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The future of neuroergonomics

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This paper addresses the theoretical, the philosophical, and the ethical considerations associated with the advent and future of neuroergonomics. These issues will demand increasing attention as knowledge of the linkage of brain function to technology-based action improves from its current coarse-grained level to a more fine-grained understanding. These developments promise to open extraordinary opportunities for improved human–machine and human–human interaction, and represent the next major step in human–machine evolution. The social and psychological implications of these changes, however, must be considered if abuse of this conception is to be circumvented.

1. Introduction

Laid before us now is the vision of a brave new world in which technology promises to grant and fulfill our every momentary wish as effortlessly as thought itself. Set against this Arcadian vision is an ever-present nightmare of machine domination in which we forfeit the very humanity by which we define ourselves. Between these two extremes lies the spectrum of future realities. Redolent of modern science fiction literature, such vistas may be rendered one step closer to reality by the birth of neuroergonomics (Parasuraman 2003). We are firm believers in the sequential dependency of history, in that actions taken now at the genesis of the next phase in human–machine interaction circumscribe what the possible futures will be. Consequently, in the present paper we offer more than a commentary on the papers in the two special issues of this journal on neuroergonomics. Rather, using knowledge garnered from these works, we wish to evaluate what directions neuroergonomics might take and what issues need be considered as such progress is engaged.

Consider the development of perceptual-motor skill. We have all seen the haphazard, effortful and sometimes comic actions of the naïve performer. Often the beginner approaching a new skill will make large, radical, excursive motions in an attempt to capture even the semblance of the required movement pattern. In stark contrast are the polished, elegant actions of the highly skilled individual which hardly seem to involve any effort at all. It is our view that the state of current human interaction with technology is more akin to the activities of the naïve beginner as compared to the polished response of the expert. This is largely because current human interaction with technology has to proceed through highly limited input–output capabilities curtailed by the qualities of perceptual processes and the response capacities of the motor system. That the contemporary inelegance of

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interaction is due to the miseries of current interface design is evident. However, it is also intrinsically limited by this traditional mode of interaction with the world. Eyes, ears and skin for input and fingers, toes and voice for output are very limited ways for the brain to convert imagination to reality. We see neuroergonomics as the next, iterative step in expanding communication channels between humans and technology, a progress that has begun to accelerate as knowledge in the neurosciences has advanced beyond its first primitive stages.

While many early forms of tools were custom-made, the explosion of the 19th century Industrial Revolution created a one-size fits all mentality which percolated beyond the workplace into the manufactured artifact itself. The advent of the information age belied this nomothetic domination and we began to see adaptation as an important design issue in human–machine systems (Hancock and Chignell 1987, Rouse 1988). Such adaptation was a general property and did not rely on the presence of a single particular individual. For example, the Pilot's Associate project, an adaptive expert system for fighter pilots (Hammer and Small 1995), was designed to work generally rather than with a specific individual. We have now moved to a situation in which we have to pay attention to individuals and design must be flexible enough not simply to present a restricted smorgasbord of choices, but rather truly adapt to the singular individual character of the current user. But how is this to be done?

In these special issues are brought together discussions of diverse applications and methods of neuroscience techniques that promise to provide answers to the above question. Each article shares a common theme of relating brain activity to information processing and, in doing so, showing both the potential power of neuroergonomics and its current limitations. For the future of neuroergonomics, we see the following major issues to be addressed (although we do not claim this is an exhaustive list):

(1) The specificity of brain state assessment (brain–cognition link).
    (a) Neural structure, psychological constructs and reductionism.
    (b) From neurons to intention.
(2) Synergy of neuroergonomics and cognitive neuroscience.
(3) The potential of neuroergonomics.
(4) Ethical and philosophical concerns.
    (a) Freedom.
    (b) Privacy and information ownership.
    (c) The fracture of unitary consciousness

2. Brain–cognition link: the measurement problem

Currently, we have only very gross measures of the functional brain status of any specific individual. Measures of mental or cognitive workload take output either from the motor system via primary and secondary task performance, from the central and peripheral nervous system (as physiological reflections) or from subjective report. These indicators were perhaps the first used to capture the dynamics of human–machine interaction. However, today these measures may appear 'antiquated' in light of the exciting, multi-dimensional pictures provided by the various new brain-imaging techniques, but the fundamental problem remains the same as it has been throughout the history of psychology—how do we connect thought to action?

Primarily, this is a problem of measurement, which in turn depends upon one's theories of neuropsychology and its relation to neurophysiology. If one asserts that psychological theories exist only because we cannot adequately specify neurological function, then cognitive neuroscience and neuroergonomics become fields that, ultimately, replace psychology and human factors as information processing theories are rendered obsolete by increasing specification of the brain–cognition link. This amounts to a monistic, reductionist approach in which psychological processes are reduced to physical ones when the latter are sufficiently understood.

Alternatively, one could take a functionalist approach more typical of cognitive psychology (see Parasuraman 2003), in which the knowledge of neurological structures does not largely constrain understanding the structure and function of cognitive processes. A less severe form of this argument is a dualist concept, that distinct physical and psychological constructs are both necessary for a complete understanding of cognition (and human behaviour in general). In this view, one might posit that there are 'emergent features' at the level of cognition that are lost when they are reduced to their physiological correlates, but that understanding neurological structures provide one of many windows into cognition.

Regardless of which of these philosophical positions one adopts, the fundamental problem of establishing good neurological measures of cognitive processes remains. This, in turn, depends on the quality of our psychological theories, since psychological constructs lend meaning to the neurological data. For example, to link EEG patterns to cognitive processes the latter must be adequately specified, and this challenge was elucidated by the authors of some of the preceding papers. For example, Scerbo *et al.* (2003) argued that EEG indices of workload must be sensitive and diagnostic for a given task, and that the engagement index they derived from EEG data must be extended beyond specific tasks such as tracking and vigilance. The broader issue is how we know that the new EEG indices actually reflect mental workload. As Baldwin (2003) pointed out, one limitation of performance-based measures of workload is that performance reflects more than one process and is, therefore, not a unique measure of mental workload (see also Gopher and Donchin 1986, Meshkati *et al.* 1990). Similarly, a challenge for neuroergonomics is to establish that specific neurological indices reflect mental workload and no other process, an exclusivity criterion that is always difficult to establish in any multifactorial situation. A complicating factor is the possibility of different patterns of workload/performance associations and dissociations (Yeh and Wickens 1988, Hancock 1996, Parasuraman and Hancock 2001). These have been observed with subjective measures of workload and they may persist as relations between performance and neurological indices of workload are established across different tasks. This point was obliquely touched upon by Scerbo *et al.* (2003) when they discussed cases where performance and mental workload were not correlated. They discussed this issue in the context of the difficulty of validating EEG against behaviour, but in addition we suggest that such relations may enhance the validity of EEG by showing (potentially) that specific patterns of associations and dissociations between EEG and performance are linked to particular task categories. A related issue concerns the inconsistency between subjective and physiological measures that have also often been observed. This issue presents important challenges for the advancement of neuroergonomic approaches to workload and, in addition, to similar problems in establishing neurological indices of all forms of stress-state. Like fatigue, workload and stress are multidimensional constructs and neurological indices of them must be sensitive to this multidimensional facet (see Hancock and Desmond 2001).

Neuroergonomics can contribute to a more accurate assessment of all multidimensional cognitive states. As Scerbo *et al.* (2003) and Sarter and Sarter (2003) clearly articulated, neural measures have the potential to allow assessment of important constructs in cases where performance and subjective measures are either impractical or impossible. We would add, however, that a multi-assessment approach is vital here. Neural measures should be explored, but in practice they should be used whenever possible in combination with other measures (i.e. performance; subjective response), so that design decisions are not based upon only one order of data alone.

2.1. *Neural structure, psychological constructs and reductionism*

The development of good neurological measures of cognitive processes is limited by the fact that many of our psychological constructs (e.g. mental resources) remain poorly defined. Since the power of neuroergonomics will come from its validity for measurement of cognitive activity, established by correlating physiological matrices to cognitive measures, the validity of neuroergonomics will rest to some degree on the validity of our psychological models (and measures) of cognition and human performance. A footnote by Hettinger *et al.* (2003) nicely illustrates this concern. They pointed out that the ability to develop neuroadaptive interfaces depends on our ability to identify the relevant cognitive and emotional states associated with a given domain or set of tasks. As is clear from each of the papers in these special issues, the development of neuroergonomics must be in tandem with not only cognitive neuroscience but also cognitive psychology.

We accept the difficulty in establishing that a physiological index really reflects a specific aspect of cognition. However, we should note that this is a problem for *all* measures of human behaviour and mental processing. For instance, the problem of valid measurement of workload is as difficult to establish for subjective report as it is for psychophysiological measures. Sanderson *et al.* (2003) faced a similar limitation in that neural imaging techniques such as Steady State Probe Topography (SSPT) cannot, by themselves, identify displays (or any interface, for that matter) as 'good' or 'bad'. This is again due to the constraint we have articulated, which is that there is no simple mapping between cortical activity and cognitive processes. The notion that more is gained by replacing constructs like workload and situation awareness with a detailed neural identification of the cognitive processes underlying the constructs suffers the misguided assumption that reduction ultimately produces 'the' explanation for a phenomenon. A strategy of endless reduction can only lead ultimately to the level of quantum mechanics, which itself is struggling to link concepts to an understanding of consciousness.

The issue of reductionism is specifically addressed here by Sarter and Sarter (2003). They argued that for neuroergonomics to fully benefit from the approaches of cognitive neuroscience, researchers and practitioners in cognitive ergonomics must be willing to embrace a reductionistic approach. This would involve reducing higher level, multidimensional psychological constructs (they use examples of decision-making, situation awareness and mental workload) to underlying cognitive activity closely tied to brain activity. They noted, however, that our understanding of psychological constructs such as mental workload requires psychological analysis that is not necessarily enhanced by correlating performance with psychophysiological data. The latter have value, but do not replace the former. This is an important point to consider as the field of neuroergonomics develops. This approach promises to yield great benefits, but one must not fall into the trap that reducing explanation from one level to a more 'basic' level will obviate the need for analysis at the higher level. Simultaneous exploration of cognitive processes at the neural and gross psychological levels must be maintained. Indeed, psychological concepts such as 'resources' should benefit from this fusion (Szalma and Hancock 2002).

2.2. *From neurons to intention*

The problem of intention pertains to these difficult measurement issues. While neural activity will, with greater precision, be linked to specific cognitive processes, it is less clear how summed knowledge of multiple neuronal states will provide information regarding intention. Indeed, is it reasonable to talk of these two spheres of discourse in the same manner? Motivational constructs are especially difficult to specify at the psychological level and this intrinsically limits the potential for specific neural processes to indicate specific motivational states. Beyond the problem of establishing a valid definition of attributes such as motivation, there is also the issue of the locus or source of intention. For instance, it is possible that the brain mechanisms that react to extrinsic motivation are distinct from those that control intrinsic motivation. Efforts to define motivational states in terms of highly specified cognitive models (e.g. semantic networks) will aid in a partial resolution of the intention issue, but the ultimate source of intention (the homunculus problem) will not likely be resolved soon by neuroscience.

3. Synergy with cognitive neuroscience

Sarter and Sarter (2003) correctly noted that neuroergonomics will have to adopt characteristics of cognitive neuroscience, since the goals for these fields are so closely related. Cognitive neuroscience seeks the discovery of brain mechanisms mediating complex cognitive activity, while neuroergonomics seeks to understand how those same brain mechanisms are involved in human performance in interaction with technology. We appear to be at a point similar to that of Human Factors in the 1940s and 1950s, as it adopted the approaches of experimental psychology, particularly perceptual psychology, in the investigation of human–machine interaction. As Hettinger *et al.* (2003) argued in their article in this special issue, a strength of neuroergonomics is its potential to link diverse lines of research in human factors, experimental psychology and neuroscience, and it can be used to explore how facets studied separately by other fields (e.g. perception, cognition, motivation, emotion) interact to impact (and produce) behaviour.

The importance of cognitive neuroscience to neuroergonomics argued so cogently by Sarter and Sarter (2003) was underscored by the complexity of the results and the difficulty in data interpretation reported by Sanderson *et al.* (2003) and Scerbo *et al.* (2003). Neuroscience techniques are not a way around the limits of behavioural measures. As discussed earlier, they will work only to the extent that we have good psychological theory to define information processing structures to which brain function can be related.

4. The potential of neuroergonomics

One of the prime forms of application of neuroergonomics is to the creation and operation of adaptive systems (Hancock and Chignell 1987). As discussed by Scerbo *et al.* (2003) and Hettinger *et al.* (2003), there is more to be done before the full potential of these systems can be realized. Here, we address some of the issues for future research in adaptive systems as well as other areas in which neuroergonomics can be employed.

The potential for adaptive interfaces to improve the human–machine interaction is clear. Hettinger *et al.* (2003) discussed how these systems could be used to modify the presentation of information to best fit the person's mental state. For instance, an adaptive interface based on neural measurement could, if reliable, make an excellent alarm system, as a change in brain state indicating inattentiveness to an environmental event could be detected by the computer, which could sound the alarm. In addition, neuroergonomically designed systems could allow thought to be directly linked to system action, so that, for example, individuals with physical impairments could be trained to perform neural control of a computer-based system, opening up new activities for them (see Parasuraman 2003).

The example of adaptive interface design for the physically impaired illustrates that the possible applications of neuroergonomics extend beyond consideration of cognition and include physical activity as well. For instance, Karwowski *et al.* (2003) described studies on the brain-action relations in muscle control. From these studies, we can envision the development of adaptive aided action that parallels adaptive automation in which a computer-based system could sense muscular limitations of an operator (e.g. fatigue) and adapt human input requirements accordingly. Karwowski *et al.* (2003) discussed the potential for Physical Neuroergonomics to alleviate musculoskeletal injury, but the implications for improving human–environment interaction go further than prevention alone. Human physical capability may be extended in both strength and speed such that, with sufficient gain, minute muscular responses could produce physical activity beyond the limits of human-range (i.e. unaided action), as discussed by Hancock (1997). In this case, thoughts would directly produce movement of the self or other objects. Returning to the earlier example of design for the physically impaired, these individuals would gain the ability to execute physical behaviours directly from the brain, thereby expanding their ability to act on their environments beyond computer-based information processing tasks (cognition) to any physical task currently beyond their action capabilities.

Hettinger *et al.* (2003) cast the problem of human–machine interaction in terms of dysfunctional communication which may be solved by enhancing communication using measures of neural activity. This offers a promising approach to addressing what they referred to as asymmetrical communication between humans and machines, which they likened to 'dysfunctional interpersonal communication' between people. For example, they noted that a computer is ill equipped to recognize the changes in a human's cognitive or emotional state and to subsequently modify its behaviour to accommodate those changes. They argued that neuroadaptive interfaces could address this problem by allowing more precise monitoring of the operator's mental state. Note, however, that developing a computer system that can assess a human's cognitive or emotional state makes the machine functionally more 'human'. One issue for future research will be the implications of such a system for function allocation, which has traditionally been based on fundamental differences between humans and machines. As machines take on human abilities (e.g. 'emotional perception'), what will the role for the human be? Indeed, as the synergy between human and machine is increased by direct links between brain activity and machine activity, with an operator's thoughts directly impacting machine performance, and the machine, in turn, directly influencing brain activity, the boundaries of human identity and consciousness blur, and we consider this in more detail below. It may well become difficult to determine, at a functional level, where the human ends and the machine begins. While this will likely substantially enhance system performance and has extraordinary potential for improving quality of life (e.g. for the physically impaired), it also raises important philosophical issues regarding human identity and changes in the human condition.

Some of the issues which surround the neuroergonomic approach to adaptive automation are similar to those already discussed for general adaptive interfaces. The work of Scerbo *et al.* (2003) also indicates that function allocation will have to be reconsidered with adaptive automation. As they pointed out, negative and positive EEG feedback have different effects on performance. An implication of this, however, is that giving the operator something to do is important for both system performance and operator well-being. While this has been discussed in other contexts (Hancock 1998, Scerbo 1998), the physiological evidence supports the argument that performance suffers when automation leaves the human with little to do (Parasuraman and Riley 1997, Parasuraman and Hancock 2001). Specifically, Scerbo *et al.* (2003) showed that in positive feedback conditions automation is activated when the person is 'disengaged' (i.e. inattentive) and deactivated when the person is attentive and engaged in the task. Negative feedback activates automation when the person's attentiveness increased and automation turned off when attention waned. Across several experiments, performance was better with negative feedback rather than positive. In other words, performance was better when automation was turned off at the point the person's engagement decreased, possibly activating the person to become more involved in the task. Hence, letting the machine take care of things when a person becomes less attentive does not necessarily improve performance.

Findings such as those described above indicate that an important question for a burgeoning neuroergonomics is how (or whether) such an approach to the study and design of human–machine interaction will relieve stress and workload, and whether the heavy loads will be replaced with the burden of boredom. In principle, a computer could detect 'boredom' and respond by providing stimulation that is engaging for the users and captures their interest. If applied properly, this would be an application of neuroergonomics to *hedonomics*, which has been defined by Hancock as *that branch of science which facilitates the pleasant or enjoyable aspects of human–technology interaction*. Hedonomics contrasts with the traditional ergonomic goal of reducing damage, injury, inconvenience and frustration. The primary concern for hedonomics is whether one can design for happiness. Neuroergonomics holds great promise for advancing this effort, as it will permit dynamic adjustments of interfaces to match the emotional state of the person and will permit individual differences in preferences to be designed into the interface. Note that such an application will be difficult, since one is trying to link fine-grained neural indices to cognitive functions that, psychologically, are articulated at a molar level (i.e. what does 'pleasant' or 'enjoyable' mean?). In addition, issues of human identity and intention discussed earlier will need to be addressed to insure that efforts to apply hedonomic principles to interface design are not undone by loss of human identity and autonomy.

One avenue for further research to answer questions regarding stress, workload and human performance is to explore whether the EEG correlates of attention and cognition will persist under different environmental conditions. That is, does environmental stress (or task stress, for that matter) qualitatively change the EEG pattern, or is the pattern the same, with the relative magnitudes of α-, β- and τ-waves shifting? It may be that a specific EEG pattern is observed when an operator is stressed or overloaded, but such a pattern may be specific to particular domains.

The papers discussed in this special issue address the establishment of brain-action relations (Karwowski *et al.* 2003), of brain-cognition relations and their application to adaptive systems (Hettinger *et al.* 2003, Scerbo *et al.* 2003), and to enhancing our understanding of the mental processes underlying performance on current display designs (Sanderson *et al.* 2003). As neuroergonomics develops, fruitful avenues for research and practice may be found in the other direction—using neurological information to design new interfaces for physical and cognitive tasks. To date, the design of controls and displays has been constrained by limitations of the human sensory and motor systems. In the future, the brain will be added as another physical structure around which ergonomic principles can be applied for interface design. The advancement of neuroergonomics and cognitive neuroscience may yield a complex neuroanthropometry for work design. In addition, with sufficient advances systems will be designed in which thought is immediately transformed into action, allowing smooth, effortless human–machine interfaces. Advances in physical neuroergonomics will be essential in this regard. As Karwowski *et al.* (2003) noted, the two areas of physical and cognitive ergonomics have not been sufficiently integrated, and this integration, while important for ergonomics, is essential for the growth of neuroergonomics if we are to achieve a comprehensive understanding of the dynamics of brain–environment interaction.

5. Ethical and philosophical concerns

A clear conclusion from the papers in these special issues is the potential for neuroergonomics to improve human–technology interaction, thereby improving overall quality of life (see Hancock 1997). However, there is also the potential for negative effects, particularly in issues of freedom, privacy, and the loss of ownership of one's mental state, and it is to these that we now turn.

5.1. *Freedom*

As neuroergonomically designed systems are implemented, concerns over freedom, privacy and property are bound to present problems which exceed the purely technical. In regard to freedom, as we move forward we must insure that in designing these systems we do not, even implicitly, create them so that the human is treated as an alienated extension of the machine (see Fromm 1941). This will involve developing ethical guidelines in the same way as we need to address cloning and human DNA research. In particular, de-centralized organizations in which autonomy is granted to the employees in defining the parameters of their tasks would be most amenable to preserving human control and dignity. Fortunately, the initial outlines of such de-centralization have been developed, both for organizations and society as a whole (Fromm 1955, Illich 1973, Deming 1986, 1993). If we develop the technology without changing our social and organizational structures, individuals who hold power in organizations will, knowingly or unknowingly, relegate their employees to the status of machine parts and treat them as such. The issue will become one of autonomy and authority—who controls an individual's mental state? Does the operator retain control or does an external authority influence a person's mental state via the machine?

5.2. *Privacy and ownership*

Another important ethical issue to be considered is the preservation of privacy. Hettinger *et al.* (2003) are correct in warning about the dangers of invasion of privacy, personality profiling and other negative effects systems designed from neuroergonomic principles could have for human well-being. We must be careful to not surrender too much control (in the form of information) to the owners of neuroergonomically designed technology. In this regard, a related issue is the ownership of the information on neural states obtained from these systems and who has access to that information. Current legal structures allow the organization for which a person works to retain ownership on intellectual property the employee creates at work (and, in some cases, outside of work—e.g. where employees surrender all patent rights to their employer). These structures will have to be changed to reflect the changes in information produced by developments in neuroergonomics. Ownership of neural information regarding mental state should be retained by the individual (in more than a purely legal sense) and access to the information should be highly restricted. In addition, organizational structures should be created that hold accountable those who do have access to such highly sensitive information. These issues may seem far from those typically considered in human factors and ergonomics, but these are the new vistas and concerns resulting from the advent of neuroergonomics. We should not fall prey to the mistake of waiting until technology is implemented before we address the ethical and legal implications of the technology. Now is the time for these philosophical issues to be addressed.

5.3. *Fracturing unitary consciousness*

Throughout history, human beings have been defined by their individuality. The events of life are experienced alone and the quintessential separation between individuals provides much of the motive force of art and philosophy as we seek to understand ourselves and our peers. Knowledge of our own certain and individual demise defines the human condition and characterizes us as a species (Hancock 2002). The advent of neuroergonomics, if its vision is realized, will transform this condition. As we noted earlier, the ways in which the brain can receive information and achieve intention are very coarse compared with what they might be. However, as neuroergonomics becomes more successful, the barrier between the human and the machine promises to dissolve and the issue of human identity noted earlier will come to a head. As that barrier is breached, the consequent separation between human beings and, thus, the unitary nature of consciousness will begin to fracture. As these stages of evolution are achieved the empirical question concerns the nature of consciousness itself. We believe that, like many other vestigial characteristics, unitary consciousness will persist but we will become much more adept at working in the context of intimate familiar groups. Neuroergonomically-endowed individuals will begin to become facile with collective group input and emergent social action as forms of response. We do not envisage the complete separation of carbon and silicon forms of intelligence as postulated by Moravec (1988), nor do we foresee replacement of human intelligence by artificial intelligence as argued by Kurzweil (1999). Although it is probable that we shall continue to use machines to explore environments hazardous to humans, the evolution of full human–machine symbiosis, and by extension more intimate human–human interaction, appears to be the path of the future.

6. Conclusions

Neuroergonomics has the potential to improve not only the performance of human–machine systems, but also to improve the quality of life while enhancing our understanding of brain function. The only clearly negative aspect of developments in neuroergonomics is the possibility that the design and implementation of neuroadaptive systems will occur faster than organizational and social progress necessary to accommodate them. If, instead of focusing solely on the capacities of systems, we devote more effort to the teleology of technology (Hancock 1997), we can use scientific understanding to convert intention to action in a benign and empathic manner. In contrast, neuroergonomics would be a dangerous tool in the hands of unfettered capitalism. That intention and ethics can and should be a part of brain sciences and design is yet another opportunity that the present proposed advance to human–machine partnership offers. We intend to watch such progress with interest.

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