations. However many educators still consider that essay type or problem solving answers tell more about the student’s analytic and communication capabilities. Devise an experiment to test the reliability of both forms of examination.
30. The interview has been shown on many occasions to be an unreliable method of personnel selection. However, the vast majority of managers still place considerable weight on their own judgment capabilities during interviews. Devise an experiment to evaluate the reliability or otherwise of individual and panel interview processes.
31. The methods of psychophysics are generally applied to assess the abilities of individuals to make judgments on single physical dimensions such as size, weight or color. The results of these experiments are usually reported in terms of “just noticeable differences” that are detected on 50 percent of trials. Devise an experiment to establish the relationship between a physical dimension and a standard and the proportion of
32. You have been asked to advise a retail chain on the perception by customers of package size and perceived value. How would you apply psychophysical methods to this task?
33. Psychophysically derived differences do not always estimate operationally significant differences. You have been asked by a fast food retailer to address the perceived hamburger size issue, with a view to cost cutting on the amount of meat used. Develop a field experiment to detect customer judgment of hamburger size.
34. Use a psychophysical experiment to assess the perception of speed – baseballs, cars, trains, airplanes, hand movement, running, walking etc.
35. Carry out a simple experiment to measure human errors (and human variability) in the recall of digit and letter strings of different lengths. Repeat the experiment with mixed lists and grouped sequences, including meaningful and nonsense syllables.
36. Write down at least 50 codes associated with person or product description. Investigate how these codes are processed.
37. You have been asked by the State Department of Transportation to revolutionize the way in which people, vehicles and licenses are coded. How would you investigate the current problems of errors and productivity? What new designs would you suggest? How would you implement and evaluate the new designs?
38. Everybody knows about learning curves, but very few people actually quantify their own learning curves. Devise an easy to use process to measure and predict changes in performance over time in booking a flight on the web, knitting, running or walking one mile, throwing darts, reading etc.
39. You have been hired by an automobile manufacturing company to investigate how many cycles it takes to get a new car line moving at a rate of one car an hour to 60 cars an hour. How would you go about this task? What about quality?
40. Murphy’s law states that if anything can be done to cause a catastrophe then someone will do that thing. Research the web for the Darwin Awards and explain why these priceless individuals did obey Murphy’s Law.
41. You have been engaged by the Office of Homeland Efficiency to investigate why airline flights are held up because of bizarre human behavior. How would you collect appropriate data on these relatively infrequent events? What changes would you suggest recognizing that you must not interfere unduly with the obedient majority?
42. You have been engaged by a cell phone company to investigate all possible failure modes of the system that are due to inappropriate human behavior. How would you investigate these problems?
43. You have decided to go into the wall and ceiling papering business, as you believe that there are a lot of surfaces out there waiting to help you make your fortune. You have estimated that one casual helper can paper three 20 \* 15 \* 10 rooms (3000 ft2) in an 8 hour day, and that you should charge by the square foot ($0.10 plus materials) and not by the hour. Unfortunately on day one you only manage to finish one room. How would you investigate the physiological causes of this low productivity? How would you revise your estimating procedure in order to make $1,000,000 per year, always assuming that you stayed competitive?
44. You wish to describe and demonstrate local muscle fatigue and recovery to a class of unruly high school students, noting that different muscle types fatigue at different rates. Devise a demonstration that involves the whole class and results in data that can be used for a peer-reviewed publication. How would you account for individual differences? What methods would you use? What experimental design would you employ? How would you address the order effect?
45. You have been engaged to investigate why the productivity of some employees in a parcel handling center stays constant over the 12 hour shifts while that of others declines significantly. How would you investigate the effects of general physiological fatigue. What changes in work design would you make given that no new equipment could be purchased?

**Chapter 13**

**The (brief) Anthropology of Work and Play**

*“And which of you, having a servant plowing or tending sheep, will say to him when he has come in from the field, ‘Come at once and sit down to eat’? (Luke 17, 7)*

*“These last men have worked only one hour, and you have made them equal to us who have borne the burden and heat of the day.” (Matthew 20, 12)*

Not only did these Biblical employees get paid, perhaps unfairly, for their work, they also got benefits. Nowadays, General Motors gives pensions to more retired employees than working employees, plus health benefits. The automobile industry is a good place to start this story because transportation of people and things represents a substantial portion of what we do but transportation, *per se*, is non value added, except to those who get paid for transporting. Transportation also represents an enormous spectrum of employment opportunities – from managers, lawyers, insurers and advertisers, through engineers, designers and manufacturing and assembly workers, to those involved in mining, petroleum production and agriculture. The car also generates work for road builders, traffic cops, hotel staff, fast food restaurants and emergency room physicians. Nowadays people, in the developed world, spend an inordinate amount of time in cars, trains and planes, just to get to work. The slogan of the American trucking industry is: “ If you eat it, wear it or use it, it came on a truck.” And all because some lazy prehistoric genius invented the wheel, because he grew tired of running after the game and carrying it home for dinner.

Over the millennia, technology and society have changed considerably but people and work have not changed very much. We continue to look (listen), think (remember) and do (say). Groups of ancients got together to hunt the mammoths while sharing the dangers and the spoils. Nowadays organizations are formed to produce the necessities and niceties of living and to spread the wealth, albeit inconsistently. Homo erectus found a rock to sit on to rest his feet. Homo sapiens found that he needed a computer, the Internet and a cell phone to expand his influence. Homo sedens got fat by sitting and working at computers all day and using the same technology for entertainment all evening. Physical work is necessary to produce the things that society needs, information work is useful to refine that production, but it is play, in its broadest sense, that is essential to satisfy the soul, while the body and brain recuperate. Great technological strides have been made to modulate the form of physical work by the harnessing of power, levers and wheels. Sensing, thinking, calculating, controlling and communicating have also been greatly enhanced by information technology. Play has become more vicarious: instead of dancing around the fire after the feast, we now sit by the fire and watch football; instead of sacrificing a lamb to the sun god, we salve our souls by watching the preacher on television. For the purpose of this article we will consider only three phases of the day – sleeping, working and playing.

The devil of course is in the details; both work and play exhibit enormous variety. The first driver of variety is society and then comes technology. A few thousand years ago populations were small and technology simple. Spears and hoes separated the small groups of hunters and the farmers, although they both used the knife, water and fire for processing. They eventually recognized the merits of enriching the gene pool by interbreeding. As time passed populations grew, cities formed and technology sprouted to deal with the movement of materials and the management of information. And rock and roll separated the young from the old. Homeland security replaced the village sentry in an attempt to prevent unwanted contamination of the gene pool, by followers of a different drummer. Commercial television replaced the village leader as a guide to behavior.

**Measurement**

There are jobs, hard jobs and jobs your fathers (and forefathers) used to do. All work has its rewards and much work has significant costs that sometimes outweigh the rewards. Some work is hard on bodies, some on minds and some on souls. Some work provides enormous personal satisfaction, with minimal tangible gain. Other work is boring but lucrative. The relationship between these different rewards and costs of work is not simple – some people, who “work smart, not hard” may get significant financial rewards, others who work physically hard may pay exorbitant costs, but have the satisfaction of substantial personal achievement. A challenge to students of work is to provide a common currency for the description of the context, content and outcome of work, so that valid comparisons may be made.

**The multiple purposes of work**

There are four principle categories of work purposes or outcomes – effectiveness, efficiency, safety and satisfaction. Effectiveness or quality addresses the expectancies of the customer for the product or service. Efficiency or productivity relates to the consumption of resources, such as time, money, space, equipment and materials. Safety addresses the prevention of acute or cumulative harm to the people or other resources associated with the carrying out of work. Satisfaction, is a uniquely individual outcome or work – one man’s meat is another man’s poison. additional purposes will include: ease of use and esthetic appeal, security and sustainability (reliability and resilience).

**Collaboration, slavery and employment**

From the very earliest of times people have formed organizations or collaborative groups to expand the effectiveness, efficiency, safety and satisfaction associated with work. When these groups are formed there is usually a division of duties and leaders emerge to guide the strategic management of the group. The leaders may be appointed (perhaps self appointed), selected or elected and sometimes these personnel processes are subject to bias. This bias may not necessarily lead to bad leaders. Indeed, many slaves may be treated very well and have considerable autonomy, except for their opportunity to chose their master.

The line between employment and slavery is very fuzzy in reality although the two conditions of work are distinct politically. In the early days of transportation it was common for groups of slaves to row boats across the sea or move large blocks of stone for the construction of pyramids, castles, churches and factories and be encouraged by physical methods. These slaves typically came from a separate ethnic, geographic or cultural community. In the recent past slave labor became a tradable commodity and shiploads of Africans came to America; to this day employee slaves are forced by their leaders and circumstances to give up their practical rights to choose what they do in the form of work. Golden handcuffs or the promise of better times ahead may be as effective as the whip.

When someone joins the military or the college football team they are typically directed by appointed or selected leaders called sergeants or coaches. When they fail to perform quality work they may be subject to physical or emotional abuse with the intention of making them stronger. In times of war, if a soldier, for very good reasons of personal survival, chooses to opt out, he may be shot. During practice, the deficient footballer may simply be given the symbolic public humiliation of ten pushups or a run around the field. Human deficiencies in the real world of war and sporting competition may be rewarded by career ending public humiliation and untold personal trauma.

It is common in business and industry to use the expression: “I work for” or “who do you work for?” The operational meaning of these expressions is simply a reflection of the appointment or selection of a leader and the symbolic placement of his name in a box on an organization chart. Sometimes appointments and selection of leaders are focused on a subset of the purposes of work – such as productivity – and sometimes these leaders may chose a managerial style that is incompatible with the wishes of the subordinate, especially where that subordinate was not a party to the appointment or selection process. The boss also has a difficult task, because his boss or customers may have expectations that diverge from those of the employee. As in war and football, rule number one in business and industry is that “the boss is always right” and rule number two is that “when the boss is wrong, go to rule number one”. The penalty for not understanding these important rules may be career shortening or more subtle modification of the conditions of work.

In government, labor organizations and academia it is common for leaders to be elected by those who they lead. The campaigns leading up to such elections commonly involve promises and quid pro quos. Another characteristic of elections is that the electorate may not be aware of all the facts about the candidates or the implication of decisions made by the successful candidate, once elected. Also elections are rarely unanimous so that once again as in war, football, industry and business, those that are being lead may not always be happy with their elected leaders. They do have a chance at the next election or even at a recall election, but once again there will usually be a minority of unhappy workers. You can’t please all the people all the time, and the context and content of work will always be constrained.

Hertzberg addressed this issue at the individual worker level. He argued strongly that it was the intrinsic content of work that motivated the worker and that the context simply contributed to dissatisfaction. Can a slave be happy picking cotton? Can an automobile assembly worker be happy attaching an exhaust pipe, overhead, to a car every 30 seconds? Can a quarterback be happy if his receivers can’t catch or his protectors don’t protect? Can a soldier be happy if the war is being lost? Can the voter be happy?

**Human variability**

Work and play are good indicators of individual differences. In professional sports these differences are documented in great detail and the influence of intangibles, halo effects and pitchfork effects become dominated by objectivity? Play can be measured by wins and losses and by salaries. So can work, but there is enough uncertainty left to create work for students of work and play for the foreseeable future. The outcome of work is measured by effectiveness, efficiency, safety, satisfaction and their derivations. The human input to work may be physical, informational or motivational and humans vary enormously on these dimensions.

**Demographics of work**

Life is divided into three parts – learning, working and smelling the roses. Ideally these activities correlate with the aging process, but the borders are so fuzzy that they may overlap considerably. There are also

**Chapter 14**

**The Grammar of Design**

# System and Process Design

The technology of system design has grown over the past half century from roots in human factors engineering (Singleton 196?), manufacturing process engineering, product design, and, more recently, information and software systems design. Many agents characterize contemporary complex systems: human, hardware and software subsystems collaborating in an integrated organization to carry out a mission in a context of environmental uncertainty and time constraints. The technology has developed its own esoteric jargon and in some instances the tools of system design have become so cumbersome that they add unnecessary complexity, cost and delays to the process. The purpose of this chapter is to explore the semantics of system design and some of the more useful tools in the context of space exploration, with occasional detours into automobile manufacturing for explanatory purposes. The chapter concludes with some simple rules for human system design.

The fundamental semantic challenge is to separate the concepts of entities and activities, agents and functions, systems and processes, nouns and verbs. Entities, agents and systems are described by nouns. Activities, functions and processes are described by verbs. A system (noun) can only be designed reliably by specifying its characteristics – adjectives - in a quantitative way. Give the engineer a number! On occasion a qualitative adjective may be used, but this will require the engineer to perform an interpretive step before design. Systems by themselves are inert. It is only when they interact with other systems that a purposeful process occurs. Processes are described by verbs and quantified (qualified) by adverbs (Peacock 1995).

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| --- | --- |
| **Grammatical Construct** | Semantic Implication |
| Adjectives | Design Specifications, Quantifiers, Qualifiers |
| Nouns | Systems, Agents, Entities, Context |
| Verbs | Processes, Functions, Activities, Purposes |
| Adverbs | Performance Requirements, Quantifiers, Qualifiers |

Systems, subsystems, components and elements may be comprised of hardware, software, humanware or organizationware. In space, extra vehicular activity requires a suit, software for control and communications, an organizational structure for supervision, and last but not least, the person in the suit and his or her support entourage. Extravehicular activity, per se has no specific purpose – activity is a generic term for a collection of purposeful functions, such as inspection, assembly, maintenance, translation, manipulation, protection etc. that can be measured. Driving to work requires a car (nowadays with a lot of software), a driver, a road and an organizational structure, including the highway patrol. Driving to work is also dependent on many supporting processes, such buying, taxing and insuring the car, filling it with gas, maintaining, starting, stopping and steering. Failure of any sub process can have outcomes that vary from the catastrophic to minor inconvenience.

**Process Outcomes**

These two activities (verbs) – EVA and driving - have common general purposes. First there is quality or effectiveness – achieving a stated objective. Next there is efficiency or productivity – consuming the minimum amount of resources, such as fuel, money or time, to achieve the objective. The third general purpose of all processes is safety – there should be no (or minimal) harm done to any of the collaborating systems, except where the conversion of systems is the purpose of the process, as in propulsion. Harm in this context includes both acute damage to a system or cumulative damage, such as wear of moving parts, radiation sickness or undue fatigue. Parenthetically, all processes result in change to some or all of the contributing subsystems, such as “normal wear and tear” or in the case of the human subsystem, temporary fatigue or learning. A unique purpose of complex processes that include human subsystems is that of satisfaction. People or their organizational supervisors must find some intrinsic satisfaction in the activity and not be overly affected by the dissatisfiers such as discomfort or insufficient rewards. (Herzberg, 1967)

Processes take place in environmental contexts, which add uncertainty to the outcomes. Space exploration involves extremely hostile environments and the lack of complete or timely information regarding these contexts can be catastrophic. The weather or the other drivers may complicate the process of driving to work. These uncertain extrinsic contexts may interact with any of the intrinsic subsystems and where these subsystems are vulnerable, process failure or subsystem damage may occur. A solar flare may tax the effectiveness of the radiation protection subsystems and a wet road will attack worn tires (Haushalter, 1971). In the case of the human subsystem, a cold environment will interfere with finger dexterity, and a surfeit of information, as occurs with cell phone use in busy traffic, will over tax the human attentional processes (Peacock 2003)

# Human Error

Two apparently contradictory opinions about design outcomes are voiced by Casey (199) and Petroski (1992). Petroski argues that “To Engineer is Human” and that engineers will usually learn from their mistakes; he sees that engineers continually break new ground and are faced by constraints and tradeoffs, which lead to risky decisions. He cites a series of catastrophic civil engineering failures and their “after the event” explanations. Hornick (1986 ) in his presidential address to the Human Factors and Ergonomics Society Annual Meeting argues that Petroski failed to understand that human error, both in design and execution, is predictable and therefore preventable. Casey presents descriptions of a collection of notable catastrophes that were caused by execution or foreseeable design errors for which there are clear human factors explanations. Examples include interface design shortcomings in an X-ray machine and a trust in automation (radar) issue by the commander of the US Fleet in 1926. The system design factors that gave rise to operator overload error at Three Mile Island are legendary. More recently the NW 255 plane crash at Detroit can be attributed to the crew failing to perform a correct procedure, together with a failure of a warning system. Beaty (1969) presents a perceptive assessment of “The Human Factors in Aircraft Accidents” and Hancock and Desmond (2001) identify the vulnerabilities of the human operator to “Stress, Workload and Fatigue”. Finally, Robinson (1993) in his fictional account of the settling of “Red Mars” eloquently identifies the psychosocial and political vulnerabilities of complex systems involving people.

# The Grammar of Design

These concepts can be drawn together using the familiar grammatical construct of a sentence:

* I want to operate my car.
* Some people want to drive their cars to work in less than half an hour, while listening to their voice mail.
* Qualified drivers want to drive their racecars quickly and safely around the wet, winding racetrack.
* Well-trained astronauts want to capture a large satellite with a robotic arm.

These sentences articulate process requirements with varying degrees of specificity. Designers of the processes – driving, capturing – need more information to satisfy their customers. The first task is to identify the customers, and their perhaps differing requirements. The end user – I, the driver, the astronaut - may not be the only customer. Other customers include trainers, maintenance engineers, managers, legislators and the general public and they may have differing, perhaps conflicting requirements. Sometimes the customer may be an individual that has a tailor made [space] suit. On other occasions the end user may be one of a large population of users for minimally adjustable hardware. (If the glove doesn’t fit, try the next size up and if that’s too big, tough!)

A requirement must be articulated as an adverb that may be evaluated, assessed or validated by objective or subjective methods. The adverbs quickly and safely can be assessed subjectively and for this assessment to be useful it should reflect the consensus of all the customers. One way of improving the reliability of requirement assessment is to provide verbal or numerical anchors to the assessment statements. For example the requirement “quickly” could be quantified by a speed or a time to cover a fixed distance, under controlled environmental conditions. The “safely” requirement is more problematical and may be quantified in a safe / not safe scale, by articulating a continuum of possible outcomes – such as mission failure, crewmember fatality, subsystem damage – or by adding probabilistic statements that can only be assessed reliably in the light of experience with the operational system, or through simulation. Parenthetically, the best available estimate of the probability of failure of the Space Shuttle mission process is 2/113; however this only predicts an expected value and where confidence limits are placed around this point estimate, using the Binomial, Poisson or Normal distributions the 95% confidence level is of the order of an unacceptable 1/30. Such historical estimates are always suspect as learning occurs in most human managed processes and possible failure modes are eliminated in the light of experience, thus changing the system design and process reliability. In the car driving context, the biggest process reliability change would be to eliminate drunk driving which contributes to almost half of the 40,000 fatalities a year in the USA, but on balance driving is a very reliable process and most drivers who are “under the influence” don’t have accidents and most drivers who drive faster than the speed limit don’t get caught.

# Risk Assessment

The technology of risk assessment has progressed over the past few decades and there exist various standard processes for linking outcomes and likelihoods. (Raafat, 1995) These methods typically use nonlinear probability scales and ordinal outcome or severity scales, which are sometimes converted to a common currency, such as dollars. A fundamental shortcoming of these risk assessment approaches is that they do not usually address the tradeoffs that must be made with positive outcomes – benefits. Where a common currency approach is adopted it is possible to develop key ratios that relate costs and benefits (Peacock, 1998). A common metric in space flight engineering is equivalent system mass (ESM); this also fails to comprehend tradeoffs between costs and benefits and is therefore an insufficient decision tool. More sophisticated analytical processes are essential if we are to comprehend how space flight tradeoff decisions are made. Another challenge is related to the costs of development of countermeasures as well as the countermeasures themselves. For example, the development of a planetary surface suit that is both protective and offers good mobility and where there may be acceptable tradeoffs between protection and mobility, may have very high development costs and conflicting operational advantages and disadvantages. Very few car buyers purchase Hummers in order to increase their personal safety, but the evidence is clear that vehicle mass is a major contributor to accident outcomes (Evans, 1985). The issue of the tradeoff between “production and protection” is also very apparent in high volume manufacturing and materials handling processes. The shareholders and management want “productivity” whereas the union fight’s for “protection” and this tradeoff has been escalated to the highest circles in the country with the debate about ergonomics standards. (Peacock, 1993)

# The Design Process

The engineer cannot do his job effectively without requirements that can be validated. In other words the requirements statements must contain verbs and their associated adverbs that define process performance and the conditions or tests under which this performance is to be evaluated. For example a sports car may be expected to go from 0 to 60 in 6 seconds. A suited astronaut may be expected to travel 100 meters over a planetary surface in 5 minutes, with a heavy load of equipment.

Given these validatable operational or process verbs and quantitative adverbs, together with contextual information, the engineer and operations designers are in a position to start addressing the systems that may be needed to satisfy these requirements. Designers create things – nouns – and can only design them with quantitative information – adjectives. For example 0 to 60 in 6 seconds may be achieved with a big heavy car with big powerful engine or with a small, aerodynamic car with a small, efficient power train. The planetary surface astronaut’s task may be achieved with a rucksack or a golf cart. Once the engineer has the process requirements, he can then explore the systems (nouns) and their characteristics (adjectives) to develop concepts that may satisfy the requirements.

Unfortunately, the design process does not always work in this tidy way. The customer may not articulate clear requirements, but may seek to specify design options and impose requirements after the fact. For example the customer may ask for a small, aerodynamic sports car and may be disappointed when his luggage doesn’t fit in the trunk. An exploration program manager may specify a lunar rather than an orbital launch platform. Conversely, the engineer sometimes seeks requirements that fit his predetermined design specifications, much like the health care specialist with a limited set of interventions may seek diagnostic information to justify those actions. Such conservatism is sometimes justified as the system design characteristics may be well evaluated. The challenge occurs when the system is expected to meet new requirements. “If your only tool is a hammer, very soon everything begins to look like a nail.” These possibly unfair references often occur because of a shortage of research and development funding, but in the long run the new challenges of long duration space travel will require new technologies.

# Quality Function Deployment

An adaptation of Quality Function Deployment (McHugh, 1986) can provide the discipline of separating systems, processes, nouns, verbs, adjectives and adverbs. Quality Function Deployment employs a series of matrices that transfer information from market research through product design, manufacturing and production processes to sales and the rest of a product life cycle, including maintenance and recycling. The vertical axes of the matrices contain information about customer requirements and their quantitative adverbs, often obtained by benchmarking tests. For example, a space suit user may expect good shoulder mobility and the adverb may require this to match unsuited shoulder girdle function (an impossible task with current hard upper torso technology). A vehicle maintenance function may involve visual, hand and tool access and the quantitative adverb may expect spark plug change in 5 minutes – a process performance standard derived from comparison with other similar vehicles.

The horizontal axes (independent variables) contain descriptions of the systems (nouns) and their quantitative adjectives. These are system design specifications. For example maintenance access may require a cone with a minimum diameter of 20 centimeters. Radiation protection may require a material thickness of x millimeters. Eventually, the engineer must design the system with these quantitative values. Give the engineer a number. Unfortunately, no single number will ever be “correct,” at least where human subsystems are concerned. A tradition in engineering has been the inclusion of tolerances in specifications – a range of values around a point that is acceptable. Commonly, the engineer may assume that if he or she stays within the upper bound of the tolerance range then the implications in terms of performance will be acceptable. Unfortunately, tolerances have a way of “stacking up” and although all subsystem designs may be within tolerance, the total system may fail. For example, a space suit may have sets of different sized modules that accommodate a range of expected crew member segment sizes, but because of human body size and shape complexity, including imperfect correlation of segment sizes and changes due to microgravity, performance of an EVA activity may be compromised.

An alternative to traditional “tolerances” is the use of loss functions. This involves the identification of a target value, that will be ideal and not interact adversely with collaborating subsystems, and a non-linear function that “penalizes” deviations. As the system design develops, these penalties are amalgamated and a total system score is calculated. (Peacock, 2001) The decision process for system acceptance is based on a policy statement regarding total system score and identification of those subsystem deviations where the greatest impact may be made regarding process performance. For example a vehicle interior may specify loss functions for headroom, shoulder room, knee room and eye height as well as many other parameters (Roe, 1993). In the final assessment of perception of interior spaciousness or performance in a standard entry – egress test the design compromise will optimize the amalgamation of these multiple loss functions.

Formal testing of the relationship between individual (or sets) of system adjectives (independent variables) and process performance outcomes or adverbs (dependent variables) is the very basis of human factors engineering and its regression or analysis of variance tools. A shortcoming of this reductionist approach is that experimental management of many interacting and concomitant variables is often prohibitive, because of system complexity. An interesting alternative approach is described by the paradoxical statement that “ if a non-conforming system passes a [process] performance test then the system can be considered to conform.” Or to use a familiar truism: “the proof of the pudding is in the eating.”

# Human Factors in Design

This paradox envelops the relationship between human factors engineering and their designer and user customers. When human factors enter the design process late with usability tests of the total operational process it is often too late or too costly to rectify fundamental system design shortcomings. For example ergonomics intervention in automobile manufacturing may influence workplace design, tool selection and task content, but cannot change the main design problem of inaccessibility of a particular component. The same is true of maintenance of space hardware; if a suit is to be maintained on a remote planetary surface, there will be very different challenges from those encountered in a well-equipped workshop on earth. Conversely, when human factors is involved in the life cycle requirements planning early in the design process, it is more likely that a comprehensive set of performance requirements will lead to a corresponding set of system design loss functions and the sequence of evaluations as the design matures.

System design specifications can be verified and process performance requirements can be validated in an appropriate context. These important design evaluation processes are effective only if reliable testing processes accompany requirements and specifications. A generic phase of the design process can be described by analogy with the familiar educational process. The first component is the articulation of performance requirements – will the exiting students have obtained knowledge that fits them for their next course or phase of their careers? The proof of the pudding is in the starting salaries of graduates or better still, the final examination should include an evaluation (validation) of performance in analogous situations. Curriculum or course design specifications flow from the outcome requirements. If the outcome requires problem solving capability then the course curriculum should specify practice in problem solving. Verification of the curriculum, like verification of system design specifications, should be straight forward if the specifications have been articulated clearly and reliable tests have been planned and implemented. All too often classes are designed based on historical specifications, rather than customer requirements. The limitation of this analogy is that the educational and design processes are extremely complex and involve many subsystems, including teachers (engineers), classroom facilities (design facilities), students (internal customers) and employers (external customers.) However the discipline of process performance requirements (verbs and adverbs) first followed by system design specifications (nouns and adjectives) will assure a more satisfactory outcome.

The root of the design and education challenge lies in human variability and adaptability. Students may succeed despite their professors; vehicle customers may tolerate poor quality if the styling is exceptional, astronauts may succeed in their tasks despite design shortcomings. Conversely unprepared students may fail despite good professors and facilities; poor drivers may fail despite well-engineered systems, and astronauts (or their support entourage) may fail if their training, experience or readiness to perform are insufficient to meet novel or emergency situations. Examples of the former performance successes, despite subsystem failures, are to be found in the Apollo 13 and Skylab solar array incidents. Evidence of the latter failures were observed in the Progress collision and the Soyuz / Salyut tragedy. (Casey, 1993)

Design for human variability may be addressed in several ways. The obvious way is to reduce the [human] variability by meticulous attention to “humanware design” - selection, training, assignment and performance monitoring. Historically NASA has had great success in this respect although performance monitoring has always been a bone of contention among crewmembers who are reluctant to publicize their shortcomings. An analogous process in professional sport does not suffer from this shortage of evidence. The sports pages are full of the most detailed performance statistics of these highly talented, selected, trained and paid athletes. At the other end of the design spectrum, consumer product design, including automobiles and their usage contexts, must accommodate a wide variety of minimally talented, marginally selected, inadequately trained and rarely monitored users. Only catastrophic failures are documented and the usually forgiving context allows recovery from gross human error and minimal monitoring of inappropriate behaviors.

Design for highly trained and talented human operators is easier and more forgiving than for the broad population of consumers. But this can lead to complacency and over reliance on the human operator to accommodate for design shortcomings. It should be noted that even the best operators suffer from human fallibilities, such as inattention, fatigue, overload and debilitation. (Hancock and Desmond, 2001). Picture a good driver finding his way through a strange city, in the fog, on icy roads, to an important meeting deadline. Translate this into an astronaut, debilitated by a long interplanetary journey (or EVA), wearing a cumbersome suit, finding his or her way to a safe haven with limited consumables. The focus of system design must acknowledge expected use and foreseeable misuse. An automobile must be designed to protect an inebriated driver in the event of a high-speed collision. Space hardware must be validated in similarly challenging contexts.

Automobile design has a considerable advantage of an enormous amount of data. Space exploration is relatively data poor. Consequently space system design must take advantage of contemporary modeling, simulation and analog facilities. These facilities, to be predictive of human performance in space, must address human shortcomings as well as their successes. It is one thing to winter over in the Antarctic and suffer from frostbite, or run out of air in NEEMO and have your buddy lend you his spare regulator. It is altogether different with a minimally redundant crew on their way to a distant planet when the doctor gets toothache, a solar flare erupts or a piece of software misbehaves. The Advanced Integration Matrix (AIM) program aims to answer the challenges of expected use and foreseeable misuse with a comprehensive suite of digital and analog simulations and an extensive repertoire of what if questions, with particular reference to the many sources of human performance variability.

# Simple Rules for Process and System Design

* Differentiate between process requirements and system specifications.
* Develop tests for specification verification and requirements validation.
* Develop a comprehensive picture of system design interactions and process performance outcomes.
* Develop digital simulations of mission process performance and carry out sensitivity analyses of hardware, software, humanware and organizationware subsystem design ranges.
* Use contemporary tools such as Failure Mode and Effects Analysis, Fault Tree Analysis, Human Reliability Analysis, Quality Function Deployment and Discrete Event Simulation to evaluate expected use and foreseeable misuse.
* Comprehend human variability on all dimensions, including physical, sensory, cognitive, psycho-social and affective.
* Design in redundancy and forgiveness – make space travel as safe as driving to work.

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**Chapter 15**

**The Myth of User Centered Design**

User centered design is not a myth – all design is user centered – but human factors engineers do not own the practice, unless of course all designers are considered to be human factors engineers. The following discussion contains an explanation of this paradox together with an articulation of the boundaries of our profession.

All animals take steps to protect themselves from their physical and social environment and extend this defense into offense by physical and operations designs that give them an advantage over their competitors, sometimes through collaboration. Darwin explained the motivation and many of the mechanisms of this competition among and within species. The annual Darwin awards describe some ingenious but failed efforts (by *homo sapiens?)* to gain some advantage, either through engineering or operations design.

The purpose of engineering and operations design is to extend human capabilities; even some small brained primates have been observed to make use of tools, such as nut crackers. The process of design is predictive and should cater for expected use and foreseeable misuse. Use involves sometimes-conflicting criteria such as effectiveness (quality), efficiency (resource utilization), safety, health and satisfaction. Human use sometimes extends satisfaction to the lofty, but nebulous, heights of pleasure. The phases of this process include a mental model of how the engineered device or process will work and how it may fail, together with an assessment of the possible positive or negative outcomes. This stage models the behavior and performance of the resultant design in its context. The second design stage is to create some representative or physical (or electronic) model of the eventual system, commonly in the form of a drawing and some specifications, a computer model or a physical mockup. In many instances an analog will contribute information to the design process. The next stage (unless your designer took a concurrent engineering class (another myth) is to design the manufacturing process. Most of us could design or at least visualize a functional pyramid, but not comprehend the challenges of getting a bunch of reluctant Hebrews to build it. Even if we could design a car and the tools to form the metal and fasten it together, it is left to the operations designer to make this manufacturing process efficiently produce 1000 similar units a day, all with high quality. After all this design has taken place we have to manage the use of the product or process. This involves making sure that some foolish or incompetent user does not misuse the product and that the product continues to perform reliably over its designed lifetime. Finally we have to bury the worn out thing and its batteries in a landfill, or REDUCE, REUSE, RECYCLE.

Where does user centered design fit in? For a start all people are users and by definition will chose and operate some device, such as a chair, car or computer to enhance their capabilities or pleasure. ***The challenge is complexity.*** Whereas most people can visualize the operational use of a particular product, the actual design, manufacture, production or maintenance of most products (including hardware, software and organizationware) is beyond the capabilities of most people *(Norman - The Design of Every Day Things).* In fact, with the exception of a diminishing number of craft industries, most products are actually designed by teams of people, including – inventors, market research, conceptual design, engineering design, manufacturing design, production design, production operations management, marketing, distribution, sales, service and maintenance and operations management. Each of these teams turns specifications into products and hands over to the next phase, unless of course they have heard about concurrent engineering. Concurrent engineering is simply a way of adding constraints into the design process as early as possible. Human factors engineers join in this gig to use their knowledge and tools to anticipate expected use and foreseeable misuse. Human factors engineers, like cost analysts, industrial hygienists, lawyers, doctors and personnel people are rarely responsible for any one of these design activities. But they do have a lot to contribute to each stage, depending on how people interface with the process.

In fact, in large organizations, human factors engineers may not directly help the person responsible for a phase rather they may play the role of advising the advisers. For example, in manufacturing operations, it is the line supervisor who actually manages the operations personnel and he or she in turn is advised by the manufacturing engineer, the safety specialist, the quality guy and the industrial engineer. The human factors engineer is usually at least one step removed. In product design the conceptual designer, marketing specialist and the various engineers and managers collaborate on a product development team, and the human factors specialist has to be very polite when he is invited to the table, often at the behest of the company lawyer. And even then the contribution of human factors may be only to add color to the warning label that informs the eventual user that use of the product may be acutely life shortening.

This dismal picture paints the human factors engineer as a cosmetic afterthought and puts our aspirations of being in charge of user-centered design in perspective. Unfortunately, some models of the human factors process place the human factors engineer as a purveyor of ambiguous requirements, using the excuse of human variability, followed much later in the process as an ergocop with an exaggerated view of self-importance as he or she interprets the vague requirements and signs off on waivers when told to do so by a wise manager. Too often this clumsy process is due to the lack of knowledge of the human factors engineer of the domain in question. In defense of the HFE the acquisition of domain knowledge is not always easy, even after grounding in the local jargon and acronyms. This lack of domain knowledge of the human factors engineer can lead to a lack of credibility, both of the individual and the profession. The excuse that “you may understand the domain, but I understand how people behave and perform” is not good enough.

The challenge to the human factors engineer is of course human and situational variability. It may be easy to design car, navigation system, entertainment system and cell phone interfaces from first principles, focus groups and usability trials and estimate average or even fifth percentile performance levels of the user population. But the reality is that all these come together in the infamous single channel that is narrowed by grandma’s age, grandad’s tipple or some unforgiving traffic light. Even without human factors engineers, designers will design systems that suit many of the people most of the time, occasionally with the help of legislation, a product liability suit or simply product failure in the market place. Human factors engineers must learn to deal with their Achilles heel – variability, and not hide behind it in the hope that Lady Luck will be on their side.

There is a better way. Human Factors Engineers should adhere to the following rules:

1. Learn about all of Human Factors – body, mind and soul; behavior, performance and preference
2. Learn about statistics and investigation design – confounding and significance
3. Learn about your domain or find a friendly expert to run interference for you
4. Know your place as a supporter of the design process, not as an ergocop
5. Recognize that there are many “users” in the design and operations process

**Chapter 16**

**Transaction Time**

**Transactions**

The fundamental measures in Ergonomics are space, mass, energy, information, affect, money and time. A “transaction” adds a time dimension to the mix of energy, information and affect, and provides the opportunity and basic unit for measurement and analysis. A transaction may be lifting a suitcase, checking the time or buying a loaf of bread. Alternatively it may be a day at work or a journey across the country. A transaction can be described, measured and repeated. It will always have a time dimension and one or more spatial, force, information or affect dimensions; it may also cost or produce money. The human participation in a transaction may result in fatigue, learning or enjoyment. A more elaborate analysis of the outcome of a complex transaction includes effectiveness (quality), efficiency (use of resources such as energy, time, people, materials or money), enjoyment and satisfaction for one or more participants (the affective dimension); transactions may be easy or difficult to conduct on energy or information dimensions. Transactions may have desirable or adverse safety and health outcomes. Finally transactions may be repeated indefinitely under compatible contexts and may be resilient or otherwise to extreme contextual demands. The observable and measureable transaction, including its variable human, technological, operational and contextual participants and its various outcomes, is central to the practice of ergonomics, in research, simulation, analysis, design and evaluation.

**Complexity, collaboration and competition**

Transactions will usually involve one or more people, simple or sophisticated technology and a plethora of physical and operational contexts that cannot be changed but must be considered in transaction analysis. The outcome of a transaction may be success or failure, in the eyes of one or more of the people involved. Outcomes may be discrete and clear or based on subjective assessment. The operational context of commercial aviation involves schedules, communication among various participators regarding the use of resources, such as airspace and runways. Other participants may represent the airlines, customs and immigration officers. In competitive field sports there are opposing teams participating in a zero-sum game – if one team wins, the other loses. Various basic transactions are combined to constitute a game, or series of games. In soccer the transactions involve dribbling, passing, tackling and shooting, which may lead to successful or unsuccessful outcomes, depending on which side you are on. Despite these varying levels of complexity, transactions can be described, observed, measured and repeated many times.

**Physical transactions**

Physics deals with combinations of mass, space and time to describe energy: 1 Joule = 1kg\*m2/ s2. Energy is described in different ways, such as potential energy, kinetic energy, mechanical energy and thermal energy all of which obey a law of conservation that suggests that energy is not lost, but it may be transferred, change its form or stored. Other important physics considerations are that we are surrounded by gravity; that Force = mass times acceleration, and that Newton offered a perceptive description of why things move or stay in place. People eat and move, and if these are not balanced they store energy as excess fat; furthermore, with training, and the right choice of parents, people greatly improve their capabilities at transferring food into mechanical energy, plus “waste” energy in the form of heat.

A basic physical transaction is “the step”, a milestone in a child’s development. This involves a contraction of the plantar flexion muscles of the ankle and knee and hip extensors to raise the body against the downward pull of gravity; the body then falls forward and the downward motion is arrested by the other heel striking the floor. The physiological mechanisms of this transaction include controlled muscle contraction, which requires energy plus tactile, proprioceptive, vestibular and perhaps visual and auditory feedback. Over time the basic mechanisms become reflexive and automated and many variations on the basic transaction (the step) are developed to enable walking, running, stair climbing, side stepping, dancing and gymnastics. This progression is the result of maturation and practice as the person develops larger, more varied and more complex transaction chunks, which are observable, measurable and repeatable.

**Information transactions**

Information science describes a ‘bit’ of information as log2n, where n is the number of (equiprobable) choices; greater mathematical complexities are needed where items of information are not equiprobable, which is usually the case. Shannon’s theory of communication describes the following elements of Information transfer: Source – transmitter (encoder) – medium – receiver (decoder) – destination, to which may be added, as with energy, the concept of storage or memory. Another important aspect of information transfer is feedback from the receiver to the sender to confirm accurate and timely transmission, although the one way broadcast mode may sometimes be chosen, sometimes with delayed feedback. The transfer of information is measured in bits per second and some communication media have greater capacity than others. Over time larger and larger chunks of information are created to produce meaningful messages. In psychology, information manipulation and transfer is called cognition, which has numerous components, including perception, prediction, decision making and control. Unlike energy, information may be lost during the transfer process or clouded in noise – information from other, usually unwanted sources. The familiar process of forgetting involves a failure to retrieve once stored information. Also multiple sources of information, when combined before, during or after a transfer process may give rise to new larger and more complex chunks of information; this, as with walking, is the process of learning. A metaphor is the book which consists of words, sentences, paragraphs and chapters that are bound and labeled to produce a story.

In applied human factors the communication of these more or less complex chunks of information are characterized as transactions. The transaction may be measured in terms of time and the accuracy or otherwise of the outcome, plus some form of immediate or delayed feedback. We switch on our computer and a log in screen appears; we enter our credentials and our home page appears; we enter a URL or click on an icon and our e-mail or a web page appears; we examine the contents, type a message and press return to complete our transaction sequence. This transaction takes a variable amount of time and the outcome success or otherwise will be fed back to us at some future time. In reality there are millions of such transactions that are measurable and repeatable with variable times and outcomes. The intent of human factors is generally to minimize transaction time, to ensure transaction accuracy and guarantee a successful transaction outcome. This simple intent is complicated by variability among the people involved, the vagaries of the technology and the influence of other external factors than cannot be changed but must be guarded against.

Consider the simple challenge of ordering a meal at a restaurant. The customer looks at a menu and makes a selection following suggestions by a smiling waiter who scribbles down the order and reads it back for confirmation, then passes it on to the, perhaps less happy, short order cook; a short time later the still smiling waiter brings the, hopefully correct, meal to your table, followed sometime later by the bill. There are of course quite a few variations on this transaction format. Now, in the interest of accuracy and productivity, we develop an automated ordering and payment system, with many colorful pictures of sumptuous meals and prices according to size and embellishments; these pictures are surrounded in emoticons aimed at replacing the waiters smile. Whether automated or with the help of a waiter, this communication transaction will take a variable length of time and may generate errors at various stages. The eventual bill, thanks to the addition of automation may contain a dozen or more information items for the sake of posterity. The transaction sequence is repeated many times, with or without automation, throughout the world in many contexts; it is observable, measureable and repeatable.

Consider next you are driving a car in a stream of traffic. The car in front brakes hard. You see the LED center high mounted stop light flash and automatically move your foot off the accelerator and across to the brake; you may be a foot lifter or a foot rocker if you leave your heel in one place. Hopefully you hit the brake hard enough and stop short of the car in front. But the driver of the car behind you is talking on his cell phone and has cruise control activated. Bang! You are shunted into the car in front and then bang again as the fourth car pushes the third car into you again. The keys to this sequence of overlapping transactions are reaction time and response time. Your reaction time was aided by the short rise time LEDs being in your forward field of view rather than the slower incandescent traditional brake lights. You may also have gained a head start on this transaction by noticing the slowing of vehicles further up the line thus enabling anticipation. The driver behind you was distracted and the cruise control continued to operate until his foot left its resting place and moved over to the brake, causing a further extension of his transaction time. This sequence of events can be described as an overlapping series of transactions, each of which is observable, measurable and repeatable. Changes in the parameters of these transactions, such as reaction times and vehicle speed and spacing, may affect the outcomes. The debate is whether adaptive cruise control is superior to attentive drivers in avoiding unwanted outcomes on urban freeways.

A third observable, measurable and repeatable transaction involves landing an airplane, with or without the aid of automation and in variable wind conditions. This transaction is constrained by time, vertical and horizontal distance, and speed. The attentive pilot will look at his instruments and out of the window, and if the changing scene suggests that he is “low and slow” he must quickly add power and “go around” to make another approach and landing. In the case of Asiana Flight 214, the pilots “over relied on automated systems that they did not fully understand”. This confusion, led to a delay in the decision to manually initiate a “go around”, given the airplane’s unsafe approach.

**Affect**

Affect is less easily measured or understood; it deals with likes and dislikes which may be combined with importance or weighting factors. These weighting factors result from past experience and anticipation of future outcomes. Affect may also be vulnerable to environmental and social pressures and fashions. Affect is what drives our emotions and motivations to create opinions and behaviors. Affect also varies over time, sometimes it drifts gradually and sometimes perhaps a minor incident may cause a monumental change; such changes in affect and perception can be articulated by the “halo” or “pitchfork” effects, depending on the direction of the change. Money is a derivation of affect, it intermingles with energy and information, to constrain behaviors, form opinions, drive motivations and explode emotions. Money makes the world go round, it is the root of all evil and “*Geld macht nicht Glücklich, aber es Beruhigt.“*  From the ergonomics viewpoint, money and affect complicate everything! The analyst who ignores these affective and emotional factors does so at his own peril!

In the case of consumer behaviour the purchaser may assess the physical and informational features of a product, but be more influenced by non-functional or cosmetic characteristics. Consider the purchase of a car, the selection of a child’s toy or the choice among alternative forms of footwear. In each of these examples the consumer may allow either fashion or price to dictate the decision, which may be done quickly, on “impulse.“

**Some notable transactions**

Drinking a cup of tea and landing an airplane are examples of transactions. There’s many a slip twixt cup and lip; spilling a hot cup of tea in your lap may be quite uncomfortable, as too may be a hard landing. These transactions are carried out many times, every day, with a wide variety of people, technologies and contexts. Both transactions involve energy, information, time, money and affect. The outcomes of the transactions may be measured on many dimensions, including time, accuracy and style. Running a marathon certainly takes motivation and time and uses energy, and various outcomes produce a lot of emotion; the motivation to return next year increases after the pain has diminished. Buying a complex product, like a car or computer, on a complex website using a complex mobile phone application also takes time and may or may not have an accurate or pleasing outcome.

These examples represent a spectrum of transactions that are repeated and measureable. They are clouded by variability among the participants, technologies and contexts. They all take time. They all have measureable outcomes. They are all amenable to ergonomics analysis and design as people are involved in some way in the transaction. The tools of analysis are measurement instruments, probability and statistics; the tools of design involve compromise and cost constraints, and are driven by affect as well as some more tangible considerations of energy and information.

**Ergonomics practice**

In practice, ergonomics deals with particular cohorts, conditions and conclusions. The transaction and its outcomes are well defined, at least in statistical terms. The ergonomist may report one thing to his colleagues through the medium of forums and publications and something else to the customer who is responsible for change. This customer will be thinking of a thousand other things apart from the reductionist ergonomics advice. Design is about compromise. Design is also about the long and short term, including the many repetitions of the transaction of interest, and its variations.

First a physical ergonomics situation will be explored to explain the compromises in transaction design. Consider a sick patient in a hospital bed who from time to time has to be moved for bathing, sleeping, eating, exercise or treatment. This movement transaction involves the patient, the nurse, some technology, time pressure, expense and certainly affect. From the physical viewpoint, the transaction involves moments (force times distance) that will be repeated many times during the nurse’s and patient’s day. Biomechanical analysis involving large immobile patients and small fragile nurses will conclude that the moments and movements are too large and transaction is impossible to perform safely. So the ergonomist suggests technology – let a robot grab the old lady and move her up the bed so she can eat her lunch. But the old lady may not like robots, and anyway robots are expensive. Impasse and rapid deterioration! Compromise is needed. The ergonomist then suggests less elaborate technology or administrative controls such as training and method change - including getting two nurses to do the job. But for reasons of mechanics and money these suggestions too are rejected. More compromise is needed. This doesn’t work either. So the result is that sick patients and motivated nurses all over the world make the best of their situation. Ergonomists need to be both finders (analysts) and fixers (designers); they also need to simulate their suggestions before implementation and objectively evaluate their designs in the real world. The same problem occurs on a vehicle assembly line where well-meaning materials handling aids are bypassed in the interest of convenience and productivity.

A second example, more related to the information dimension, involves a professor and a class of students. Here we have people, information, technology, money, affect and time. The transactions are repeated many times for years and years. The solution to this mass transfer of information is technology? First it was the printing press and books, but these did not make the teacher redundant, because the teacher’s job is to motivate and explain and not just to be a knowledge delivery vehicle. Now the delivery media are the Internet and portable technology, but still we need the teacher for elucidation and motivation. This contemporary teaching technology manacles the students and teachers to a knowledge conduit (lap top or smart phone?) for long periods of time. This is not conducive to effective learning or good health, unless it is punctuated by active participation with the teacher, colleagues in study groups, and with the vast amount of related information on the Internet and in the academic and technical literature, and through empirical investigation. Currently the explosive development of eLearning tools is being pushed upon rather than pulled by the student community. The transactions include elements of motivation, delivery, discussion, consolidation and examination at the micro and macro levels, according to Blooms taxonomy of learning stages. In practice these transactions may be more chaotic than precisely managed. The educational transactions, like chunks in information theory, vary in size and content; they stick together and grow; they need fertilizer and sunlight, and not torrential rain or frost. They need collegiality and collaboration, not inundation and asphyxiation. They need clarity, not obscure metaphors.

**Affect - The Kano Model**

The Kano model describes different levels of requirements in product design – “must have”, “more the better” and “excitement” factors; over time as the product matures the “excitement” and “more the better” features may become “must have.” These requirements are extracted from existing and potential customers by questionnaire, interview and focus group methods. Whereas many of the factors may relate to physical and informational dimensions, most have overtones of affect and preference. The earlier application of this Kano approach to product design may be extended to service evaluation, and more recently to job and organization evaluation. A recent study of employment of elderly Singaporeans indicated, similar in some ways to the Herzberg two factor theory, that basic requirements of collegiality and job content were must have features, even more so than salary. These investigations using the Kano principles revolved around describable activities or “transactions”. The Kano model is a powerful concept because it describes the influence of affect in transaction strategy, behavior and performance.

**EPICTC**

EPICTC stands for Effective Performance in Information Complexity and Time Constraints. It is the title of a research project to study why transactions have successful or unsuccessful outcomes. The transactions of interest may include: How does a nurse deal when confronted with a rapidly deteriorating patient? How does a pilot land an airplane when the supporting technology fails? How does a games player or referee decide what to do in a developing dynamic situation? When should a policeman decide to use his weapon? What should a driver do when the car in front stops quickly and the driver in the car behind is on cruise control or using his cell phone? Such transactions occur frequently and have common components – information complexity, outcome stress, time constraints and various levels of expertise.

These transactions occur for real in the outside world and can be simulated in the laboratory with widely available computer based virtual reality. Similar transactions are also found in the widely popular video game world. Children of all ages participate in these transactions for entertainment; they fail and succeed and progress to the next level of complexity; they practice to reduce their transaction times. They develop expertise in dealing with information complexity. The key to the success of these games is the provision of immediate feedback regarding the outcome of a transaction. Learning theory is full of material on positive and negative outcomes and feedback. Human transaction performance related to real world situations may be tested under manipulated conditions of outcome stress, information complexity, time constraints and expertise.

**Transaction Time**

Transactions may involve one or more people, various levels of sophistication of technology, rules and regulations and many outcomes. Transactions involving energy, information and affect often in an unpredictable context. The challenge for the human factors engineer is to define, describe and delimit the transaction, and then develop appropriate measures and methods of measurement, including measures of process – the input variables, contexts and outcomes. The human factors specialist will also describe the target population and develop reliable samples, in theory random samples, but in practice usually convenient samples. Given these data and, appropriate statistical analyses the investigator will identify causes and effects and suggest technological or operational interventions.

**Chapter 17**

**Rule # 1: The Customer is Always Right?**

This article is about the pitfalls of usability testing, the importance of sound methodology and reliance on proven theory.

**Preference, Behavior and Performance**

The ultimate purpose of ergonomics / human factors is performance – transactions should be carried out effectively, efficiently, safely and to the satisfaction of all concerned. A transaction is any interaction of a user with an engineered or natural situation in whatever context. Think of a transatlantic flight, jumping out of an airplane, booking a flight on the web, handling your baggage and deciphering the small print when your baggage has been lost. Performance measures can usually be reduced to measures of time and accuracy – accuracy being a measure of the deviation between the intent and the result; time is usually a reflection of efficiency – the utilization of resources. Sometimes “performance” is indicated by customer satisfaction, perhaps with esthetic underpinnings, such as the “performance” of a hairdresser.

We often have difficulty with performance measurement in usability testing – sometimes this is due to our failure to describe performance in tangible terms. Behavior begets performance. People have different physical, sensory and cognitive characteristics; consequently, when faced with a given set of circumstances they behave differently. This different behavior may result in satisfactory or unsatisfactory performance. Just look at differences in web page navigation techniques – even among those pages that have passed the usability tests.

Despite all our attempts to study and design for performance and accommodate a wide range of behaviors, we are often faced with the ultimate challenge - individual preference. This fact has been brought home to me in a resounding fashion by my attempts to please the buyers and builders of cars and the users of space vehicles. The customer is always right?

In a fair world we would define the range of acceptable performance, accommodate the spectrum of possible behaviors and allow as wide a range of preference that is compatible with the restrictions of behavior and performance. We should not allow the use of sledgehammers to crack nuts, even if some nuts prefer that behavior. We should not allow our sixteen year olds to drive our Corvettes, even if they have passed driver’s ed’. We should not design low contrasts into our computer interfaces, just because some (younger) users prefer it that way.

**The Rules of Measurement**

We apply measurement and analysis so that we can design something. We measure people, the things that we can change (the independent variables), the things that we cannot change (the context of use) and the outcomes of our designs – performance, behavior and preference (the dependent variables). If we had paid attention to our first few classes in quantitative methods we would remember that there are some vary important rules of measurement. First we must calibrate our instruments – whether they are rulers, electronic sensing devices, simple checklists or surveys. We must be confident that our tools don’t produce “measurement artifacts”. Even simple psychophysical techniques are susceptible to errors imposed by the instructions to the subject. Our measures must be accurate. They must not result in systematic bias, we must minimize the random or residual error and we must avoid blunders. For example, have a sample of measurers measure the joint angles of a sample of subjects? You will observe systematic and random errors, and blunders.

The next rules of measurement include resolution and precision. They are not the same. Resolution is the number of decimal places. The distance between my home and my work is 1.2345678 miles, as the Shuttle flies. The last six digits are unlikely to be of any use to anyone. The height of my chair is 16.54321 inches. So what? We should not attempt greater resolution in our measurement than is likely to be useful. Precision works in the opposite direction. The dimensions of my roll-on suitcase are 22x14x9 and weighs about 70lbs., more or less depending on how much I have packed. A lack of sufficient precision could cause me considerable inconvenience and embarrassment when I find that the bag will not fit into the overhead bin and I have to pay excess baggage. When measuring people, our instruments must be sufficiently precise. The questions: how much can you lift? or how fast can you run? are best supported by precise instrumentation.

Finally we have reliability and validity. Reliability is about repeated measures, perhaps in different contexts. We may have multiple instruments, multiple observers, multiple subject samples and multiple occasions. Reliable measures are not affected by these contexts. “Get real,” you may be thinking. In practice reliability (or lack of it) is a major headache for human factors engineers that demands considerable expertise in experimental design. Validity is another challenge that comes with many faces. The bottom line is that the measurement should be predictive of the eventual performance, behavior or preference in the real world. If the usability test is not predictive, then it is not useful. But validity is a two edged sword, sometimes we use invalid tests to prove a point that is not important in the long run. For example we sit the customer in a car in the showroom and ask him to assess seat comfort, without discussion the context of use – commuting, off road or long distance. On some occasions we have to do our best to simulate the eventual context – it is difficult to study microgravity effects on performance and behavior on earth (except through flying parabolas in a KC135 or riding in a centrifuge).

**Expected Use and Foreseeable Misuse**

Engineers design things for intended and expected use. Lawyers thrive on foreseeable and unforeseeable misuse. Ergonomists have the unenviable challenge of pleasing most of the people most of the time, including the users, the engineers, the lawyers, the juries and the historians. Expected use begs the question of who is the expected user. Will it be average Joe, granddad or a superhero? Will it be on a train or in the rain, with a spoon or on the moon, with a plant or in a plant? Does foreseeable misuse include the operation of a car at night, when intoxicated or when someone else crashes a red light? Does foreseeable misuse include our less than average Joe using a weight-training machine designed for an NFL lineman? Should grandma be “allowed” to use an ATM, a VCR, a cell phone, a PDA or the Internet? Should a rock star be allowed to fly into space? Should a handicapped person be allowed to work?

A recently popular term is “universal design.” Taken at face value this is an impossible and unrealistic dream. System design must comprehend the capabilities and limitations of the expected users. This means that some amount of selection, training and assignment is implicit in design. In reality “universal design” implies the accommodation of a greater variety of people in a greater variety of contexts. The challenge to usability testing is to offer reliable and valid evaluations for expected users and foreseeable misusers of all or most shapes, sizes and abilities and in a broad range of contexts. What exactly is meant by “most”? Finally, remember we have to keep both the engineers and the lawyers happy as well as the intended and unintended users.

**Statistics and Experimental Design**

Fortunately the well-prepared human factors engineer acquired the knowledge necessary to address all these challenges while he or she was in graduate school. Unfortunately many conveniently forget the rules of measurement and design, because they are too complex, inconvenient or perceived as being infeasible in the context of their work. Statistics is simple – all it requires is knowledge of probability, agreement on risk levels and application of various tests to assess probable differences and associations. Experimental design is another kettle of fish. If you don’t ask the right questions of a reliable and valid sample of users, no amount of statistical analysis will give you the right answers. This sampling issue is a common shortcoming of human factors investigations.

All human factors investigations (experiments, evaluations, measures – call them what you will) involve the following elements – conditions (independent variables), contexts (uncontrollable variables that must be taken into account in the design so as not to confound the conclusions) and dependent variables – usually measures of performance, behavior or preference. It is common for human factors investigators to focus on the conditions (independent variables) of interest. This may be a work place, a work task, a work load, a work pace or a work piece. We manipulate the levels of each of these conditions and balance them to allow us to assess interaction effects and to avoid confounding. Confounding is the assignment of cause to the wrong source. For example if we were to measure driver habitual speed as affected by type of vehicle and did not control for road and traffic conditions we may get spurious results.

The biggest challenge is those contextual “uncontrollable but important” variables. The issues of physical context are generally amenable to understanding and produce caveats on the conclusions. Behavior and performance in a simulator will always lag (or exaggerate) reality to some extent. Indeed the use of simulators to take the user beyond normal safe operations and through failure (and perhaps recovery) may be very beneficial in both training and design. The most important “uncontrollable” variables are the between and within subject factors. Unfortunately these challenges are ubiquitous and the Achilles heel of human factors investigators. Even with the best will in the world it is rare for a human factors investigator to have access to a truly representative (unbiased) sample of expected users and possible misusers. Also it is impossible to prevent subjects from learning things that affect their behavior and performance (the experimental outcomes – dependent variables). Sample size requirements in reliable “between” subjects design is much greater than the more efficient “within” subjects design where an individual subject may be exposed to multiple experimental variables. Validity is another kettle of fish.

These challenges are attacked by adopting between subject designs – where different subjects or subject samples are assigned to different experimental conditions. The analysis of these “mixed model” or “random factor” designs involves robust comparisons between the main effects and the main effect times subject interaction. But such designs are often inefficient – they require many more subjects. They may also be unintentionally biased because of non-random assignment of subjects to conditions. Within subject designs make good use of subjects – while you have the subject there you might as well use him in all the conditions. You may also use the subject as his own “control” so that inherent subject biases are removed. (Think of the paired sample T test). But subjects learn and may also become fatigued – which in a general sense has the opposite effect of learning. These between and within (learning) subject effects may often completely obscure the effects of the conditions of interest – the only reliable solution being to have unrealistically large sample sizes.

Because subject and learning effects are ubiquitous, it behooves us to always address the problem in the design of experiments with as much gusto as we address the conditions of interest. If the informed reader will permit the assumption that there are no other systematic interactions between the condition and trial or the condition and subject then the Latin Square can come to our rescue:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Subject / Trial | **1** | **2** | **3** | **4** |
| **1** | C1 | C2 | C3 | C4 |
| **2** | C4 | C1 | C2 | C3 |
| **3** | C3 | C4 | C1 | C2 |
| **4** | C2 | C3 | C4 | C1 |

In this basic design each subject is exposed to each condition and each condition occurs at each location on the learning (trial) curve. The astute observer will note that the conditions are in a fixed sequence (C2 follows C1), which may result in unwanted (but hopefully unimportant carry over effects. However, the philosophy behind this design is sound – it accounts for the unwanted confounding of subject and trial effects. Where the main condition effect is complex, such as where there are multiple conditions, some of which may interact, then these factors must be balanced within the main Latin Square. Tombs have been written on the intricacies of experimental design; it is the responsibility of the investigator to ask the question – “are my conclusions accurate, reliable and valid?”

**The Voice of the Customer**

The foregoing discussion should have convinced the honest ergonomist of the sea of landmines inherent in extracting an accurate, reliable and valid voice (performance, behavior and preference) of the customer. Frequently, our sample of customers (users) are biased, our sample sizes are not sufficient, our contexts are invalid and our predictions are likely to be inaccurate. If you don’t get the right answer ask another customer (focus group). We should give up now while there is still hope! Ergonomists should stop measuring people! But there is hope – we have an ocean of accurate, reliable, valid and useful evidence in our literature. This evidence was collected by researchers (not only human factors researchers) who obeyed all the rules and whose communications passed the peer review processes. Much of the evidence has stood the test of time and much of it is based on sound scientific logic and principles to support the empirical evidence. Unfortunately, some of our “evidence” is mythical – unsupported by sound theory or data. So there is job security for our research brethren. There should also be job security for the practitioner community, so long as they obey the rules.

**Chapter 18**

**The Yin and Yang of Ergonomics in Design**

**(with Chui Yoon Ping)**

**Key Words:** Yinyang, design tradeoffs, cars, smart phones, educational technology, production lines and pretty shoes

**Abstract**

Yin yang is a concept, attributed to Confucius, which suggests that apparently opposing forces or dualities are actually complementary, interacting and inevitable. All designs have these positive and negative characteristics and a broad ergonomics approach can help with the balance between the desired and unwanted outcomes of design. Examples are offered from transportation, mobile technology, educational technology, production lines and products whose functions are primarily esthetic.

**Introduction**

The purpose of this paper is to look at ergonomics from a big picture viewpoint, reflect upon some classical concepts, present some cases and offer some suggestions.

Yin Yang is a concept, attributed to Confucius, which suggests that apparently opposing forces or dualities are actually complementary, and inevitable. Gaia theory suggests a high level self-regulating mechanism between organic and inorganic earth systems to maintain conditions for life on earth. Dynamic equilibrium in Chemistry describes reversible reactions to maintain stability. Newton demonstrated that static equilibrium occurs in the presence of equal and opposite forces; he goes on to show that unbalanced forces cause change. The regulation of heart rate, blood pressure, body temperature, balance, eye movements and body weight are examples of the interactions between external demands and internal responses, all aimed at maintaining stability. Even social, economic and political systems can be viewed from this dynamic equilibrium viewpoint, as can riding a bike or flying an airplane. Winning does not exist without losing. Beauty and speed are relative. Design is about creating change without generating too much opposition.

**Product and Service Design: Many Stakeholders and Purposes**

These examples describe control activity aimed at creating change according to some predefined purpose. However, when we design a product or service there may be many users and stakeholders who have different purposes. These purposes may be described as follows (E4S4):

* Effectiveness – does the product or service achieve the intended purpose?
* Efficiency – does the product or service make optimal use of resources, such as time, money, people and materials?
* Ease of use – Is the product or service easy to use by the intended user and difficult to misuse?
* Elegance – Does the product or service have emotional appeal?
* Safety – Is the product or service safe and healthy to use?
* Security – Is the product or service vulnerable to malicious misuse?
* Satisfaction – Have all the stakeholders and their various purposes been considered?
* Sustainability – Is the product or service reliable under intended conditions and resilient in unexpected or extreme conditions?

Ergonomics in design must consider all these purposes and the tradeoffs among various stakeholders, who may have different priorities. When we design any product or service that is aimed at making a change for a particular purpose we will encounter failures in the eyes of other stakeholders. For example, what would we call a product the kills 100,000 people a year? A car! What would we call a product that puts an end to a war? A nuclear bomb! What would we call a product that causes untold frustration for teachers and students? Educational technology! What would we call a process that causes a tenfold increase in productivity? A production line! What would we call a process that causes carpal tunnel syndrome? A production line! What would we call a product that gives us infinite connectivity with our friends and the Internet, and causes countless distractions and casualties on the roads? A smart (?) phone! A pretty pair of shoes may fulfill their esthetic purpose but fail miserably in the rain or snow.

**Ergonomic Ergonomics: it all depends on the context**

Ergonomics is both a process and a profession. The word “ergonomic” should be banned forever. An “ergonomic “chair may have dimensions and adjustability features that match the anthropometric details and activities of a certain population of users and uses, but when overused it causes back pain, obesity, circulatory disorders and eventually death. An easy to use cap for a medicine container may be misused by children, but a cap that protects the unintended user may also interfere with use by the intended, perhaps old and feeble, user. An efficient airport security or website access system that gets users through quickly, may not offer sufficient security capabilities to deter malicious misusers. “Ergonomic” usually refers to a subset of the intended purposes of a product or service. Almost all product or process designs, even though successful by some criteria will fail on others. Therefore “ergonomic” is only relevant given the context and some purposes of a subset of stakeholders. Ergonomics on the other hand is a process of evaluating all intended uses and users and advising the designer regarding the tradeoffs that should be considered.

**Yin and Yang, Action and Reaction, Benefits and Costs**

All product or service designs, that by definition are intended to cause some “unbalanced force” or desirable change, will inevitably encounter some unwanted outcomes or reactions, for some stakeholders on some criteria. So what is the role of the ergonomist in design? In most situations it is the task of the ergonomist to “lay all the cards on the table.” Given this Yin-Yang information and an understanding of the possible biases and probabilities, it is the role of the designer, marketer, manager, consumer and society at large to weigh the ergonomist’s evidence and make wise decisions with due regard to the benefits of success and risks of failure on all important dimensions. The ergonomist is usually an advisor, not a decision maker.

**Applied Ergonomics: the Yin and Yang**

The ergonomist can contribute to making cars safer, smart phones really “smart,” educational technology easy to use by all concerned, production lines user friendly, and elegant items functional. The hierarchy of controls puts engineering controls first, but when that cannot be achieved, which is often the case, administrative controls must be designed, evaluated and implemented. Engineering controls include process elimination, substitution, intrinsic design, or built in barriers to misuse, including personal protective equipment. Administrative controls include selection, training and assignment, facilitators (instructions, warnings, and procedures), exposure control, and operational context management. All of these interventions must themselves be cognizant of the yin and the yang, actions and reactions, and the costs and benefits. A tall order! The following examples address ergonomics measurement and advice regarding some familiar dilemmas.

**Making cars safer**

The price of modern cars includes of the order of 10% for safety features. These include hazard detection and warning devices for the vehicle, roadway and driver, and mitigation devices, such as air bags and crumple zones, in the event of an accident. Despite these costly engineering features the car and its two wheeled motorized cousins remain intrinsically unsafe devices. “Speed kills.” Smart, driverless cars, will need considerable intelligence to deal with contextual and “controller” variability. It is one thing to drive hands free along an empty freeway, but altogether a different challenge navigating busy city traffic. Thus it is the task of the system designer to address the roadway, the driver and the operational context through engineering and administrative controls in order to significantly reduce the global carnage on the roads.

On the roadway, segregation is one policy, but intersections and journey flexibility remain a challenge. Segregation of all different sizes and speeds of vehicles would be a design and organizational nightmare. The self-limiting Gaia solution is to allow so many vehicles into limited roadway space so that congestion slows the traffic to a crawl and the severity of accidents is reduced, although the incidence of minor accidents may increase. The opposite strategy – “build more roads” – will inevitably attract more traffic and the cycle will continue. The economic solution (Singapore imposes large taxes on cars) aimed at increasing traffic speed is viewed by the less fortunate as discriminatory, although effective, efficient, safe and appealing public transport can soften the blow to one’s emotional reaction. Another economic solution – raise the price of fuel and city center road taxes – inevitably precipitates a public outcry. Speed management though administrative controls is open to abuse so engineered interactions of the cars with external systems, perhaps using GPS, may be a feasible alternative. However, these engineering and administrative “solutions” all have their downside; they are all restrictive, rather than enabling for “the common good.” Consideration of these interventions, limitations, benefits and costs may be beyond the pay grade of your average ergonomist. However, the ergonomist should go beyond the micro ergonomics level of product and process evaluation and consider the bigger picture of the yin and the yang. Cars are a great invention, except for the traffic.

**Really smart phones**

Smart phones have only been with us for a few years, but now they are ubiquitous. They are amazingly useful devices and attractive nuisances. Quite inexpensive too. A recent informal survey on the Singapore MRT, perhaps a biased sample, indicated 75% utilization at any one time for communication, entertainment or work. A similar survey, while walking down the street, showed 25% of pedestrians not looking where they were going. When these devices are mixed with wheels, 20% of taxi drivers use them, as do many cyclists, these wonderfully attractive devices become lethal weapons. The hands free argument is invalid – the main issue is cognitive capture that adds to the visual and manipulation resource overload. Users on public transport are considered by many to be annoying, but it is important to let your spouse know that you will be home soon.

What about feasible engineering controls? Using GPS, one could disable the device if the vehicle or person is moving, especially at a high speed. This would be very unpopular. Consequently the solution to the inevitably increasing downside has to be administrative controls. Education and training? Not a chance! Enforcement through fines? Infeasible because of the scale, but sufficiently large fines could be a deterrent. Automated monitoring by Big Brother? The civil liberties lobby would have a lot to say on this strategy. This is a problem without an immediate solution. Long term self-regulating Gaia may be the only answer?

**Educational technology**

The world of education is moving like a Tsunami towards e-Learning. The education technology pushers are offering an exponential variety of systems to help the professor teach and the student learn. Collaborate, articulate, cogitate, investigate, resonate, assimilate, evaluate, asphyxiate, etc.etc.etc. The physical interfaces are somewhat usable, but it is the informational interface that presents the greatest barriers to effectiveness, efficiency, ease of use, elegance, safety, security, satisfaction and sustainability. The educational technologists proclaim: “any place any time,” but the students are gregarious and like to come to class. The traditions in face to face education have a lot of inertia. The students are also cunning; they will contrive and cooperate to adapt the system to their own purposes. The professors are equipped with so many delivery options, dreamed up by the educational technologists who fail to recognize that education is no longer about the transfer of knowledge; this can be done far more effectively by the Internet. Rather the contemporary role of the teacher is motivation, explanation, guidance and testing, not inundation and intimidation. More testing will become automated as this Tsunami gathers force. Is being taught and tested by a live teacher really necessary?

So what can the ergonomist do? Well he or she could start by canvassing the voice of the customers – the students, lecturers and administrators. But the voice of the customer is often biased by their experience with the promises of benefits by the purveyors of educational technology and the education administrators who don’t want to be left behind. Second the cognitive interfaces could be improved enormously by allowing an easier selection of functions and features, one size does not fit all. Third Gaia could be accelerated by implementing field based ethnographic trial and error approaches to remove the ineffective, inefficient, uneasy to use, inelegant, unsafe, insecure, unsatisfying and definitely unsustainable systems. Even ergonomics professors face these challenges.

**Production lines**

Frederick Taylor, Henry Ford, the Gilbreths and their generation made enormous productivity and quality contributions to industry by the introduction of standardized, short cycle work on production lines. These principles are alive and well today, especially as manufacturing moves to the developing countries where labor is cheap. Where was your smart phone or tablet manufactured? The down sides of production line work are physical, mental and social damage. But the workers have no choice because of their economic condition. A ten to fifty second job cycle putting together cars, computers and cell phones or cutting and packing meat and vegetables is not what the readers of this article would want their children to aspire to. Ergonomists should all spend some time on a production line.

The engineering intervention is through robotic assembly and automation, but that is more costly than manual labor and anyway the developing country’s employees need employment to buy food, shelter and contemporary commodities. The ergonomist can help through workplace and tool design and even by product design for assembly, but the real challenge and opportunity are through administrative controls. Team structures, job enlargement and job rotation may not lead to job enrichment, but they will reduce the ravages of repetition. Carpal tunnel syndrome and tendinitis are no joke; but labor is cheap and employees are dispensable. The Yin and the Yang have returned to their Chinese birthplace. The Japanese manufacturing industry a few decades ago introduced participative and collaborative team based structures to provide employees with a voice in this labor intensive production environment. Progressive companies can become more paternalistic and intervene before Gaia has her say through combative unions. The problem lies with industrial management and governments where productivity and safety departments talk at rather than with each other. The ergonomist, with a broader view, can be the peacemaker, balancing the yin and yang of production lines.

**Form and Function, Preference and Performance, Elegance and Emotional appeal**

Consumers buy products for their elegance and emotional appeal, sometimes at the cost of effectiveness, efficiency, ease of use and safety. Take women’s’ high heeled shoes as an example. Or the large shiny car? Or a smart phone, full of fancy features that are never used. Or a costly meal full of the wrong kind of food. Pretty packaging and promises can sell products. Even educational technology is a consumer business and both airlines and universities obsess about branding. Such human behavior is normal. People have an affective domain that often trumps “rational behavior.” Perhaps form is more important than function in many cases. Preference may outweigh performance. An “ergonomic” chair may be ugly!

The ergonomist has tools to assess these affective tendencies and in turn advise the product or process designers and marketing staff about design and delivery strategies that have a better chance of sustainability. These tools include focus groups, surveys and affective design enquiries embedded in or disguised as usability testing studies. The two century old technologies of psychophysics for the perceptual differentiation of physical quantities can easily be converted to likeability scaling, using paired comparison or rating techniques. “How much more would you pay for this shiny modern product compared with your old obsolete item?” These are important tools in the ergonomist’s toolkit, they can be adapted to seek a balance between the yin and the yang.

**Conclusions**

This article emphasized the inevitable co-presence of plusses and minuses, benefits and costs, productivity and safety, performance and preference, and yin and yang in the world of ergonomics in design. The practicing ergonomist must comprehend these yin and yang interactions and interdependencies and address them in both analysis and design. Failure to do so shortchanges their internal and external customers and is a disservice to the profession. Ergonomics can improve upon Gaia - simply waiting for market forces to have their say. Yin and yang are universal; ergonomics in design must seek a balance.

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**Chapter 19**

**A Macro-ergonomics view of Transportation**

**Evolution**

Bramble and Lieberman (2004) provide a detailed description of the evolutionary development of endurance runners. They suggest that, although quadrupeds exhibit considerable strength and speed, it is the biped human that developed the greatest stamina capabilities. This evolution gave man an advantage as a hunter. The human desire to travel greater distances in shorter times was given a boost by the introduction of the wheel and then the internal combustion engine. Visitors to the NASA Johnson Space Center will see an unused Atlas rocket – another “giant leap for mankind.” Electric vehicles of all shapes and sizes now compete for space on the roads and sidewalks, and the sky too is rapidly becoming congested with manned and unmanned aerial vehicles. A downside of all this vehicular activity is considerable environmental pollution. Another downside of powered transport is the death of more than one million people a year on the roads as shown in this interactive graph from the World Health Organization:

(<http://gamapserver.who.int/gho/interactive_charts/road_safety/road_traffic_deaths3/atlas.html>

Similar statistics for aviation accidents and fatalities can be found at:

<http://aviation-safety.net/statistics/period/stats.php?cat=A1>

It should be noted in this context that the NASA Space Shuttle flew 135 missions, two of which (Columbia and Challenger) failed. Ironically, the use of mobile phones, even while walking, is responsible for an increasing number of collisions, due to distraction.

Vehicle manufacturers are driven by legislators to add substantial costs by the inclusion of devices that only come into effect when things go wrong. Cars have antilock brakes, seat belts, airbags, crush space, and a plethora of mechanisms to warn the driver of impending dangers and to keep the vehicle upright and stable in the event of loss of control. As the driver is often cited as the prime culprit in transportation accidents an exciting, but challenging, prospect is the evolution of the driverless vehicle. (Benenson et al, 2008). The shortcoming with most automation is when things go wrong, perhaps for contextual or technological reasons, and the driver (pilot) is unable to cope, as demonstrated by the Asiana Flight 214 crash at San Francisco:

<http://www.theguardian.com/world/2014/jun/24/asiana-crash-san-francsico-controls-investigation-pilot>

A more down to earth experience is the increasing likelihood of being run down by a policeman on a Segway or a small child or teenager on a motorized scooter on a public sidewalk. These issues beg the question of system design that includes the context and operational traffic management over and above the micro ergonomics of the driver and technology.

Another, more insidious, result of adding power to transportation is that people no longer have to perform as much physical work as the hunters of yester year. The evolution of sedentary lifestyles has resulted in obesity, diabetes and other metabolic disorders. In the future we may no longer walk to the bus stop; this “last mile” chore will be aided by an electric scooter or even a moving walkway. Elevators and escalators replace the need for us to use our own energy to combat gravity.

These issues beg the question of a sometimes articulated objective of ergonomics to reduce the need for physical activity by making tasks more convenient and comfortable. In the long term powered transportation leads to illness as well as injury.

**Transportation System Purposes and Outcomes**

### This evolutionary introduction sets the scene for consideration of the role of ergonomics in transportation system design. First it is appropriate to consider the multiple purposes and outcomes of processes and systems that have some human involvement. Useful operational definitions are that systems themselves are, following Edward’s SHEL model (Edwards 1972), things such as technology, people, contexts and operational rules that combine as an interactive process to produce multiple measureable outcomes as articulated by the E4S4 model:

* Effectiveness
  + The process should fulfill its intended function – the “quality” requirement
  + A transportation system uses vehicles to move people and goods along roads, rails and through the air, in all kinds of weather, according to many traffic rules. People are usually very competent and flexible in managing these systems in the face of technological, environmental and regulatory complexity.
* Efficiency
  + Processes have measureable efficiency or productivity in terms of resource utilization, such as people, money, fuel and time.
  + Mass transportation systems aspire to move many people quickly and inexpensively over long distances. Motor cycles are more efficient than cars with one or two occupants.
* Elegance
  + One expectation of systems and processes is that they should satisfy the affective requirements of their users. The affective dimensions have considerable impact on peoples’ purchase and operational decisions. (Watada….)
  + The affective response to “Daisy Bell” (Harry Dacre 1892)  
     reflects one instance of the affective domain:
    - *“If you can't afford a carriage*

*There won't be any marriage*

*Cause I'll be switched if I'll get hitched*

*On a bicycle built for two”*

* Ease of use
  + A familiar objective of ergonomics is ease of use by the intended user and difficulty of misuse by intended or unintended users
  + The unfamiliarity of the pilots in the Asiana Flight 214 with the auto throttle (automation) led to its crash on approach to the San Francisco airport. Many taxis on our streets have four or five aftermarket visual displays which all compete for attention with the driver’s primary task. Some of these systems have not very easy to use interfaces which compound their distraction potential.
* Safety and health
  + An inevitable downside of all technology is that human health and safety will be compromised in some form and to some extent, in use, in manufacturing or in disposal.
  + Worldwide there are more than one million fatalities on the roads each year.( Op cit ) Interestingly the transportation medium of these fatalities varies considerably among countries. In the USA auto accidents dominate, in much of South East Asia the culprit is the motorcycle. Pedestrian vulnerability also varies widely in different regions
  + The ubiquitous health downside is pollution, with cities in developing countries being particularly prominent; global warming is a universal unwanted outcome of transportation.
  + Trends towards central conversion of energy to electricity at fossil fuelled and nuclear power plants also present the potential for catastrophic system failure.
  + The regular daily chores of sitting in a car, sitting at a desk and sitting in front of the television are not conducive to good physical health.
* Security
  + Security issues result from the malicious actions of some system user or third party
  + Aviation security is a familiar challenge as well as vehicle theft. These system security challenges impose considerable financial loads on system manufacturers and operators.
  + The ergonomics contribution is to design access systems to only permit use by intended users, and this has become a major industry. How many passwords do we need? How reliable are scans and computer analysis of our faces, eyes and thumbs?
  + The rise in electronic controls of cars and airplanes presents the opportunity for malicious hacking.
* Satisfaction
  + There are many stakeholders associated with any system or process - the share holder who wants to make a profit, the manufacturer who wants to cut costs, the user who may want function, elegance or efficiency, the maintainer who spends most of his life under a vehicle, and the legislator who looks for tax revenue while shouldering the responsibility of traffic management. These satisfaction issues often pit one stakeholder against another with the result being unsatisfactory compromise.
  + Most vehicle purchasers trade off effectiveness, efficiency (cost), elegance (styling) and safety. The solution to these satisfaction issues is for the manufacturer to offer a wide variation in styling and features, at various costs. But this strategy is expensive.
  + These issues of customer expectancies are well described by the Kano approach to product and service design (Kano , Hartono). This approach identifies product features as “must have”, more the better” or “excitement”. As products and customers mature the “excitement and “more the better” features become “must have.” For example, contemporary cars now include reversing and navigation aids which used to be luxury items a short time ago.
* Sustainability
  + Sustainability has two forms. First there is reliability – the system or process should continue to act as intended over the expected life cycle. Resilience on the other hand requires that the system or process performs well under unintended or extreme conditions.
  + Airplanes and cars do not perform well in bad weather or with bad pilots or drivers.
  + Complex ‘planes, trains and automobiles often have a limited useful life with the maintenance costs increasing rapidly as the vehicle ages. On the other hand a good bicycle, properly maintained, can last a lifetime!

The challenges for system design are the many stakeholders in the system life cycle and the tradeoffs among these often conflicting purposes and outcomes. In the transportation context it is common to see conflicts between efficiency or journey time and safety. Stationary vehicles don’t crash, but also don’t fulfill their primary purpose. The landfills are full of vehicles that have passed their useful life. Beauty is relative and the judgment of beauty is fickle but the marketers place a lot of reliance on this elusive aspect of vehicles.

**Human variability**

Most ergonomists do not get to deal with this big, macro ergonomics, picture. Rather they deal with micro problems at the behest of some individual stakeholder. The most familiar stakeholders is the intended user. This produces another, sometimes insurmountable problem. This user is usually not an individual, rather he or she is a cohort or population that exhibits considerable variability on many dimensions.

To illustrate this challenge one should consider the design of operator and passenger seats in public transport. Driver’s seats are usually adjustable in two dimensions. In this way they accommodate much, but not all, anthropometric variation of the driver for the purpose of vision and control actuation. The drivers in the tails of the anthropometric distribution may need special consideration by aftermarket add-ons, or simply not get selected for the job.

The passengers are not so lucky, usually “one size fits all.” In the case of an airliner or bus seat the requirements of the company to fit in as many paying customers as possible creates knee room challenges for many; Some airlines provide reclining seats to allow for more comfortable sleep but this may lead to altercations with the passenger behind. Seat heights may be a problem for shorter vulnerable passengers on long journeys. (Vink and Brauer ). The height of most airline and bus seats fails miserably to match the ergonomics requirement (dogma) of accommodating the popliteal height of 95% of the passengers (5th percentile female popliteal height, shod or unshod?) Similarly the seat widths also fail miserably to match the ideal 95% hip or elbow widths. In practice the actual design of seat dimensions and materials is the prerogative of an efficiency driven policy maker, based on many other criteria, only occasionally with the help of an ergonomist.

An example of this “one size fits all” seat design challenge is found in mass transit railway vehicle design (Peacock,1978). As the distances and journey times are often quite short, it is common to have benches on either side of the carriage facing the center. This provides more space for the standing passengers who have a smaller “foot print” and can increase the payload at tolerable comfort costs. The ergonomics opportunity is the selection of the dimensions of these seats, including height, width and depth. Again, because of short journey time the heights are usually such that many passengers’ feet don’t easily reach the floor, but are unlikely to cause undue circulatory stress. The widths, as with airplane seats, do not accommodate many larger passengers. One solution adopted by the early Hong Kong Mass Transit seats was to allow variable widths by removing the scallops. Variants of this strategy could be adopted, perhaps with a pricing premium, in airplane seats.

Some ergonomists and customers for ergonomics advice consider that the ubiquitous seat is the be all and end all of ergonomics, but, as was illustrated in the previous paragraph advice based on this ergonomics dogma of pleasing 95% of the population, is rarely accepted. Ergonomists will be quick to insist that the profession goes beyond the design of seats, and the fact of variability and principles of accommodation on many other human dimensions sometimes stretch to the holy grail of universal design.(Erlandson, 2007) A little thought will show that such an aspiration is totally impractical unless we include selection and assignment of intended user populations to our ergonomics armory. But here again our paying customers rarely allow such a comprehensive responsibility to be undertaken by the ergonomist. A familiar response of engineers and managers of complex vehicles is simply to “train the user”.

Our target populations vary considerably on physical, sensory, cognitive and affective dimensions. Furthermore the contexts of use also vary considerably in terms of the physical, operational and social environments. The example of seat design is presented to illustrate the challenges of human variability in a familiar context. Some of the challenges of sensory, cognitive, behavioral and contextual variability will be explored in the following sections.

**Human flexibility**

In the one size fits all case of public transport seats, human musculo-skeletal flexibility allows individuals to adapt to the spatial constraints of the seats. In the broader sense of transportation system design, especially public transport and commercial aviation, human flexibility is required to adapt to the temporal restrictions of system design. Economies of scale require that airplanes, buses and trains carry large passenger loads and that full vehicles are needed to allow providers to charge the minimum price. In practice many providers try to meet the customer half way by offering large capacity long haul and small capacity more frequent short haul options. Minibus and taxi services increase the level of ground system accommodation, using price as the way of offering more comfort, convenience and shorter waiting and journey times. Even so the slack in service offerings is taken up by human temporal flexibility. Analysis of these server–customer systems is based on queuing theory. With more complex systems, discrete event simulation is the technique of choice to search for optimal solutions – maximum profit for the provider and minimum waiting and travel times for the customer.

A more complex model of human requirements and behavior places the transportation system as one component of the larger system that includes housing, places of work and education, and other services, such as shops and recreation. Human temporal flexibility is required when their employment is in an organization that requires shift work to provide 24/7 service. In the long run there is a human cost to this flexibility in terms of fatigue and greater incidence of metabolic illness. This bigger picture implies a need for adaptation of the transportation systems to accommodate the demands of the other services. Rush hour traffic is a common problem in all large cities. Some bus services offer greater frequencies during the morning and evening rush hours. Aviation services may offer greater capacity around public holidays when demand for transportation increases. However the costs of this adaptation in terms of capital equipment and variable manpower must be offset by the less tangible gains in passenger waiting times – customer satisfaction.

A different opportunity for human flexibility in transportation system design is through operator training and assignment. It takes a highly trained person to steer a boat, drive a bus or pilot an airplane, and some sub specialization is the norm. Greater system capacity and less reserve manpower cost can be achieved by cross training which allows flexibility in the assignment of drivers or pilots to vehicle types. Such a strategy must be offset against the cost of training and the increased possibility of error due to cognitive interference and lack of practice. As airplanes, especially, become more complex, type rating becomes more important. Similar specialization and generalization issues also occur with vehicle maintenance. Eventually the tradeoffs have to be made between the cost of waiting times for vehicles and the costs of training, hiring and assigning flexible people.

**The cognitive Perspective**

Physical and cognitive micro ergonomics studies of cars address matters of pedal and steering wheel placement, instrument panel reach, the number, size, shape, discrimination, direction and range of motion of knobs and switches. Similarly, the design of displays address physical issues such as size, color contrast, font and marking size, and scales and ranges of movement. One pre computer era issue was also the location and number of information sources. Classical studies also investigated the interactions between controls and displays including direction of motion stereotypes and control – display gain (Wierwille ). As vehicle information systems proliferated, debates flared regarding the value of analog or digital detail and the utility of simpler status lights. Talking cars addressed the visual workload problem by repeating messages such as “please put on your seat belt.” Contemporary car navigation systems use the auditory channel to relieve the visual channel for control activity.

The modern information system era offers a considerable increase of information types, forms and details that are accessed by touch screen menus. The primary tasks of the car driver - speed and heading control - remain paramount while the secondary navigational, operational and vehicle system information tasks continue to compete for attention, with even more insistence. The tertiary tasks, such as entertainment and climate management, also contribute to a sometimes impossibly cluttered informational context. Meanwhile the driver’s capacities remain the same, perhaps marginally improved with familiarity, and the contextual demands of traffic density increase. An anecdotal instance of these cognitive workload and distraction issues is found in taxis, which often sport four or five aftermarket attention demanding displays that crowd the forward view. (GPS navigation, hand phone, fare meter, forward video recorder, toll road meter)

These well-meaning opportunistic information system interventions, driven by technology, are even more prevalent in modern airplanes. Traffic density may not be as great as on the roads but the cost of failure is infinitely greater; gravity is unforgiving. Airplanes are commonly equipped with information sources that allow the “instrument” trained pilot to fly “heads down”. Modern GPS systems make navigation and collision avoidance relatively easy, although remote management by Air Traffic Control is still needed to achieve separation and route guidance. It should be noted that with the trend towards GPS guided “free flight” there is an increasing opportunity for confusion between pilots and air traffic controllers . Pilots, like car drivers, are only human, albeit well trained and tested. The human factors challenges of this information management and flight control problem can be easily demonstrated in a multiplayer flight simulation environment, without the significant costs of failure. In fact the frequent occurrence of failure that is not possible in a real flight environment can be very instructive to aviation students and hobbyists.

**The Behavioral Perspective**

Behavioral analysis in ergonomics is usually through the methods of ethnography in which the observer classifies and counts activities and their outcomes which are usually reflected in terms of time and error. One general observation is that different behaviors can sometimes lead to the same outcome and that the same behaviors can result in different outcomes, depending on the context. Behavioral variability among different individuals adds to the analytic noise. In these cases behavioral analysis may transition from quantitative to qualitative descriptions, in either case the analysis may lead to system outcome prediction and design opportunities. An example related to sitting behaviors of children in airplane and car seats demonstrates a plethora of alternatives, to some extent controlled by restraints. Behavioral “restraints” in the cognitive domain are achieved by training. Drivers and pilots are trained to scan the outside scene and their instruments depending on the task at hand, such as collision avoidance or navigation.

These examples are conducive to micro ergonomics investigation in which contexts are controlled, performance requirements specified and appropriate and inappropriate behaviors identified. An example in car control is the analysis of foot behavior where, in automatic drive vehicles, either one or two foot behaviors may be acceptable. Anecdotal evidence is that drivers of automatic transmission taxis in some big cities habitually use one foot on the accelerator and the other on the brake, similar to the toggle pedal on some fork trucks. Also in vehicles, eye movement and fixation research can clearly indicate the utility and pitfalls of variable visual behaviors. Similar approaches are used in pilot training with regard to instrument scanning and the transition to glass cockpits that require deliberate selection of display content.

Whereas human overt behavior, such as foot, hand or eye movements, is generally easily accessible using ethnographic or video methods, these approaches do not necessarily tell the whole story of those more elusive cognitive factors that predicate performance outcomes. A complementary approach is to use verbal protocol or “think aloud” techniques in which the subject describes what he is attending too or thinking or why he chose a particular action. These methods are sometimes contaminated by hindsight bias, depending on the performance outcome. More intrusive methods such as EEG are available but interpretation requires substantial experience and expertise and may therefore be unreliable; furthermore such methods are intrusive and may affect subject behavior.

**The Contextual Perspective and Resilience**

The Edwards’ SHEL model (op cit) emphasizes the interactions among people, technology, operational rules and contexts in all processes. Process outcomes (E4S4) will be dictated by the capabilities, contributions and compatibilities the contributing systems and their interactions. Resilience is achieved by the capabilities of one component compensating for the limitations of another.

A car driving example is the introduction of anti lock brakes which compensate for slippery roads and inadequate driver braking behavior. Also in cars the introduction of “talking maps” reduced the navigation workload and distraction vulnerability of drivers. The advent of the glass cockpit in airplanes opened the door for powerful computer capabilities to aid the pilot in aviation, navigation and communication. Most of these devices are aimed at compensating for driver / pilot limitations, however it is the predictive and problem solving power of the driver / pilot that saves the day when technology is unable to deal with extreme physical and operational contexts. Drivers in traffic look beyond the vehicle immediately in front of them in order to anticipate the need for foot movements between pedals. This human capability places the attentive driver ahead of the technological developments in adaptive cruise control which simply reacts to the car in front.

Technocrats predict the future of driverless cars, however consideration of resilience in demanding contexts will render this aspiration unlikely. For example one paramount duty of a car driver and pilot is to maintain separation from other vehicles. The density and two dimensional nature of ground traffic make this separation management a greater challenge than three dimensional airplane separations, although relative speed differences between cars and airplanes closes the temporal gap on this separation challenge. The separation challenge is also important in shipping as they navigate congested waterways. In shipping and aviation the use of computers to calculate closure rates and suggest avoidance maneuvers has considerable promise, assuming all the participants have location sensors and responders. GPS based ADS-B technology is vastly superior to radar in terms of time and resolution and this technology enables pilots and ships captains to avoid collisions without the help of the traffic control organization. Such a transition, involving greater autonomy of individuals may fail in comparison with the traffic controller’s ability to optimize throughput by imposing non selfish decision making. Another hindrance to the widespread introduction of the ADS-B technology is that many small boats and airplane do not have or refuse to buy the technology. Other challenges to advanced technological innovations in cars and airplanes are aging, cost and scale. Advanced systems may demand that all vehicles in a congested traffic context be fitted with the technology. Remote radar has this capability in air and sea contexts, but there are significant temporal lags. GPS based technology such as ADS-B reduces the time delays and provides information directly to the pilot, but not all airplanes and small boats have this technology.

The density of road traffic presents a greater order of complexity. Road traffic also has to contend with large buses, trucks, motor cycles, bicycles, pedestrians and a plethora of new electric transport aides. The example of a typical South East Asian city intersection will illustrate the problem. In some city intersections there is no attempt to regulate the traffic. It is left up to the individual driver to detect obstacles and carry out collision avoidance maneuvers. It is evident that training and experience go a long way to support effectiveness, efficiency, satisfaction and resilience in this context. However the accidents statistics show that reliance on individual behavior and performance is far from adequate. The introduction of technology to manage separation is likely to do so at the cost of reduced efficiency – intersection throughput. Also, the cost and deployment difficulties of technology may be prohibitive.

The challenge for the proponents of driverless cars to address is to mimic the human ability to predict and anticipate. If car separation algorithms simply relied on closure rate with the car in front then, given normal speeds and variable following distances, there would still be rear end collisions. Good drivers maintain sufficient headway and monitor the behavior of vehicles ahead of the immediately preceding car in order to buy time for anticipatory behavior.

**Transportation Safety**

An articulation of the scope of ergonomics by Edwards – the SHEL model – indicates that systems consist of the interactions among, people (liveware), technology (hardware), rules and regulations (software), and the context (social and physical environment.) (op cit) A perceptive extension of this model adds interpersonal interactions – a social dimension. The importance of these concepts is that system failure may result from the failure of a subsystem or between two or more subsystems. In the transportation context there is the micro interface between a driver and vehicle but there are also other vehicles and their drivers, roads, intersections, traffic management systems and weather that may interact to cause an accident.

A macro view of transportation safety is that accidents happen due to situational changes in the interactions among technology, people and contexts, including both the physical and operational context. The accident may result from changes in individual systems over a long period of time or quite rapidly. A tire or tired driver may wear out gradually and eventually fail; similarly a driver may accumulate bad habits over time and eventually pay the price. It should be noted that accidents rarely happen directly from a failure of their physical components, rather accident causes usually have information processing or cognitive causes, such as failures in anticipation, attention, memory, perception, decision making and control behavior. Some failures are due to deliberate risk taking or violations of correct procedures, whereas most are simply to the ubiquitous “human error. The Human Factors Analysis and Classification System (Wiegmann and Shappell, 2000) describes accidents as a combination of unsafe acts (errors or violations), preconditions (in the technology, driver or context,) a failure of the supervisory system (tolerance or even incentives for bad behavior) and finally the organizational climate which may precipitate adverse conditions by for example cost cutting in traffic management. The HFACS system is a perceptive approach to aviation accident analysis and the concepts have spread to medical error and beyond. The concepts are applicable to all forms of transportation and can apply both to accident analysis and preventative design. This HFACS analytic approach to accident reconstruction and design is greatly enhanced when amalgamated with the Edwards SHEL model, the 6Us model and the E4S4 model of design purposes and tradeoffs.

**Simulation and Simulators**

Simulation methods offer various degrees of realism, but usually without the stress caused by the threat of real damage to the individual, technology or the environment. The principal advantage of simulation for research and training is that scenarios can be constructed to tax various human systems and repeated for training purposes and to examine and correct erroneous behavior. The recent crash of Trans Asia GE325 in Taiwan was followed quickly by a requirement of all ATR 72-600 pilots to take remedial training and testing regarding actions following the burnout of one of the two engines. Simulators vary considerably in their level of sophistication. Low fidelity simulators are freely and widely available on the Internet as games and for more serious uses. Such simulators test the same cognitive mechanisms as their high fidelity cousins, but with less realism. The intermediate level of simulators such as Microsoft Flight Simulator, now offered as Prepar3D ( [http://www.prepar3d.com/](http://www.prepar3d.com/%20) ) offer realistic cognitive challenges, again relatively inexpensively.

More expensive simulators are motion based on robotic arms that accurately mimic the system movement responses to pilot input and external forces.

The SIMVA (SIM University, now SUSS) project requires large classes of aerospace students to form teams to navigate around various airspaces. The teams consist of a pilot (attitude and airspeed), navigator (altitude and heading), communicator and ATC (route planning and separation), observer (cockpit voice recorder and activities monitor). As the team members have minimal experience with flight although variable experience with operations, the occurrence of communication and crew resource management error is frequent and informative. Distraction is a common culprit. Lack of situation awareness regarding navigation, operation and control status is commonplace. The sequel to this simulator experience is a real world accident analysis, using the Human Factors Analysis and Classification System approach to identify the human factors causes.

Simulation based research that addressed the introduction of head up displays into cars, following their successful use in flying, offered two important conclusions. First it is important to consider context; airplanes usually don’t rely on out of the window detection of other airplanes, while this mode is usual and continuous in cars. The second observation was that it was not just the visual interference of head up displays, rather it the cognitive capture of the information contained in the display that is the greatest hazard. An example of such a hazard occurs where multiple menu steps are required to obtain the required information. Such sequential procedures may take many seconds to navigate, while the view outside is ignored. Simulation based research, although sometimes criticized for lack of face, ecological and outcome validity is an invaluable medium for the demonstration of cognitive workload issues.

**Human System Design**

A second model – the 6Us and 2Ms will be used to explain the factors that must be considered in human system design. (Peacock and Resnick, 2009)

* Utility – Is the system useful?
  + Most technology is developed with particular functions in mind, but in the long run, technology itself is subject to Darwinism – survival of the fittest.
  + Notably the likes of the Titanic were replaced by Jumbo jets for trans-ocean transportation, but survived as cruise ships.
  + The perception of utility is in the eye of the customer, again explained by the Kano model.
  + A car, bus, train or airplane may have considerable utility, but the choice among these modes will vary according to context and customer preference.
* Usage
  + What is the intended use of a system or process?
  + Is the car intended to take the driver to work or the family on a camping trip? Such questions will give rise to alternative design solutions or compromise where the driver has only one vehicle.
* Misusage
  + Can the system be used for other than its intended purpose?
  + Is a family car also used for transporting building materials or pets? In either case the choice of make and model may change from small sedan to the more resilient large utility vehicle.
* User
  + Who is the intended user? What are his or her intentions and capabilities? Might there be many users each with a different role?
  + What kinds of variability does the user exhibit?
  + The family minivan has many users, including the driver and family members of various sizes and requirements.
  + Another source of “user” variation is their ability and interest in paying more for more features, services, comfort and convenience. The commercial aviation industry exploits these differences by offering different classes of travel.
* Misuser
  + System security is a universal concern in transportation, from hijacked airplanes to stolen cars.
  + At a less sensational level the misuser may be legitimate but incompetent or incapacitated
  + Should a teenager be given the keys to a Corvette? Perhaps with 5th and 6th gears locked out?
  + How can a fatigued or inebriated driver or pilot be detected and prevented from using the vehicle?
  + At what age should an elderly pilot or driver hand over the keys?
* Utilization
  + How often will the vehicle be used and in what kinds of environments? These temporal questions of intensity, frequency or duration of use will also influence the design of a product or service.
  + The demands for maintenance of vehicles with high utilization, such as public transport, are such that the designs should be robust in order to reduce the incidence of component wear and failure, and conducive to frequent or regular maintenance operations.
  + What should be the denominator in transportation accident analysis, number of journeys or passenger miles?
* User error
  + Can normal or abnormal conditions be conducive to human error?
  + Can the driver hit the wrong pedal or switch at the wrong time? User errors occur all the time but the consequences of these errors are only important in the context of a pre existing hazard
* Usability
  + Usability is a widely used word to describe how easy it is for a user to interact with some hardware or software. However as perception is in the eye of the beholder, usability is in the hands of the user in the context of use.
  + An expensive golf club may be usable in the hands of a good golfer; conversely a rear wheeled muscle car will not be very usable in icy conditions and a large passenger airplane will require careful pilot training and selection.
  + Usability therefore begs the question of the user and the context, and this again begs the question of the accommodation assumptions in design.
  + It should be noted that the automobile is probably one of the most widely used and therefore by definition one of the most usable systems ever developed, given certain assumptions about driver training and selection.
  + As automobiles, airplanes and computer technology evolve user selection may have to become more discerning.

**The Kano approach**

In maritime and aviation contexts passengers may have choices among competing companies which do not differ in their functional attributes – the same models and performances of airplanes are common to all the competing companies. The competition among companies is therefore dependent on cost, comfort and service dimensions. Some airlines are low cost with minimum service levels in terms of interior design, meals and baggage allowances. Other airlines offer greater creature comforts and luxury levels in First and Business levels, but at a premium price. Similar tradeoffs have long been exploited in many areas of public transport such as trains and passenger boats. Private cars however demonstrate by far the greatest opportunity for non-essential feature exploitation. The human factors approach to the understanding of these function and form dimensions has historically been through analysis of purchase behavior after the event and through surveys and focus groups before and after the point of sale.

It is widely recognized that product choice, given basic functional requirements, is often based on affective dimensions of likeability. The Kano model was developed for the purpose of product evaluation and has since been applied to services evaluation and to job and person(al) evaluation. The model suggests that there are three types of feature in a product or service: “Must have”, “more the better” and “excitement”. The absence of must have features will make the product or service unacceptable or unusable, but an increase may not increase the vehicle’s attractiveness. In the case of a car, the “must have” features include four wheels, an engine and transmission, and a body containing seats and controls. More wheels, engines or seats would not help. “More (or less) the better” features may include increased speed, more trunk space, better fuel consumption, lower price and fewer service visits. The absence of excitement features does not necessarily reduce the car’s utility, but its presence may increase the car’s attractiveness. Examples of these excitement features could include leather seats, a navigation system or automatic driver recognition. Another concept in the Kano model is that over time these excitement and more the better features may become “must haves”.

The value of this Kano approach is that the principles can be applied to all levels of the vehicle or transportations system. Typically data are gathered from samples of various cohorts, such as drivers, passengers, manufacturing employees, sales representatives, safety analysts, and so on. As with most kinds of ergonomics data, between subject variability is to be expected and the analysis will include various strengths of opinion.

**The “Excitement” Domain**

Running, driving, sailing and flying are technically difficult behaviors in which performance improves with practice. However, they bring with them another domain and purpose – enjoyment, the affective domain. In the Kano classification, these are the excitement factors. Consider the excitement waiting to start in the Boston marathon, driving at 100 mph or more on the open freeway, fighting a gusty sea breeze or flying coast to coast at 10,000 feet. The transportation affective domain has its downsides too: “hitting the wall” at Heartbreak Hill, seeing the flashing lights in your rear view mirror, or seeing thunder clouds ahead. The tecdhnologies themselves contribute to the enjoyment. Consider a group of runners discussing their shoe styles, classic car owners extolling the virtues of past styling arts, and dingy sailors and pilots drooling over the intricacies of their technology designs. These conversations are reflected beautifully in the discussions in Harry Potter of the Nimbus 2000 Quidditch Broomsticks and Toad of Toad Hall in the Wind in the Willows: “Whether a Ford or a Ferrari, whatever I can get to carry me near or far, just give me any car. I love to ride the Tar, an old Excalibur; yes, any motor car. And I'll be happy - ho-ho! Messing around in cars!” Notably one ‘upside’ of the Boston marathon is the “traffic” – 20,000 runners (arranged by qualifying time) who have trained for months or years to participate in this prestigious event - the world’s greatest foot race. Traffic on the road or in the air definitely puts the brakes on the pleasures of powered transportation.

**Segregation or Integration**

Before the internal combustion engine walkers and riders of horse drawn carriages shared the same roads. The cautious walker heard the horses’ hooves and moved out of the way. Over time various levels of segregation have developed. First sidewalks and roadways, and now the roadways are sometimes but not always segregated for bicycles, buses, heavy vehicles and cars. In many cities integration is the roadway rule for wheeled vehicles. Intersections can be facilitated by costly segregation facilities, bridges and tunnels, or by temporal management – traffic signs and lights.

Other traffic management strategies use priority systems. Despite these engineering and operational interventions there remain many safety and temporal problems. The safety problem is a result of mass and speed variability where spatial and temporal sharing is permitted. The temporal problems arise when the control system is not adaptive to demand – batches of cars wait at traffic lights even though there is no cross traffic. The roundabout with various levels of complexity provides a priority based continuous flow alternative, which requires compliance by the participants to the prioritization rules. Human adaptation to these temporal and safety challenges creates situations where bicycles and now various electric vehicles use the sidewalks to escape from the cars. Another hybrid approach involves the use of the car horn or bicycle bell to create temporal segregation where the general rule is integration. These surface situations are being mirrored in aviation, which although there is an additional dimension to play with, is experiencing increasing densities that demand administrative solutions.

These segregation and integration strategies may be of theoretical interest; they may be subject to modeling and optimization approaches. However the complexity in terms of spatial and temporal capacity, and size and speed variation, the costs of engineering solutions (segregation) and fallibility, in terms of efficiency and safety, of administrative solutions is such that there is no generally acceptable solution apart from tolerance of one million road fatalities a year.

Contemporary technology, such as GPS and various sensing systems, such as near and rear obstacle detection systems, to aid the driver or pilot achieve separation provide an opportunity for the micro ergonomist to evaluate the utilities of these al

**Conclusions – the Big Picture**

Transportation is a complicated business that continually responds to technological innovation and customer demand. Managers and users seek optimal solutions in terms of effectiveness, efficiency, safety, comfort and convenience. Transportation becomes complex with the addition of human variability and flexibility, particularly in the affective domain. Further complexity is introduced by environmental and operational forces. The system becomes chaotic due to the interactions among technology, people and contexts, and attempts by regulators to achieve order and predictability.

Opportunities for micro-ergonomics analyses and interventions are everywhere – from seats and safety through controls and communication to artistic design and affection. These opportunities have been met over the years by piecemeal pursuit of topics that interest the researcher or are highlighted by the various customers. Many of these contributions have been extremely successful. Altimeters in airplanes were redesigned to remove confusion between orders of magnitude on the scales. The center high mounted stop light has reduced the incidence of rear end collisions by shortening the driver response time. The brake transmission interlock addressed the human causes of many unwanted acceleration incidents. The addition of a shoulder strap to the lap belt and the addition of a head restraint have reduced many injuries in cars, but this safety technology has yet to be transferred to airplanes.

Three Japanese design processes have addressed the affective domain and the broader aspects of customer requirements. The Kansei approach (Nagamachi, 2011) translates customer statements into design criteria. The Kano approach differentiates among “must have (must not have)”, “more (less) the better”, and “excitement” factors in product or service design, and notes that over time some “excitement” features may become “must have” as in the case of entertainment and navigation systems in cars. The third, Kaizen, approach emphasizes the importance of continuous improvement in product and service design, based on customer articulations and other system outcome feedback. These three approaches have been prominent and successful in the Japanese automotive industry and abroad over the past few decades. Collectively, these three approaches move the practice of micro-ergonomics from reductionist laboratory centered research into the broader context of macro ergonomics.

Macro-ergonomics can be articulated as a high level, comprehensive approach to addressing human centered design constrained by technological, contextual and operational complexity. Furthermore, macro-ergonomics comprehends human physical, sensory, cognitive, social and affective variability as they interact with external complexity and demands. Finally macro-ergonomics accepts that there are many stakeholders associated with the design process and these stakeholders may emphasize different outcomes in terms of effectiveness, efficiency, ease of use, elegance, safety, security, satisfaction and sustainability. Macro ergonomics is the process of making tradeoffs in design.

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