Neo-Symbiosis: The Next Stage in the Evolution of Human Information Interaction

Douglas Griffith, General Dynamics Advanced Information Systems, USA

Frank Greitzer, Pacific Northwest National Laboratory, USA

ABSTRACT

The purpose of this paper is to re-address the vision of human-computer symbiosis as originally expressed by J.C.R. Licklider nearly a half-century ago and to argue for the relevance of this vision to the field of cognitive informatics. We describe this vision, place it in some historical context relating to the evolution of human factors research, and observe that the field is now in the process of re-invigorating Licklider's vision. A central concept of this vision is that humans need to be incorporated into computer architectures. We briefly assess the state of the technology within the context of contemporary theory and practice, and we describe what we regard as this emerging field of neo-symbiosis. Examples of neo-symbiosis are provided, but these are nascent examples and the potential of neo-symbiosis is yet to be realized. We offer some initial thoughts on requirements to define functionality of neo-symbiotic systems and discuss research challenges associated with their development and evaluation. Methodologies and metrics for assessing neo-symbiosis are discussed.

Keywords: please provide keywords

BACKGROUND

In 1960, J.C.R. Licklider wrote in his paper "Man-Machine Symbiosis,"

The hope is that in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human brain has ever thought and process data in a way not approached by the information-handling machines we know today.

This statement is breathtaking for its vision — especially considering the state of computer technology at that time, that is, large mainframes, punch cards, and batch processing. The purpose of this article is to re-address Licklider's vision and build upon his ideas to inform contemporary theory and practice within the broader field of human factors as well as to offer a historical perspective for the emerging field of cognitive informatics.

It is curious to note that Licklider did not use the term symbiosis again, but he did introduce more visionary ideas in a symbiotic vein. A paper he co-authored with Robert Taylor, titled "The Computer As a Communication Device," made the bold assertion, "In a few years, men will be able to communicate more effectively through a machine than face to face" (1968). Clearly the time estimate was optimistic, but the vision was noteworthy. Licklider and Taylor described the role of the computer in effective communication by introducing the concept of "On-Line Interactive Vicarious Expediter and Responder" (OLIVER), an acronym that by no coincidence was chosen to honor artificial intelligence researcher and the father of machine perception, Oliver Selfridge. OLIVER would be able to take notes when so directed, and would know what you do, what you read, what you buy and where you buy it. It would know your friends and acquaintances and would know who and what is important to you. This paper made heavy use of the concept of "mental models," relatively new to the psychology of that day. The computer was conceived of as an active participant rather than as a passive communication device. Remember that when this paper was written, computers were large devices used by specialists. The age of personal computing was off in the future.

Born during World War II, the field of human factors engineering (HFE) gained prominence for its research on the placement of controls — commonly referred to as knobology within the field of HFE, which was an unjust characterization. Many important contributions were made to the design of aircraft, including controls and displays. With strong roots in research on human performance and human errors, the field gained prominence through the work of many leaders in the field who came out of the military: Alphonse Chapanis, a psychologist and a Lieutenant in the U.S. Air Force; Alexander Williams, a psychologist and naval aviator; Air Force Colonel Paul Fitts; and J.C.R. Licklider. Beginning with Chapanis, who realized that "pilot errors" were most often cockpit design errors that could be corrected by the application of human factors to display and controls, these early educators were instrumental in launching the discipline of aviation psychology and HFE that led to worldwide standards in the aviation industry. These men were influential in demonstrating that the military and aviation industry could benefit from research and expertise of the human factors academic community; their works (Fitts, 1951a) were inspirational in guiding research and design in engineering psychology for decades. Among the most influential early articles in the field that came out of this academic discipline was George Miller's (1956) "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity to Process Information," which heralded the field of cognitive science and application of quantitative approaches to the study of cognitive activity and performance.

An early focus of HFE was to design systems informed by known human information processing limitations and capabilities — systems that exploit our cognitive strengths and accommodate our weaknesses (inspired by the early ideas represented in the Fitts' List that compared human and machine capabilities; Fitts, 1951b). While the early HFE practice emphasized improvements in the design of equipment to make up for human limitations (reflecting a tradition of *machine centered computing*), a new way of thinking about human factors was characterized by the design of the human-machine system, or more generally, *human-* or *user-centered computing* (Norman & Draper, 1986). The new subdiscipline of interaction design emerged in the 1970s and 1980s that emphasizes the need to organize information in ways to help reduce clutter and "information overload" and to help cope with design challenges for next-generation systems that will be increasingly complex while being staffed with fewer people. Emphasis on human cognitive processes, and on the need to regard the human-machine system as a joint cognitive system, represented a further refinement that has been called *cognitive systems engineering* (Hollnagel & Woods, 1983).

Fundamental to all of these approaches and perspectives on HFE is the overriding principle to "know your user." In a recent critical essay, Don Norman (2005) asks us to re-assess the human-centered design perspective: Developed to overcome the poor design of software products, human-centered design emphasized the needs and abilities of users and improved the usability and understandability of products. But despite these improvements, software complexity is still with us. Norman goes on to ask why so many designs of everyday things work so well, even without the benefit of user studies and human-centered design. He suggests that they all were "developed with a deep understanding of the activities that were to be performed." Successful designs are those that fit gracefully into the requirements of the underlying activity. Norman does not reject human-centered design, but rather encompasses it within a broader perspective of *activity-centered design*. Further, he questions a basic tenet of human centered design that technology should adapt to the human, rather than *vice versa*. He regards much of human behavior as an adaptation to the "powers and limitations of technology." Activity-centered design aims to exploit this fact.

Other perspectives suggest that the focus of design should be on human-information interaction rather than human-computer interaction. Gershon (1995) coined the term Human-Information Interaction (HII) to focus attention on improving the way people "find, interact with, and understand information." As such, HII includes aspects of many traditional research efforts, including usability evaluation methods and cognitive task analysis, but also design concepts that address the ethnographic and ecological environment in which action takes place. Examples of work in this area include distributed cognition (Zhang & Norman, 1994), naturalistic and recognition-primed decision making (Zsombok, 1997); and information foraging and information scent (Pirolli & Card, 1999).

In summary, over the last half century or so, the field of human factors has evolved through a series of modest perspective shifts and insights that have yielded a fair degree of success in approaches, methods, and techniques for design and evaluation of systems that are created to support and enhance human-information interaction. The many labels that have been applied to the field (cognitive engineering, human-centered computing, participatory design, decision centered design, etc.) are all "differently hued variants of the same variety" (Hoffman, Feltovich, Ford, Woods, Klein & Feltovich, 2002).

Engineering psychology and human factors are moving to a more encompassing scope of the field. Raja Parasuraman (2003) married neuroscience with ergonomics and termed it neuroergonomics. Don Norman (2004) incorporated affect (emotion) into the field with his book, *Emotional Design: Why We Love (or Hate) Everyday Things*. Hancock, Pepe and Murphy (2005) are developing the concept of hedonomics. They have developed a hierarchy of ergonomics and hedonomic needs derived from Maslow's (1970) hierarchy of needs: safety, the prevention of pain, forms the foundation of this pyramid; next comes functionality, the promulgation of process; then usability, the priority of preference (the transition from ergonomics to hedonomics begins at the usability layer); the next layer is pleasurable experience; and the apex of the pyramid comprises individuation and personal perfection. So the field is beginning to address the enhancement of individual potential. Recent research in the emerging field of cognitive informatics (Wang, 2005a, b) addresses Maslow's hierarchy of needs within a formal model that attempts to capture the relationships among human factors and basic human needs.

Recently a new research thrust has emerged that aims to shift the focus once more to not only enhancing the interaction environment, which is the aim of cognitive systems engineering, but also to enhance the cognitive *abilities* of the human operators and decision makers themselves. The Augmented Cognition program (Schmorrow & Kruse, 2004) within the DARPA Information Processing Technology Office (IPTO) aims to monitor and assess the user's cognitive state through behaviorally and neurologically derived measures acquired from the user while interacting with the system and then to adapt or augment the computational interface to improve performance of the user-computer system. Schmorrow and McBride (2005) explain that this research is based on the view that the weak link in the human-computer system may be attributed to human information processing limitations, and that human and computer capabilities are increasingly reliant on each other to achieve maximal performance. Much of the research within the augmented cognition program seeks to further our understanding of how information processing works in the human mind so that augmentation schemes might be developed and exploited more effectively — in a variety of domains from clinical restoration of function to education to worker productivity to warfighting superiority. Thus, as described by Schmorrow and McBride: "the DARPA Augmented Cognition program at its core is an attempt to create a new frontier, not by optimizing the friendliness of connections between human and computer, but by reconceptualizing a true marriage of silicon- and carbon-based enterprises."

While augmented cognition exploits neuroscience research as a path toward symbiosis of humans and machines, research in cognitive informatics embraces neuroscience research as a potential model and point of departure for "brain-like" machine-based cognitive systems that may someday exhibit human-like properties of sensation, perception, and other complex cognitive behaviour (Anderson, 2005a, b). We believe that neo-symbiosis provides a strong contextual framework to organize and guide research in cognitive informatics.

NEO-SYMBIOSIS

Once more, then, we are on the threshold of resurrecting a vision of symbiosis – but today we have the advantage of far greater computational resources and decades of evolution in the field of human factors/cognitive engineering. Licklider's notion of symbiosis does require updating. First, the term "man/machine symbiosis" is politically incorrect and would be more appropriately termed "human/machine symbiosis." Then there is a problem with the term symbiosis itself. Symbiosis implies *co-equality* between mutually supportive organisms. However, we contend that the human must be in the *superordinate* position. The Dreyfuses (Dreyfus, 1972, 1979, 1992; Dreyfus & Dreyfus, 1986) have made compelling arguments that there are fundamental limitations to what computers can accomplish, limitations that will never be overcome (Dreyfus & Dreyfus, 1986). In this case, it is important that the human remain in the superordinate position so that these computer limitations can be circumvented. On the other hand, Kurzweil has argued for the unlimited potential of computers (Kurzweil, 1999). But should it be proven that computers do, indeed, have this unlimited potential, then some attention needs to be paid to Bill Joy and his nightmarish vision of the future should technology go awry (Joy, 2000). In this case, humans would need to be in the superordinate position for their own survival. Griffith (2005a) has suggested the term neo-symbiosis for this updated vision of symbiosis.

The augmented cognition research community is taking Licklider's vision quite literally in exploring technologies for acquiring, measuring, and validating neurological cognitive state sensors to facilitate human-information interaction and decision-making. Neurobiologically inspired forms of symbiosis, while consistent with the metaphor that Licklider used, were not a focus of Licklider's vision; but the possibilities for enhanced cognitive performance are enticing. Clearly, however, much work is required to achieve a brain-computer interface that might be called neo-symbiotic. Much of the effort in this field to date has focused on cognitive activity that tends to be more oriented toward attention and perception processes, and less toward decision making and thinking. In this sense, augmented-cognition neurological inputs can help to approach neo-symbiosis by providing information to the computer that can in turn be fed back to the human in the form of adaptive displays and interactions or other functions aimed to mitigate the effects of stress or information overload. More ambitious goals of increasing total cognitive capacity through augmented cognition technologies are still on the horizon of this research program and recent offshoots of augmented cognition R&D such as DARPA's Neurotechnology for Intelligence Analysts program[1]. Our interest, similarly, is in the current potential for enhanced human-computer collaboration that will achieve a level of performance that is superior to either the human or the computer acting alone.

The principal reason that the beginning of the 21st century is so propitious for the re-invigoration of Licklider's vision is the result of advancements in computer technology and psychological theory. Therefore, one of our major objectives is to increase the human's understanding, accuracy, and effectiveness by supporting the development of creative insights. Understanding involves learning about the problem area and increasing the variety of contexts from which the problem can be understood. Enhanced accuracy/effectiveness can be achieved by endowing the computer with a variety of means to support the task or activity. Revisiting thoughtful prescriptions for such computer-based intelligent support capabilities from two decades ago, we find examples such as knowledge of the user's goals and intentions, contextual knowledge (Croft, 1984). and "cognitive coupling" (Fitter & Sime, 1980) functions that include (Greitzer, Hershman & Kaiwi, 1985) the ability to inform the user about the status of tasks, remind the user to perform certain tasks, advise the user in selecting alternative actions, monitor progress toward the goal, anticipate requests to display or process information, and test hypotheses. In the context of information analysis tasks, examples of such neo-symbiotic contributions by the computer include considering alternative hypotheses, assessing the accuracy of intelligence sources, and increasing the precision of probability estimates through systematic revision. These types of activity-based support functions, enhanced by cognitive models, are the concepts that we believe will put us more solidly on the path to the original vision of Licklider, a neo-symbiosis where there is a greater focus on cognitive coupling between the human user and the computer.

NEO-SYMBIOSIS RESEARCH AGENDA

Requirements: Implementing Neo-Symbiosis

How should neo-symbiosis be implemented? Fortunately, Kahneman (2002, 2003) and Kahneman and Frederick (2002) has provided guidance through a theoretical framework. In his effort to organize seemingly contradictory results in studies of judgment under uncertainty, he has advanced the notion of two cognitive systems introduced by Sloman (1996, 2002) and others (Stanovich, 1999; Stanovich & West, 2002). System 1, termed Intuition, is fast, parallel, automatic, effortless, associative, slow learning, and emotional. System 2, termed Reasoning, is slow, serial, controlled, effortful, rule-governed, flexible, and neutral. The cognitive illusions, which were part of the work for which he won the Nobel Prize, as well as perceptual illusions, are the results of System 1 processing. Expertise is primarily a resident of System 1. So are most of our skilled performance such as recognition, speaking, driving, and many social interactions. System 2, on the other hand, consists of conscious operations, such as what is commonly thought of as thinking. Table 1 summarizes these characteristics and relationships. The upper portion of the table describes human information processing characteristics and strengths, interpreted within Kahneman's (2003) System 1/System 2 conceptualization. The bottom portion of the table represents an update of traditional characterizations of functional allocation based on human and computer capabilities, such as the original Fitts' List (Fitts, 1951b), cast within the System 1/System 2 framework.

System 1 is effective presumably due to evolutionary forces, massive experience, and by constraining context. Most of the time, it is quite effective. System 1 uses nonconscious heuristics to achieve these efficiencies, so occasionally it errs and misfires. Such misfires are responsible for perceptual and cognitive errors. One of the roles of System 2 is to monitor the outputs of System 1 processes. It is the System 2 processes that require computer support, not only with respect to the pure drudgery and slowness of human System 2 processes, but also with respect to the monitoring of System 1 processes. In most cases, however, it is a mistake to assign System 1 processes to the computer. This was the fundamental error in many automatic target recognition and image interpretation algorithms that attempted to automate the human out of the loop. Even to this day, computer technology has been unsuccessful in modeling human expertise in System 1 domains[2]. The perceptual recognition processes of most humans are excellent. System design should capitalize upon these superb processes and provide support to other areas of human information processing such as search (there is a tendency to overlook targets); interpretation keys to provide a check and support for the recognition process; analysis and synthesis (e.g., to augment reasoning processes); support to facilitate adjusting to changes in context (e.g., to maintain situational awareness); and computational support (e.g., to make predictions). The bottom portion of Table 1 exhibits examples of how human and computer contributions can be allocated to System 1 and System 2 processing in a neo-symbiotic system.

Greitzer (2005b) has discussed the importance of identifying cognitive states in real-world decision-making tasks. A critical question here is, what are the cognitive states that need to be measured? What are the cognitive states that, if identified and measured, could enhance neo-symbiosis? Clearly it would be beneficial to identify neurological correlates for System 1 and System 2 processes. It would be especially beneficial to identify neurological correlates of System 2 while monitoring System 1 processing. Perhaps there is a neurological signature when potential errors are detected in System 1 processing. It is conceivable that some of these errors remain below the threshold of consciousness. If these errors were detectable in the neurological stream, computers could assist in this error monitoring process.

As was mentioned previously, the identification of neurological correlates is not a requirement, nor is it the only enabler for neo-symbiosis. Griffith (2005b) has argued that neo-symbiosis can be achieved over a wide range of technological sophistication. Overviews and tutorials can be presented on basic human information processing capabilities, limitations, and biases. A software agent, or avatar, can pop up at strategic times with reminding prompts or checklists. Of course, the capability to monitor the human's cognitive state through neurological correlates will enhance the ability of the avatar to pop up at strategic times. It might also be possible to monitor the content of the interactions with the computer to identify potential processing problems. Differences in processing time present is yet another potential source of information for detecting errors and biases.

In our view, the thrust of the HII research agenda should be targeted at enhancing neo-symbiosis. A major focus of HII research today is aimed at visualization technology that processes and seeks to represent massive data in ways that facilitate insight and decision making. Data visualization technology seeks to facilitate visual thinking to gain an understanding of complex information, and perhaps most particularly to gain insights that would otherwise not be apparent from other data representations. A famous example of a successful visualization is the periodic table of elements (conceived by Mendeleev and published in 1869), which not only provided a simple display of known data but also pointed out gaps in knowledge that led to discoveries of new elements. However, creating novel visualizations of complex data (information

Table 1. System 1 and System 2 processes

Human Processes		
	System 1: Intuition	**System 2: Reasoning**
Processing Characteristics[a]:	o Fast o Parallel o Automatic o Effortless o Associative o Slow-Learning o Emotional	o Slow o Serial o Controlled o Effortful o Rule-governed o Flexible o Neutral
Type of Processing (Examples of Human Information Processing Strengths)	o Expertise o Skilled Performance o Most Perception	o Thinking o Goal-driven Performance o Anomaly and Paradox Detection
Neo-Symbiotic Functions		
	System 1: Intuition	**System 2: Reasoning**
Examples of Human Contributions	o Providing Context o Detecting Contextual Shifts o Intuition o Pattern Recognition o Creative Insights	o Supervision/Monitoring o Inductive Reasoning o Adaptability to Change o Contextual Evaluations o Anomaly Recognition/ Detection o Goal-Driven Processes/ Planning o Creative Insights
Examples of Computer Contributions	o Recognize Cognitive State Changes o Adapt Displays/Interaction Characteristics to Human's Cognitive State	o Deductive Reasoning o Search o Situational Awareness o Analysis/Synthesis o Hypothesis Generation/ Tracking o Computational Support o Information Storage/ Retrieval o Multiprocessing o Update Status of Tasks o Advise on Alternatives o Monitor Progress o Monitoring System 1 Processes

[a] *This portion of the table based on Kahneman (2003)*

visualization) does not guarantee success; there are arguably more examples of visualizations that have not lived up to expectations than success stories. A leap of faith is required to expect that a given scientific visualization will produce the "aha!" moment that leads to an insightful solution to a difficult problem. We assert that the key to a successful scientific visualization is its effectiveness in fostering new ways of thinking about a problem — in the System 1 sense as exemplified in Table 1 (e.g., seeing contextual shifts, recognizing new patterns, finding creative insights). This view stresses that the interaction component of HII needs to be emphasized. The human should not be regarded as simply a passive recipient of information display, however creative that information display might be. The human needs to be able to manipulate and interact with the information. The ability to manipulate information and view it in different contexts is key to the elimination of cognitive biases and to the achievement of novel insights (e.g., finding the novel intelligence in massive data). The goal is a neo-symbiotic interaction between the human and the *information*.

Thus, requirements should be defined so that a neo-symbiosis can be achieved between humans and their technology. Questions to guide the requirements definition process for neo-symbiotic systems designed to facilitate HII include:

- *How can such systems be designed to mitigate or eliminate cognitive biases?* Detecting/recognizing possible bias is one part of the challenge; an equally critical R&D goal is to define mitigation strategies. What types of interventions will be effective, and how should interventions be managed? We suggest that a mixed-initiative solution will be required that maintains the supervisory control of the human.
- *How can such systems be designed to leverage the unique processing skills of humans?* A prerequisite here is to identify the unique processing skills of humans. Technologies and approaches for developing idiosyncratic user models would be most useful. Moreover, expert users can identify and contribute their own unique skills: Consider an image interpretation system in which an expert with knowledge of a certain area could correct and elaborate upon outputs of image interpretation algorithms.
- *How can such systems be designed to facilitate collaboration?* One aim is to realize the assertion made by Licklider and Taylor (1968) that people will be able to communicate more effectively through a machine than face to face.
- *How can such systems promote a more pleasurable experience?* The goal here is to address some of the objectives outlined by Hancock et al. (2005).
- *How can such systems help someone to leverage personal potential or overcome a personal deficit (e.g., through augmentative/assistive technology)?* A major area of interest for neurally-based symbiotic studies is the use of implant technology in which a connection is made between technology and the human brain or nervous system. Important medical applications include restoring lost functionality in individuals due to neurological trauma or a debilitating disease, or for ameliorating symptoms of physical impairment such as blindness or deafness. Other applications that do not address medical needs but instead aim to enhance or augment mental or physical attributes provide a rich area of research in the growing area of augmented cognition. Warwick and Gasson (2005) review the field of research and describes his research and experiences as a researcher and experimental subject who is the first human to have a computer chip inserted into his body that enabled bidirectional information flow and demonstration of control of a remote robot hand using the subjects' own neural signals (Gasson, Hutt, Goodhew, Kyberd & Warwick, 2002; Warwick & Gasson, 2005). Warwick and Gasson (2005) observe:

By linking the mental functioning of a human and a machine network, a hybrid identify is created. When the human nervous system is connected directly with technology, this not only affects the nature of an individual's ... identity, ... but also it raises serious questions as to that individual's autonomy.

It should be appreciated, however, that assistive technology need not necessarily entail implants or any involvement with neurology. Indeed a great deal has already been accomplished via adaptive software and input and output devices (Griffith, 1990; Griffith, Gardner-Bonneau, Edwards, Elkind & Williges, 1989).

- *What are implications and requirements for computer architectures to achieve neo-symbiosis?* A central point underlying neo-symbiosis is that humans need to be included in the computer architecture or system design. It is anathema to the concept of neo-symbiosis that computers and humans be regarded in isolation. They need to be considered together with the objective of each exploiting the other's potential and compensating for the other's weaknesses. Ideally the interaction between the two will achieve a multiplicative effect, a true leveraging.

Metrics: Measuring Success

An important question is how to identify neo-symbiotic design and how to assess it. It is important to recognize instances of neo-symbiotic design that are already among us in the form of productivity enhancement tools or job aids. For example, spell checking in contemporary word processors compensate for memory and perceptual/motor shortcomings; thesauruses leverage communicative abilities. Various creativity tools, such as concept mapping, leverage creative potential. In the augmented cognition domain, various neurologically-based "cognitive state sensors" are emerging as indicators of cognitive load and as potential cognitive prosthetics for medical purposes. In each of these cases, particularly the most recent developments that aim to enhance cognitive functions and effectiveness, evaluation methods and metrics are needed to guide research and facilitate deployment of technologies. For more advanced development of neo-symbiotic designs that aim to enhance human information processing and decision making (e.g., intelligence analysis performance) or knowledge/skill acquisition (e.g., training applications), we recognize the need for more rigorous evaluation methods and metrics that reflect the impact of the technology on performance.

Of course, standard subjective measures can readily be expanded to include neo-symbiotic potential. Many subjective measures are interpreted in terms of usability. There are several sources of established guidelines for usability testing (e.g., Nielsen, 1993). Commonly used criteria include efficiency, ability to learn, and memorability. Usability measures the address of the experience of users; whether or not they found the tool useful, easy to learn, easy to use, and so forth. Often, users are asked to provide this sort of feedback using qualitative measures obtained through verbal ("out loud") protocols and/or post-hoc comments (via questionnaires, interviews, ratings). Likert scales, in which respondents indicate their degree of agreement or disagreement with particular statements using numerical ratings, can use question stems such as: "Using this application/system enhanced my performance"; or "Using this application/system compensated for my information processing shortcomings."

Subjective measures such as these are designed to assess the acceptance by users of the system. It is unfortunate that the term subjective is used in a pejorative sense and that subjective measures are all too often regarded as second rate measures. Whether or not a system is perceived favorably and judged to be useful are central questions in evaluating the system's value. Especially relevant to neo-symbiosis is the user's assessment of the extent to which his or her potential has been enhanced.

It is possible to use magnitude estimation to assess the subjective amount, or lack of, neo-symbiosis in an application/system.

In magnitude estimation (Stevens, 1975), stimuli are evaluated with respect to a standard stimulus, or modulus. That standard stimulus is assigned a value, and other stimuli are evaluated proportionate to it. So if the modulus was assigned a value of 50, and the stimulus being rated was regarded as half of whatever the rating dimension was, it would be rated 25. Were it regarded as having twice the value on the rating dimensions, it would be rated 100. A given version of Microsoft Word™ could be assigned a value of 50. If someone regarded another word processor as being twice as neo-symbiotic as this version of Word, it would be rated 100. Were it regarded to be only half as neo-symbiotic, it would be rated 25. A desirable property of magnitude estimation methods is that they produce ratio scales. Magnitude estimation is a remarkably robust methodology. Its validity has been demonstrated with stimuli ranging from the loudness of tones to the seriousness of crimes. It uses an anchor to a standard that allows proportional assessments of where an issue, item, stimulus stands with respect to that standard. Thus, statements can be made that a product is 20% better than a related product, 40% worse, and so forth. These ratings are more meaningful and interpretable than many other subjective rating techniques.

Whenever feasible, subjective measures should be supplemented with objective measures. Greitzer (2005a) has argued for development of measures of effectiveness based on performance impact in addition to the continued use of traditional subjective usability measures. User satisfaction is a necessary, but not sufficient measure. Behavioral measures are needed to address more cognitive factors and the utility of tools or technologies: Does technology *X* improve the throughput of cognitive tasks of type *Y*? Does it yield more efficient or higher quality output for certain types of tasks? Quantitative measures that assess utility may include efficiency in completing the task (time, accuracy, completeness). These will be most useful in comparing the utility of alternative tools or assessing the utility of a given tool vs. baseline performance without the tool. For example, in information analysis tasks, it has been observed (Scholtz, Morse & Hewett, 2004) that analysts tend to spend more time in data collection and report generation than in analysis activity (hence a kind of "bathtub curve" as described by Wilkins (2002) in the context of product reliability); tools or technologies that help alleviate the processing load for the collection phase and allow more time for analysis, for example, would be valued for their positive impact on performance (Badalamente & Greitzer, 2005). Time-based measures such as total time on task and dwell times can provide insight on user preferences and efficiency/impact of technologies being assessed (Sanquist, Greitzer, Slavich, Littlefield, Littlefield & Cowley, 2004). Other performance measures must be derived from specific decomposition of cognitive tasks. Greitzer (2005a) described examples of such analysis, within the information analysis domain, based on a decomposition of chains of reasoning (following the work of Hughes and Schum (2003) and analysis of behavior chains based on work of Kantor (1980) that was originally applied to evaluation of library science applications. While subjective measures provide weak support for neo-symbiosis, behavioral or performance measures provide strong support for neo-symbiosis. Absent behavioral or performance measures, questions remain as to the justification for the subjective ratings. Further research is needed to understand the basis for the subjective ratings.

SUMMARY AND CONCLUSIONS

The convergence of developments in different fields provides the foundation for a quantum leap in HII. Advancements in computer technology, cognitive theory, and neuroscience provide the potential for significant advances. Moreover, there is a movement for a more encompassing view of the scope of the field of human factors and ergonomics. The objective has been raised from making technology usable to using technology to enhance human potential, which was the original goal set by Licklider in 1960. The fulfillment of this objective will require collaboration and interaction among the fields of cognitive science, neuroscience, and computer technology. Most of the work in human factors and ergonomics has been empirical. Only occasionally has the field drawn upon theory. The field of HII has been primarily technology driven. Programs and systems are developed on the bases of intuitions and what is regarded as cool and challenging by the developer, rather than from considerations of the information processing shortcomings and potential of the users. Very often techniques are not even subject to empirical assessment. But a strategy of generating an idea and then evaluating it empirically will not prove successful in the long run. HII requirements need to be developed not only on the basis of what a given system is being designed to accomplish, but also on the basis of theory and data in cognitive science and neuroscience.

To sum up, we have argued that the field of HII is on the threshold of realizing a new vision of symbiosis — one that embraces the concept of mutually supportive systems, but with the human in a leadership position, and that exploits the advances in computational technology and the field of human factors/cognitive engineering to yield a level of human-machine collaboration and communication that was envisioned by Licklider, yet not attained. As we have described, the field of human factors/HII is not static, but rather must inexorably advance. With advances in computer technology, cognitive science, and neuroscience, human potential and fulfillment can be leveraged more, yielding a spiral of progress: As human potential is raised, then that new potential can be leveraged even further. We think this vision provides a useful framework for cognitive informatics.

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ENDNOTES

1 A research program at DARPA, Neurotechnology for Intelligence Analysts, seeks to identify robust brain signals that may be recorded in an operational environment and

that are correlated with imagery data of potential interest to the analyst. Investigations of visual neuroscience mechanisms have indicated that the human brain is capable of responding to visually salient objects significantly faster than an individual's visuomotor response—i.e., essentially before the human indicates awareness. The program seeks to develop information processing triage methods to increase the speed and accuracy of image analysis. http://www.darpa.mil/dso/thrust/biosci/nia.htm

2 As Anderson (2005b) has observed, human expertise in System 1 domains has been very difficult to model in computers, and many researchers (connectionists, behavior-based roboticists) have used this to argue that digital computer metaphor is flawed.

Dr. Griffith is an applied cognitive psychologist in the Cognitive Solutions Laboratory of General Dynamics Advanced Information Systems. He holds a PhD from the University of Utah and has 32 years of applied experience in government and industry. A former president of Division 21 (Applied Experimental and Engineering Psychology) of the American Psychological Association, he is particularly interested in systems that produce a synergism between the human and the machine. One project was the Computer Aids for Vision and Employment (CAVE) Program. The goal was to design better computer systems and training packages for the visually impaired. He managed a subcontract on a project to study cognitive aids for intelligence analysts to counter denial and deception. The work consisted of a review of human information processing shortcomings with an emphasis on those shortcomings that make analysts vulnerable to denial and deception techniques. Then remedies, the cognitive aids, were identified to compensate for these shortcomings and increase the analysts' awareness of the likelihood of denial and deception activities. In addition to neo-symbiotic systems, he is currently working on collaborative technologies and with metrics for collaboration and the analysis of nonconventional imagery.

Dr. Greitzer leads the Cognitive Informatics R&D area within the Computational and Information Sciences Directorate at the Pacific Northwest National Laboratory (PNNL). He holds a PhD in mathematical psychology with specialization in memory and cognition and a BS degree in mathematics. His professional experience includes thirty years of research and development in cognitive psychology, human information processing, user-centered design and incremental development of advanced technology software systems. In addition to performing applied research in human memory and cognition, he has substantial experience in system design and implementation of advanced and innovative performance support tools in command/control operations and information analysis. Dr. Greitzer has led or supported research and development projects in the area of human information interaction in support of intelligence analysis decision making and human performance modeling; and he has been instrumental in spearheading efforts to establish evaluation methods and metrics for intelligence analysis products. Dr. Greitzer's interests also include applying cognitive principles and advanced technology to develop innovative, interactive, student-centered education and training. In addition to his work at PNNL, Dr. Greitzer serves as an adjunct faculty member at Washington State University, Tri-Cities campus, where he teaches courses for the computer science department on interaction design.