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Revolutions and shifting paradigms in human factors & ergonomics

Kenneth R. Boff*

Air Force Research Laboratory/Human Effectiveness (AFRL/HE), 2610 Seventh Street, Bld 441, Wright-Patterson AFB, OH 45433-7901, USA

Abstract

The "Revolution in Information Technology" has spawned a series of transformational revolutions in the nature and practice of human factors and ergonomics (HFE). "Generation 1" HFE evolved with a focus on *adapting* equipment, workplace and tasks to human capabilities and limitations. Generation 2, focused on cognitive systems integration, arose in response to the need to manage automation and dynamic function allocation. Generation 3 is focused on symbiotic technologies that can amplify human physical and cognitive capabilities. Generation 4 is emergent and is focused on biological enhancement of physical or cognitive capabilities. The shift from HFE Generations 1 and 2 to Generations 3 and 4 profoundly alters accepted boundary constraints on the adaptability of humans in complex systems design. Furthermore, it has opened an ethical divide between those that see cognitive and physical enhancement as a great benefit to society and those who perceive this as tampering with the fundamentals of human nature.
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1. Wherefore human factors?

1.1. Origins and destinations

'Human factors' has been around a long time and is a concept nearly as old as mankind itself. It could be argued that the fashioning of tools and weapons for fit and function from stone and antelope bones is prima facie evidence of design for effective use. The early industrial revolution systematized manufacturing work using humans as components—in concert with machines and automation—often resulting in drudgery and stultifying routine. The science of ergonomics or the study of work was formalized as a discipline (Jastrzebowski, 1857) motivated by an interest in increasing the efficiency and productivity of workers. By the 1930s, industrialists such as IBM's founder, T.J. Watson, purported to shift human jobs away from work that machines could do better—"Machines should work. People should think". This was a precursor to the now famous Fitt's List.

> Assign to men those functions men perform best … Assign to machines those functions machines perform best (Fitts, 1951)

Human factors engineering or human engineering was codified in terms of designing machines, operations and work so they match human capabilities and limitations during WWII (Chapanis, 1959) and held true up through the dawn of the revolution in information technology during the late 1970s. It is interesting to note that futurists, at that time, predicted a new era—in which technology would relieve people from tasks that are difficult, time-consuming, and subject to error.

1.2. Revolutions begat revolutions

The "Revolution in Information Technology" (IT), like the Neolithic and Industrial Revolutions that preceded it, has had very profound, pervasive economic, social, cultural, political and military effects. We now live in a world mediated by embedded micro-processors and explicit computer interfaces, pervasive and networked at all levels of social, interpersonal, recreational, family, and workplace environments. In turn, cheap computing power to the masses has dramatically affected or transformed the

*Tel.: +1 937 255 6327 (Day), +1 937 426 6576 (Evening); fax: +1 937 656 7617.
E-mail addresses: ken.boff@wpafb.af.mil, ktalk11@mac.com.

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Table 1
Four generations of human factors and ergonomics

Gen 1	Physical fit	Adapt equipment, workplace and tasks to human capabilities and limits	Mature[a]
Gen 2	Cognitive fit	Harmoniously integrate humans, technology and work to enable effective systems	Growth[a]
Gen 3	Neural fit	Amplify human physical and cognitive capabilities to perform work through symbiotic coupling with technology	Emerging[a]
Gen 4	Biological fit	Biologically modify physical and/or cognitive capabilities to maximize human effectiveness	Embryonic[a]

[a]Adopted from Roussel et al. (1991) third generation R&D.

fundamentals of society, education, industry, the office, and the military. A major irony of this revolution in IT, is that IT was expected to be a panacea for complexity—simplifying work for people, aiding and enhancing productivity with automation, and improving quality of life overall. While IT has certainly delivered enormous positive effects, it has also created many costly unintended outcomes (Tenner, 1996).

The revolution in IT also accelerated the nascent revolutions in biological & nano technology which have had, in turn, a huge impact, both push and pull, on research and development (R&D) of cognitive science, modeling and engineering. In addition to raising the interest and demand for applicable cognitive data, IT enabled new 'affordances' for studying and understanding how people perceive, think and act in naturalistic contexts and, in turn, revolutionizing the practice of HF&E.

In particular, the disruptive innovations enabled by the Revolution in IT begat a revolution in military affairs (RMA) driving increased military reliance on IT in which: information has become the new "fog of war" (Owens, 2000), bits and bytes have become strategically equated with bombs and bullets and advances in networking and communications technologies have dramatically changed the nature of conflict (Rouse and Boff, 2001). This is particularly true with respect to the speed and range of options available for military command and control whereby the speed of decision making has been pushed ever closer to the speed of thought (Arquilla and Ronfeldt, 1997). With respect to military human factors and ergonomics, the RMA raised the challenges and expectations for effective 'human systems integration'. This is indicated by an unprecedented level of attention and financial support to understanding and enhancing 'situational awareness', collaboration, decision-making and human-system performance, and to resolving unintended complexity arising as a consequence of clumsy implementations of IT (Woods, 1996; Parasuraman et al., 2000).

2. Generations of human factors and ergonomics

The rapidly evolving state of knowledge and technology in the information, biological and cognitive domains has dramatically transformed, indeed revolutionized, the technology and practice of HFE. While the end-goal of harmonizing the capabilities of humans and the demands of work and work environments remains fundamentally the same, the research, development and practice of HFE appears to have differentiated into four separable paradigms or generations, distinguishable from one another by disciplinary perspective, approach and level of maturity a la Roussel et al. (1991). These are shown in Table 1 and elaborated below.

Each of these generations of HFE coexists and shares a common interest in human effectiveness. However, what differentiates HFE Generations 3 and 4 from Generations 1 and 2 is a change in the fundamental role of the human as a variable in human system integration. In Generations 3 and 4, human cognitive and physical capabilities may be enhanced well outside the range of normal biological variation thereby altering traditional boundary constraints on the adaptability of humans in complex system design.

2.1. Generation 1

First generation human factors and ergonomics is focused on adapting the "physical fit" of equipment, workplace, and tasks to match human capabilities and limitations. Its overall goal is to optimize human efficiency, well-being and quality of life. Generation 1 human factors practitioners and ergonomists are involved both in the study and application of principles of ergonomic design of equipment and operating procedures and in the scientific selection and training of operators to produce people who get the best performance possible within machine design limitations.

Those who became involved in the study of HFE in equipment design and its application came from various branches of psychology and engineering and simply invented the science and practice of human factors on the job. HFE formalized in the UK in 1917 in WW I when the Medical Research Council (MRC) investigated industrial conditions of munitions workers. In response to issues arising during WWII, key thought leaders arose who conceptually shaped the thrust of Generation 1 HFE to the present. In the UK, the MRC Applied Psychology Unit in Cambridge provided the critical mass from which intellectual leaders such as Alan Baddeley, Donald Broadbent, Kenneth Craik, Norman Mackworth and Christopher Poulton emerged. In the US, it was the military laboratories concerned with aviation psychology that provided fertile ground for the formalization by Fitts (1947, 1951) of human engineering—i.e. first understand and specify the capacities and limitations of humans from which the choice of a better design should be directly deducible. Some key thought leaders of this era included Alphonse Chapanis, Walt Grether, Ed Fleishman, Conrad Kraft and Arnold Small among others. See Meister (1999) for an excellent review of this history.

A very influential publication in this era was "the magical number seven, plus or minus two: Some limits on our capacity to process information" by Miller (1956). It promoted quantification of cognitive limits and focused interest of the budding HFE community on the human as information processor thereby serving as a critical precursor to the emergence of Generation 2. The mantra of Generation 1 became the Fitt's List used to represent what tasks men versus machines are best at. The Fitt's List was very provocative and influential in its day, but with the advent of computers and software, it proved overly simplistic and unable to address the more intricate relationships inherent in complex and dynamic human systems. For example, the problem of supervisory control (i.e. supervisory attention allocation and timing) or overlaps of functions where both humans and machines are consistent but inflexible or where both are complementary rather than comparable.

2.2. Generation 2

In large measure, Generation 2 was spawned by the growth in complexity of work environments and systems and to manage issues in automation and dynamic function allocation not conceptually anticipated by Fitts. Its focus is on systems (Meister, 1999) and, in particular, cognitive systems *integration*… in which humans, technology and the environment are designed into a "harmonious" system relationship to accomplish work. In other words, achieving "cognitive fit". In particular, it deals with the challenges that have arose in conjunction with introducing IT to complex work domains such as power plants, aircraft cockpits, air traffic control etc. (Rasmussen et al., 1994).

Complexity is an unintended byproduct of combining people, technology and work. A major irony of the revolution in information technology (IT), is that IT was expected to be a panacea for complexity. It has, in many instances, added new complexities with consequences for value outcomes that are just beginning to be understood. In principle, HFE provides options for dealing with complexity in the design of integrated human-IT systems. In practice, HFE often focuses on solutions to component problems while failing to consider these in the context of the whole system. In other words, the failure to consider each element of the system viewed in terms of its interaction with other elements of the system may inadvertently add to system complexity and/or costs.

The evident shift from Generation 1 to Generation 2 is towards designing technology to fit minds, as well as bodies and is indicated by emphasis on:

- systems engineering, cognitive systems engineering and Human Systems Integration,
- cognitive science, modeling and engineering,
- intelligent tutoring and aiding
- usability engineering (Nielsen, 1993),
- human computer interaction (HCI) and information visualization,
- "cognition in the wild" (Hutchins, 1995), ecological systems (Flach et al., 1995) and "Naturalistic Decision making" (Klein et al., 1993).

Among others, some key Generation 2 thought leaders are Gary Klein, David Meister, Neville Moray, Richard Pew, Jens Rasmussen, James Reason, Brian Shackel, Tom Sheridan and David Woods.

2.3. Generation 3

As with Generation 2, Generation 3 is concerned with human systems integration but it is characterized by a marked *shift from building better work environments towards enabling humans to work better*. While Generation 2 was focused on enabling a good cognitive fit with technology and work, Third generation HFE is concerned with achieving a tightly coupled neural fit between equipment (e.g. controls, displays, actuators) or computing devices and the human Central Nervous System. In Generation 3, technology becomes a means for aiding, augmenting or amplifying human physical and cognitive capabilities to overcome limitations and to maximize system effectiveness. It may be enabled by either external or implanted bio-electric sensing of neuro-muscular control impulses or cognitive state.

A cyborg, also referred to as a bionic system, is a fusion of the organic and the technical. In the physical domain, cybernetic, cyborg or bionic technologies are rapidly advancing from their original therapeutic basis in prosthetic joints and limbs to devices such as exoskeletons that are expected to extend the normal range of physical capabilities of normal workers to super-human ranges of strength and endurance (Gray et al., 1996). Of interest to note is that a growing number of individuals within the population are already cyborgs in the technical sense. These include individuals with electronic pacemakers, bionic joints and limbs, drug implant systems, implanted corneal lenses, etc.

The first commercially available robotic exoskeleton has already been developed at the University of Tsukuba, Japan and Cyberdyne, Inc. and was originally designed to assist older people or those with disabilities to walk or lift heavy objects. It is called HAL-5 for hybrid assist limb and it functions as a bio-cybernetic system using bio-electric sensors attached to the skin on the legs to monitor control signals transmitted from the brain to the muscles. The signals are relayed to a backpack computer and, in turn, are used to control electric motors at the hips and knees of the exoskeleton. The response time is reported to be quicker than the natural capabilities of the wearer's own muscular system (Boyd, 2005; Guizzo and Goldstein, 2005). Devices such as this will transform the nature of workplace ergonomics in the future.

Enabled in recent years by advances in IT, the focus of Generation 3 HFE is on developing options for aiding and augmenting the human as an information processor and decision-maker. During the age of big iron mainframe computing, JCR Licklider envisioned the potential of *Man-Computer Symbiosis* (1960) based on computerized interfaces with the brain.

> "Tightly coupled human brains and computing machines"…that…"enable men and computers to cooperate in making decisions and controlling complex situations without inflexible dependence on predetermined programs…" (Licklider, 1960)

Today, the rapidly increasing capabilities of computing systems coupled with the increasing demands for powerful command and control systems are pushing the development of highly integrated human-computer systems that are seamlessly collaborative and able to augment human strengths and compensate for human weaknesses. In the cognitive domain, Generation 3 HFE activities extend from adaptive aiding by computers able to sense operator state with respect to attention or capacity to prosthetic-like devices that directly aid sensory or cognitive performance. In a sense, Generation 3 is about combining what people and machines each do best from the Fitts list (Table 1) into a single entity. Futurists such as Kurzweil (2005) see this integration of biological and silicon based cognition as a natural stage in the evolution of the human species "resulting in a world that is still human, but that transcends our biological roots".

Based on a growing understanding of how the brain works—i.e. thinks, reasons, remembers, etc.—neuro-engineers are bioengineering brain prostheses and neural interfaces between silicon and biological "wet ware". In addition to enabling the equivalent of spare parts for the brain that can restore cognitive functions, others are considering the potential of this technology to enhance cognition (Huang, 2003; Naam, 2005).

The US Defense Advanced Research Projects Agency's (DARPA) Augmented Cognition Program (AugCog) is aimed at maximizing human cognitive abilities through the unification of humans and computational systems. Augmented cognition revolutionizes Generation 2 human-computer interaction by coupling traditional electromechanical interaction devices (e.g., mouse, joystick) with psycho-physiological interaction (e.g., eye blinks, respiration, heart rate, electroencephalogram), such that subtle human-physiological indicators can be used to direct human–system interaction. The goal is for the resulting human-machine dyad to provide integrated solutions to demanding situations "at a previously unimagined rate". The design requirement is not for automating all that can be automated and leaving the rest to the operator, nor for automating all which people find difficult. Instead, the requirement is to balance the known capabilities and shortfalls of the human and computer processor into a distributed system of information processing communication, decision and control. The expectation is that dependencies will inevitably develop as the joint system achieves functions that neither alone can produce. Furthermore, the goal is that the cognitive processes of an augmented human should appear to the bystander and be perceived by the user as nothing more than a natural process of cognition at work. AugCog expects to achieve this by capitalizing on advances in the speed, memory, miniaturization and power efficiency of digital systems as well as the effectiveness of software data mining and storage and advances in real-time cognitive state sensing.

2.4. Generation 4

Forth generation HFE is focused on biologically altering or modifying human physical and/or cognitive capabilities to maximize *human* effectiveness. In effect, this is a biological fit to the system. Information, biological and nano technologies are enabling the ability to redesign our basic human factors—that is, how we think, how we feel, how we look, how we age, and how we communicate with one another. In other words, HFE from the inside out.

At present, Generation 4 is emergent and focused on applications of pharmacology, bio-technology and genetic medicine seeking to stall, reverse or modify effects of disease or aging. The HFE implications derive from the inevitable consideration of these techniques to enhance capabilities and overcome the limitations of otherwise normal individuals. The human desire for cognitive enhancement is not a new phenomenon since for thousands of years people have brewed, chewed or smoked substances in the hopes of boosting their mental abilities. More recently, the use of pharmacological ergogenic aids such as human growth hormone (hGH), testosterone and other anabolic-androgenic steroids for the purpose of enhancing athletic performance have provoked a vexing controversy about sportsmanship and the unfair advantage they can bestow the user. Aside from potential deleterious side effects—which haven't stalled demand by athletes—what prevents future industrial or military applications outside of the sports arena (Eichner, 1997)?

2.4.1. Psychotropic pharma

In the US, \$18B is lost in industrial productivity every year because of sleepiness on the job. On US highways, drowsiness cost more than \$12B/yr in lost productivity and property damage. About 1500 deaths and 76 000 injuries occur on the road due to motorists who fall asleep (Caldwell, 2002). In the military, fatigue can be as dangerous as intoxication by alcohol with similar decrements in cognitive (attention, complex thinking, judgment, decision-making and motivation) and motor skills comparable to blood alcohol levels of .1% (Caldwell and Caldwell, 2003). "Go" pills, in use today (caffeine, dextroamphetamine and modafinil or providgil) can counter high levels of operational fatigue in intense sustained operations (Caldwell, 2003). Modafinil, for example, significantly attenuates flight-performance decrements from fatigue with no other subjectively noticeable cognitive effects. Sleep inducing hypnotics for inducing and maintaining sleep are the "No Go" side of treating sleep deprivation and its negative cognitive effects. The armed forces seek sustained vigilance and cognitive superiority in military operations and continue to be at the forefront of testing and implementing safe and effective psycho-pharmacological agents. This class of pharmaceuticals has been increasingly accepted over a range of industrial work domains and is merely the leading edge of a wave of new psycho-tropic agents directed at cognitive enhancement.

The potential market created by an aging post WW II baby boomer population has driven huge investments by the pharmaceutical industry in pursuit of life style drugs to counter geriatric decrement in physical and mental performance and to fill future medicine cabinets with life style drugs to elevate intellectual power. The market is very large and estimated at about 80 M people aged 50 or older in the US that is slated to double by 2030 (Hutchison and Morgenthaler, 2004). Never mind restoring impaired cognitive functions, the race is on to bring to market the next Viagra, only this drug will be for the brain and will be used to boost cognitive normals into a hyper-range of capabilities (Langreth, 2002). The increasing availability of these new cognitive performance-enhancing compounds offers extraordinary 'benefits' to industrial and military users, and to the extent these are adopted, the practice of HFE will be transformed.

Biotech firms are investing huge sums on R&D to unravel the mysteries of memory and to develop brain boosting or nootropic Drugs (from the Greek words "noos" (mind) and tropein (turn) for "acting on the mind"). One such drug, Pramiracetam (Warner Lambert/Parke Davis) is a powerful cerebral stimulant that appears to improve learning and memory by enhancing the firing of neurons in the Hippocampus (the area of the brain associated with formation of long-term memory). Small doses appear to increase the flow of information between the right and left hemispheres. One patient on a trial with this drug reported that it enhanced his ability to concentrate for extended periods. He described his experience as complete lucidity with no intoxication. At the present time, there are approximately forty such nootropic pharmaceuticals under development.

DARPA has sponsored research with a class of compounds known as AMPAKINEs. In human trials, a compound labeled CX515 administered daily for 12 weeks demonstrated some startling effects.

> "At the start of the trial, I could remember less than 5 words out of a list of twenty. By the second week, I could get 14 out of 20. The patient in this trial reported that it was heartbreaking to go off the drug and that "I had been thinking of some other way to get it, and I don't give a damn if it is legal or illegal." (Arnst, 2003)

What's the downside? Can too much enhancement be counter-productive for healthy people? Squire and Kandel (1999) point out in their book "*Memory: From mind to molecules*" that there is a reason why the brain forgets things. That is, to prevent cluttering up our minds. "People with the natural ability to remember all kinds of minute details often get bogged down in them and are unable to grasp the larger concepts." To the degree that these next generation nootropic drugs have no adversive side effects and are accepted in society and the workplace, what impacts on the practice of HFE can be foreseen? If for example, workplace productivity and performance and thereby profits can be markedly improved, will workers and companies be compelled to adopt nootropic drugs in the brave new workplace?

2.4.2. Genetic engineering

One company, Amgen, is testing a controversial neurochemical stimulant against Parkinson's disease with indications that it may promote re-growth of nerve fibers. While the intent is to provide cures for brain diseases such as Parkinson's, Alzheimer's, epilepsy etc., others see the potential for this technology to improve upon the limitations imposed by our biology. Clinical protocols for genetic engineering with humans—the custom insertion of genes into plants and animals—began in 1990 (Blaese, 1990). A key potential benefit of this approach over drug interventions described earlier is that drugs are eventually metabolized or flushed from your system whereas gene therapy effectively gives the body the ability to manufacture the given protein, enzyme or other bio-chemical. Hence, for example, athletic endurance can be improved by regular injections of the drug EPO that boosts production of red blood cells thereby increasing O2 carrying capacity that, in turn, increases endurance. As an alternative, it is possible, through genetic engineering to insert genes that promote as much continuous production of EPO that is needed (Zorpette, 2000).

Significant fundamental research is also underway to tackle the challenge of genetically engineering the enhancement of cognition and intellect. Tang et al. (1999), Tsien (2000) and others have shown it is possible to genetically engineer a smarter than average mouse through NMDA receptor-dependent modifications of synaptic efficacy. The implications of this research on the feasibility of genetic enhancement of mental and cognitive attributes of higher-level mammals are clear. Indeed, genetic engineering that modifies biochemical processes in order to enhance physical and cognitive performance, whether for therapeutic or elective enhancement purposes, promises to be the next ethical battlefield in medicine and human factors.

3. Opportunities and challenges in the quest for cognitive enhancement

> "I think, therefore I am" Descartes maxim.

The complexity of the human brain as the seat of consciousness presents a conundrum for those seeking to understand its nature and, in particular, the causal relationships between neural anatomy, consciousness, intellect and behavior. As a domain of interest, cognition refers to a myriad, complex of functions. It allows us to recall memories, concentrate, learn, communicate, solve problems, and make decisions. If impaired, simple tasks like showering, getting dressed, going to work or doing work become difficult.

With the growth of interest in developing "artificial intelligence" modeled on human intelligence, computer and cognitive scientists have advanced myriad theories and models of consciousness and cognition. Most suffer from the "Homunculus Fallacy in that they treat the brain as if there were some agent inside it using it to compute with (Searle, 1990; Correia, 1997). That is to say, they promote the view that consciousness is mediated as a separate computational function located at a specific site within the brain versus being an emergent property of distributed functions of the brain.

Cognitive enhancement under Gens 3 and 4 is focused on overcoming "natural" limitations in speed of processing or working memory, etc. that may impede the performance of work. The development of an effective strategy for overcoming these sources of impedance is challenged by a lack of practical understanding of the linkages between brain physiology and behavioral performance. For example, processing speed for a given task may be affected by any of a multitude of factors including:

- speed of transmission between neurons within a mechanism,
- number of iterations required by cooperative processes within a mechanism,
- speed of transmission for top down processing or cooperation with other mechanisms in different cortical areas,
- the complexity (e.g. difficulty, frequency, tempo), work context (e.g. concurrent demand, total load, interdependence) and criticality (cost, benefit, consequence) of the task.

3.1. Cognitive variability and "plasticity"

Other opportunities for cognitive enhancement become evident when you consider the enormous range of variability in human intellect from idiots to Einsteins and the remarkable plasticity of the brain to adaptively enable compensatory functions when needed. Wide ranging variability in cognitive function is also found across the normal aging population. Generally the longstanding belief that we lose vast numbers of brain cells as we grow older has been overcome by evidence from neuroscience that suggests that our brains can continue producing new neurons well into the seventies and beyond (Naam, 2005). As a case in point, in 2000 Stanley Kunitz, at the age of 95, was named the Poet Laureate of the US. Now, over 100 years old, he is still writing new poems and reading to live audiences. The challenge this poses for Gens 3 and 4 HFE is to understand the bases of these capability differences and to human engineer appropriate compensatory aids, augmentation or re-engineering of our neuro-biology to enable humans to perform to their fullest potential throughout their lives.

Other intriguing evidence on enhancing the cognitive information processing capabilities of the human brain derives from observations and studies of autistic savants. These are autistic individuals who are capable of extraordinary cognitive abilities in math, language, memory and the arts. For example,

> "Daniel Tammet is an autistic savant who can perform mind-boggling math calculations at breakneck speed. He can calculate prime numbers and square roots without hesitation and Pi to 22,514 decimal places. He speaks seven languages and is devising his own. On the other hand, he is incapable of independently carrying many daily activities needed to care for himself. At the age of three, he suffered an epileptic fit and has since been obsessed with counting." (Johnson, 2005).

The focused cognitive abilities demonstrated by autistic savants indicates that limitations of processing speed and working memory may be overcome within the existing neuro-anatomical architecture of the brain. The HFE question is how to effectively exploit this understanding to enhance the cognitive abilities of normal individuals. A key enabler to future bio-management strategies for cognitive resources is the degree to which brain functions are mutable. As it turns out, there is considerable evidence of plasticity of the brain within constraints. Animal studies, for example, have shown that sensory deprivation in one modality can have striking effects on the development of the remaining modalities. Similarly, studies of deaf and blind humans have also provided convincing behavioral, electro-physiological and neuro-imaging evidence of increased capabilities and altered organization of spared modalities (Lessard et al., 1998; Lenay et al., 2003).

3.2. Feasibility of cognitive enhancement through neural and genetic engineering

Is human genetic engineering of cognition realistic? Can we systematically engage and manage the mechanisms that control neuronal growth through bio-chemical or other means? NGF is a chemical that triggers growth of neurons. As we age, levels of NGF drop. Researchers have found that adding extra copies of the NGF producing gene not only prevented age-related shrinkage in mice and monkeys, but could actually restore neurons to their youthful size, shape and activity... and have a corollary effect on learning and memory (Tsien, 2000).

Hundreds of labs are exploring gene therapeutic approaches—insertion of normal DNA into cells—to cure diabetes, sickle cell anemia, cancer, etc. Though most approaches to overcome defective DNA have met with mixed results, many genetic researchers remain optimistic that someday it will be possible to correct many of the inherited single-gene diseases that afflict the human race. On the other hand, many respected scientists believe that safe human genetic engineering may never be practical, since most human traits—both desirable and deleterious—are the result of the interactions among multiple genes. The combinatorial explosion resulting from these interactions yields a conundrum for predicting and managing the outcome of a given intervention.

> A combinatorial explosion occurs when a huge number of possible combinations are created by increasing the number of entities that can be combined. For example, there are 86,493,225 ways to pull 12 rabbits out of a hat containing 30 rabbits, and more than 635 billion 13-card bridge hands that can be dealt from a 52-card deck. The combinatorial problem grows mind-bogglingly huge when one considers the various ways just 30,000 human genes and the 100,000 or so proteins they produce can be combined in human cells and tissues (Bailey, 2003).

The leading criticism of the potential to genetically engineer high intelligence is that intelligence results from a complex interaction of both nature and nurture and the complexity of the combinatorial explosion becomes intractable when the effects of the environment are factored in. As an example, Naam (2005, p. 158) estimated that only one in 400 Einstein clones raised in an average environment would have an IQ greater or equal to Einstein.

4. Ethical quandaries

The shift from HF Generations 1 and 2 to Generations 3 and 4 also demarcates a boundary across which social ethics issues have arisen that are somewhat unprecedented for HFE. With Generations 1 and 2, the argument was often posed that it was unethical not to consider good HFE that could reduce discomfort, injury, mishaps and loss of life. The focus on augmenting or altering human capabilities in HFE Generations 3 and 4, have deepened the social divide between those that see cognitive and physical enhancement as a great benefit to society and those who perceive this as tampering with the fundamentals of human nature.

According to Malik (2002), the biological sciences ability to tinker with the human mind and body seems to have divided the world into two camps: utopians and dystopians.

- Utopians view science positively as means to solving the world's problems—i.e., to eliminate hunger, eradicate disease, and to improve the human race by enhancing our bodies, intelligence, and personalities.
- Dystopians view scientific advances as threatening to transform human nature, undermine human dignity, and usher in a new era of eugenics (Kass, 2002).

> Our present condition is this: we have entered a new age of eugenics. That science which attempts to improve the inherited characteristics of the species and which had gone so suddenly out of fashion after WWII and the Nazi doctors now climb steadily back to respectability. G Meilander, US Bioethics Panel.

This ethical rift is especially evident for cognitive enhancing technologies. Some examples that illustrate these ethical concerns follow.

- Overwhelmed with class assignments, a college student consults with his physician. The doctor prescribes a cognition enhancer. As a result the student maximizes his exam scores.
- A soldier fights next to his comrade who is killed instantly. "Witnessing this, the surviving soldier goes into shock, despite the continuing firefight. Quickly, he reaches for a pouch, takes out a pill, and swallows it. Seconds later, he forgets what he saw and resumes shooting–and makes it out alive."

These vignettes (adopted from Russo, 2004) illustrate the types of ethical quandaries likely to surface if cognitive pharmacological agents become accepted as appropriate treatments for persons not deemed sick. What if an individual consumes a drug that changes the fundamental valence of their personality such as a soldier made less fearful with drugs? What continues to be their personal responsibility? Are they, in fact, the same person? What if their friends and loved ones can no longer recognize them? Furthermore, who should be entitled to such drugs, what should be the level of oversight, and when do the benefits outweigh the safety concerns?

Dystopians argue that instant performance enhancers would have dire social consequence by reducing human drive and hard work and that neurophysiological and genetic engineering technologies for sculpting the human mind would threaten our sense of identity and might further widen the gap between rich and poor. Utopians counter that enhanced cognition and human performance will lead to increases in productivity and wealth further flattening the world and the differences between first and third world nations.

5. Endnote

> Will there ever be a cure for stupidity?
> (Hancock, 2000)

At the time Peter raised this question, he was referring to the fact that for most of human existence, the vast majority of people have lived their lives in ignorance of our accumulated wisdom. His main thesis was that despite the potential of IT to enable access to the summed store of mankind's knowledge*, increased data does not provide a cure for stupidity.*

Norman (1993) suggests that though the mind is limited in capability (i.e. there are limits to how much we can remember or learn), that technology can help us think better and more clearly by enabling greater access to accurate info and support collaboration and networking with others irrespective of geography. Conversely, he also suggests that technology can make us stupid by consuming intellectual productivity and attention as with television and "sound bite" news.

The revolution in IT has indeed altered the nature of work, creating a shift towards cognitive work where the emphasis is on thinking, decision making and problem solving–as opposed to strength and dexterity. The enormous potential for technologically aiding and enhancing cognition is evidenced by the normally occurring range, variability and plasticity of cognitive traits and intellect. Each successive generation of HFE has evolved options to exploit this potential. Generations 1 and 2 have focused on training, aiding, selection, HCI and human systems integration. Generation 3 has a focus on Joint Cognitive Systems that maximize cognitive abilities through the unification of human and computational systems. Generation 4 may enable the neural and genetic optimization of human information processing.

Predictably enough, the market demand for cognitive enhancement is extremely high. The human desire for cognitive enhancement is not a new phenomenon and is probably as old as HFE. A Google search of the Internet readily turns up thousands of advertisements for costly appliances, devices, nutritional supplements, and books for enhancing cognitive capabilities. This same market may lead to a new frontier for elective medicine: "Cosmetic Neurology". While neurologists currently try to protect ailing brains from conditions like Parkinson's disease or migraine headaches, their practice could one day extend to normal brains focused on sharpening intelligence, reflexes, attention, mood and memory (Chatterjee, 2004).

Future scientific and technical interventions are bound to have dramatic impacts on human factors and ergonomics. Unraveling the genetic code has demonstrated the potential to cure our bodily ills by enabling drugs designed to match genetic makeups. New research in cognitive systems will revolutionize the way we design, deploy, and depend on computing systems with implications for the future nature of intellect and ultimately for fabricating an intelligence that exceeds our own. In the future beyond fourth generation HFE, it is likely that we will be able to systematically manipulate the language of genes. This greater power over the human brain and mind will have profound effects on society, human productivity, the nature of work and ultimately the practice of human factors and ergonomics.

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