

# Putting the Brain to Work: Neuroergonomics Past, Present, and Future

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**Objective:** The authors describe research and applications in prominent areas of neuroergonomics. **Background:** Because human factors/ergonomics examines behavior and mind at work, it should include the study of brain mechanisms underlying human performance. **Methods:** Neuroergonomic studies are reviewed in four areas: workload and vigilance, adaptive automation, neuroengineering, and molecular genetics and individual differences. **Results:** Neuroimaging studies have helped identify the components of mental workload, workload assessment in complex tasks, and resource depletion in vigilance. Furthermore, real-time neurocognitive assessment of workload can trigger adaptive automation. Neural measures can also drive brain-computer interfaces to provide disabled users new communication channels. Finally, variants of particular genes can be associated with individual differences in specific cognitive functions. **Conclusions:** Neuroergonomics shows that considering what makes work possible – the human brain – can enrich understanding of the use of technology by humans and can inform technological design. **Application:** Applications of neuroergonomics include the assessment of operator workload and vigilance, implementation of real-time adaptive automation, neuroengineering for people with disabilities, and design of selection and training methods.

## INTRODUCTION

Discoveries and developments in science tend to be cumulative and only occasionally revolutionary. Human factors/ergonomics (HF/E) is no different. Over its history, HF/E has often looked to other disciplines to break new ground. Behaviorism once ruled psychology and HF/E but was abandoned by both in the 1960s in favor of the information-processing approach, which remains current today. More recently, ecological psychology and anthropology have led to the development of cognitive engineering. Neuroscience is the latest area of impact.

Neuroscience has transformed cognitive psychology and is shaping all of psychology, for palpable reasons. Psychology is the study of human behavior and the mind. The brain enables the mind; in turn, experience modifies both brain structure and function. Hence psychology must study the

brain. The logic can be extended to HF/E. Because HF/E examines behavior and the mind at work, it should include the study of what makes work possible – the human brain: hence *neuroergonomics* (Parasuraman, 2003).

Neuroergonomics should be thought of not as revolutionary but rather as another cumulative step in HF/E. Neuroscience is yielding spectacular new findings; HF/E should not ignore them. It should use them to understand the neural bases of such functions as seeing, attending, remembering, deciding, and planning in relation to technologies and settings in the real world (Parasuraman & Rizzo, 2007). Because the brain interacts with the world via a physical body, neuroergonomics is also concerned with the neural basis of physical performance – grasping, moving, or lifting objects and one's limbs (Grafton, Fagg, Woods, & Arbib, 1996; Karwowski, Sieminow, & Gielo-Periczak, 2003).

## IS NEUROERGONOMICS NECESSARY?

Whenever a new interdisciplinary venture is proposed, it is legitimate to ask whether it is necessary. Readers are also entitled to be skeptical whenever they see the prefix *neuro*. Does it do anything other than just add to the growing “neuro A-Z” list, from neuroanatomy to neuroeconomics to neurozoology? With apologies to British cuisine, does adding *neuro* to a discipline provide any more substantive nutrition than “having chips with everything”? We submit that in the case of HF/E, it does. But the term *neuroergonomics* itself may be necessary only in the short term and could be abandoned in the future.

Consider cognitive psychologists. Once they used only behavioral measures. Consequently, researchers who used neural measures to study cognition coined the term *cognitive neuroscience*. But modern cognitive psychology is dominated by studies using the full gamut of current human neuroscience techniques, and theories of cognition are often couched in neural terms. Therefore, the term *cognitive neuroscience* no longer seems necessary because cognitive psychology now involves the study of the brain. The same is true of neuroergonomics. At some future time, HF/E researchers may naturally consider the brain, without necessarily referring to neuroergonomics.

## NEUROERGONOMICS METHODS

Diverse methods are used in neuroergonomics, but neuroimaging has been a major influence. Neuroimaging methods fall into two categories: those that reflect cerebral metabolic processes associated with neural activity, such as functional magnetic resonance imaging (fMRI) and transcranial Doppler (TCD) sonography, and those that measure neural activity directly, such as electroencephalography (EEG) and event-related potentials (ERPs). The merits and disadvantages of these techniques can be considered in terms of three criteria: (a) spatial resolution in localizing neural activity within the brain, (b) temporal resolution in identifying the timing of neural processing, and (c) ease of use in HF/E. Thus, fMRI scores highly on the first criterion but not the second and third criteria, whereas EEG/ERPs are advantageous by the second and third criteria but not the first criterion (see also Parasuraman & Rizzo, 2007). Here we discuss mainly neuroimaging and genetic stud-

ies, but the reader should note that other techniques – computational, psychophysiological, and neurochemical – have also been used in neuroergonomics.

## MENTAL WORKLOAD AND VIGILANCE

We begin our review by considering theories of mental workload, which have long been debated (Kahneman, 1973; Moray, 1967). Patterns of dual-task decrement have often been used as support for different theories. An additional evaluative criterion is neural plausibility. Viewing mental workload as *brain work* has a long historical precedent and can be traced to the work of Sir Charles Sherrington (Roy & Sherrington, 1890). Sherrington’s prescience has been vindicated by fMRI findings showing that increased cerebral blood flow in regions of the prefrontal cortex (PFC) can be used to quantify mental workload (Parasuraman & Caggiano, 2005). Furthermore, neuroimaging findings (e.g., Just, Carpenter, & Miyake, 2003) have supported the distinction between perceptual/cognitive, verbal/spatial, and focal/ambient visual processing, which are components of Wickens’s (1984) multiple resource model.

Neuroimaging research has also guided understanding of a fundamental contributor to workload – working memory (Baddeley & Hitch, 1974). Several fMRI studies have shown that PFC activation during a working memory task increases as a function of memory load (Cohen et al., 1997). The neural correlates of *maintaining* information in working memory have also been identified. For example, Jiang, Haxby, Martin, Ungerleider, and Parasuraman (2000) required participants to keep a target face in working memory for several seconds while responding to targets and rejecting distracter faces. Ventrolateral PFC activation rose above baseline during the first target presentation and remained at that level for each subsequent presentation of the target within that block.

P300 studies have also contributed to an understanding of the structure of mental workload. P300 is a positive ERP wave typically elicited by low-probability targets interspersed with more frequent nontargets. P300 latency increases with the difficulty of identifying targets but not with increases in the difficulty of response choice, suggesting that P300 provides a relatively pure measure of perceptual processing/categorization time, independent of response selection/execution stages

(Kutas, McCarthy, & Donchin, 1977). P300 amplitude is also proportional to the amount of cognitive resources allocated to the target (Johnson, 1986). Thus any diversion of resources away from target discrimination in a dual-task situation will lead to a reduction in P300 amplitude. Isreal, Wickens, Chesney, and Donchin (1980) showed that P300 amplitude decreased when a primary task, tone counting, was combined with a secondary task, visual tracking. However, increases in the difficulty of the tracking task did not lead to a further reduction in P300 amplitude. Thus P300 reflects processing resources associated with perceptual processing and stimulus categorization but not response-related processes. Baldwin and Coyne (2005) also found that P300 was a diagnostically sensitive workload measure in the context of simulated driving under conditions of reduced visibility. These and other P300 studies (e.g., Luck, 1998) have contributed significantly to theory development in mental workload research, particularly the multiple resource model (Wickens, 1984).

Neuroergonomics has also contributed to mental workload assessment. Spectral power in different EEG frequency bands is sensitive to increased working memory load and demand for attentional resources. Specifically, frontal theta activity (4–7 Hz) increases while alpha power (8–12 Hz) decreases as more resources have to be allocated to the task (Gevins & Smith, 2003). Thus these EEG measures are well suited to assessment of operator mental workload (Gevins, Smith, McEvoy, & Yu, 1997; Wilson & Eggemeier, 1991), not just in the laboratory but also in operational environments such as flight, air traffic control (ATC), and road and rail transportation (Brookhuis & De Waard, 1993; Hankins & Wilson, 1998; Wilson, 2001, 2002).

Brookings, Wilson, and Swain (1996) recorded EEGs from Air Force controllers while varying the difficulty of a simulated ATC task along two dimensions, the number or volume of aircraft to be controlled and the aircraft mix (complexity). Right hemisphere frontal and temporal EEG theta band activity increased with workload. Midline central and parietal areas showed theta band activity to also increase with increased workload in both types of task manipulation. Alpha band activity decreased with increased task complexity but not volume. Thus EEG was sensitive to changes in mental workload and the nature of the cognitive task being performed.

Given the predominance of automation in current systems, evaluating operator vigilance is as important as workload assessment. Several vigilance studies have used TCD to noninvasively monitor blood flow velocity in intracranial arteries in the left and right cerebral hemispheres (Tripp & Warm, 2007). The results reveal a close coupling between vigilance decrement over time and blood flow. In addition, the vigilance/blood flow link is stronger in the right than in the left hemisphere, consistent with other findings indicative of right hemispheric control of vigilance (Parasuraman, Warm, & See, 1998). Overall, the results indicate that blood flow represents a metabolic index of resource depletion during vigilance (Warm & Parasuraman, 2007). TCD thus offers a noninvasive tool to “monitor the monitor.” It could help decide when operator vigilance has declined to a point where task aiding is necessary or operators need to be rested or replaced. This is a feature of adaptive human-machine systems, a topic we turn to next.

## ADAPTIVE AUTOMATION

Adaptive automation (AA) refers to flexible allocation of functions to human and machine agents during system operations. The adaptive automation concept has a long history (Hancock & Chignell, 1987; Parasuraman, Bahri, Deaton, Morrison, & Barnes, 1992). Only recently, however, have technologies matured to enable effective real-time adaptive systems (e.g., the Rotorcraft Pilot’s Associate; Dornheim, 1999). At the same time, human-in-the-loop simulation studies have shown that adaptive automation can enhance human-system performance (Hilburn, Jorna, Byrne, & Parasuraman, 1997) while reducing such potential costs as reduced situational awareness, complacency, and skill degradation (Kaber & Endsley, 2004; Parasuraman, Mouloua, & Molloy, 1996; for reviews, see Inagaki, 2003; Scerbo, 2007).

Several methods to implement AA have been examined. Prominent among these is real-time assessment of the operator’s functional state. Physiological measures may provide more accurate state assessments than behavioral measures because many contemporary systems use some form of automation that reduces the frequency of measurable operator behavior (Kramer & Parasuraman, 2007; Wilson & Eggemeier, 1991). To provide AA at the optimal time, one needs to have

real-time or near-real-time assessment with an accurate operator state classifier. Several have been identified, including discriminant analysis (Berka et al., 2004; Wilson & Fisher, 1991, 1995) and artificial neural networks (ANNs; Wilson & Russell, 2003a, 2003b). These have been implemented in real time and typically provide accuracies of 70% to 85%. Classifiers have involved EEG (Berka et al., 2005; Gevins et al., 1998), peripheral measures (Wilson & Fisher, 1991), or a combination (Wilson & Russell, 2003b, 2004).

These findings show that neuroergonomic assessment of the operator's state can trigger adaptive automation. Moreover, such adaptive aiding enhances performance. Wilson and Russell (2007) had participants monitor simulated unmanned aerial vehicles (UAVs) while downloading radar images and identifying targets under different task load levels. EEG, horizontal and vertical eye movements, and heart rate were monitored and used to train an ANN to recognize low and high mental workload. On detecting high workload, AA kicked in by slowing the speed of the current vehicle of interest, thus giving the operator additional time to complete the targeting task before the vehicle reached the weapon release point. The ANN accurately (84% of the time) discriminated between the low- and high-workload conditions in real time. More important, the AA led to a 50% improvement in targeting performance compared with the non-aiding condition. The effect of AA was also greater than when the same amount of aiding was presented but randomly distributed.

We emphasize that neuroergonomic assessment should be used in the context of current and future task demands on the operator. Using *only* physiological measures during complex system operation could result in inappropriate AA. For example, landing an aircraft produces signs of increased workload, which are expected and in the context of landing. AA should not be implemented unless even higher workload is detected. An adaptive system manager would determine the intervention that reduces workload in the current task situation. In complex job situations, a number of mitigations would be available, but only the ones that are appropriate at a given time would be selected.

Whereas current research has had the goal of detecting existing mental overload, future research should focus on detecting when an operator is becoming overloaded. Using this information, peo-

ple could implement interventions to prevent overload. This would have the effect of further reducing errors and improving job success. States other than high mental workload—fatigue, vigilance, and inattention—should also be investigated.

Implementing neuroergonomic AA in real settings (St. John, Kobus, Morrison, & Schmorow, 2004) will require progress in artifact detection and development of nonintrusive sensor suites, “dry” electrodes, and off-body sensor systems such as eye point-of-regard and pupillometry. Operational test and evaluation show that AA must also provide added capabilities, be acceptable to operators who have to wear and operate the AA system, and be cost-effective. So long as *realistic* goals are set, they will be attainable given continued research, development, and design efforts.

## NEUROENGINEERING

Neuroengineering involves using brain signals as an additional communication channel for human interaction with the environment. This area of research and practice, also called *brain-computer interfaces* (BCIs), has had significant progress in recent years. Different types of brain signals are used to control external devices without the need for motor output. This is advantageous for individuals who either have only limited motor control or, as in the case of “locked-in” patients with amyotrophic lateral sclerosis, virtually no motor control. The idea follows from the work on “biocybernetics” in the 1980s pioneered by Donchin (1980) but has progressed beyond the earlier achievements with further technical developments.

BCIs allow a user to interact with the environment without engaging in any muscular activity (e.g., without the need for hand or eye movements). Instead, the user is trained to engage in a specific type of mental activity that is associated with a unique brain electrical “signature.” The resulting brain potentials are processed and classified so as to provide a control signal in real time for an external device. Invasive BCIs include recording of field potentials and multiunit neuronal activity from implanted electrodes; this technique has been reported to be successful in controlling robotic arms (Nicolelis, 2003). Such invasive recording techniques have a superior signal-to-noise ratio but are obviously limited in use to animals or to patients with no motor functions in whom electrode implantation is clinically justified. For example,

Radwin and colleagues have developed a BCI based on the electrocorticogram to allow paraplegics to compose letters and other written material on a computer (Felton, Wilson, Radwin, Williams, & Garell, 2005). Noninvasive BCIs have used a variety of brain signals derived from scalp EEG recordings. These include quantified EEGs from different frequency bands (Pfurtscheller & Neuper, 2001) and ERPs such as P300 (Donchin, Spencer, & Wijesinghe, 2000) and contingent negative variation (Birbaumer et al., 1999). BCIs based on these signals have been used to operate voice synthesizers and move robotic arms. Currently, noninvasive BCIs have relatively slow throughput rates, but this is likely to improve in the future (for reviews, see Birbaumer, 2006; Mussa-Ivaldi, Miller, Rymer, & Weir, 2007).

### **MOLECULAR GENETICS AND INDIVIDUAL DIFFERENCES**

Molecular genetic studies of individual differences provide a final example of neuroergonomics research. These studies have capitalized on the recent decoding of the human genome and on neuroimaging studies that have linked cognitive functions to the activation of specific cortical networks (Parasuraman & Greenwood, 2004). Gene expression can influence the efficiency of these networks – for example, through modulation of neurotransmitters innervating a particular network. Some (but not all) genes come in different forms (alleles), with one of the two alleles in a paired DNA strand being inherited from each parent. A given person may have none, one, or two alleles in a specified location within the gene. One then can examine the functional consequence, if any, of such allelic variation. Studies using this approach have shown that individual differences in cognitive functioning can be linked to variations in specific genes (Goldberg & Weinberger, 2004; Parasuraman & Greenwood, 2004; Posner, Rothbart, & Sheese, 2007).

Parasuraman, Greenwood, Kumar, and Fossella (2005) genotyped a sample of about 100 healthy adults for a cholinergic gene, *CHRNA4*, and a dopaminergic/noradrenergic gene, *DBH*. DNA collected from cheek samples was tested for the cytosine (C) allele in a specified region of the *CHRNA* gene and the guanine (G) allele for the *DBH* gene. Participants were administered a cued attention task modeled after the well-known paradigm developed by

Posner (1980). They were also given a working memory task requiring participants to keep up to three spatial locations in mind over a short interval. The efficiency of shifting attention in the cueing task was proportional to the number of C alleles (0, 1, or 2) in the *CHNRA* gene that participants possessed but was unrelated to the *DBH* gene. Conversely, working memory accuracy was directly related to the number of G alleles in the *DBH* gene but was unrelated to the *CHRNA* gene. Thus, there was a double dissociation between the effects of *CHRNA4* and *DBH* on attention and working memory. The results were consistent with the known functions of these two genes in cholinergic and dopaminergic/noradrenergic transmission in the brain, respectively.

The new field of the molecular genetics of cognition is still in its infancy, and hence its future impact on neuroergonomics is still uncertain. The research to date has established a theoretical framework for examining genetic associations for basic cognitive functions. Preliminary findings indicate that genetic associations may also be found for more complex cognitive functions such as decision making (Parasuraman, in press). As more such studies are conducted, greater potential for practical applications will emerge, particularly if gene-environment interactions are examined (e.g., studies of training in subgroups of individuals defined by genotype). Individuation of the design of user interfaces might also be informed by a better understanding of the genetic basis of cognitive abilities (Oron-Gilad, Szalma, Thropp, & Hancock, 2005).

### **CONCLUSIONS**

The future of neuroergonomics seems assured because of its initial successes and because of the ever increasing understanding of the brain and behavior at work in the real world. Neuroergonomics blends neuroscience and ergonomics to the mutual benefit of both fields and extends the study of brain structure and function beyond the basic tasks used in cognitive psychology and neuroscience. Neuroergonomics can provide rich observations of the brain and behavior at work, at home, in transportation, and in other everyday environments involving human operators. However, neuroergonomics should be viewed not as simply the use of neural measures in applied work but also as a stimulus for theory development in HF/E. The

neuroergonomics approach allows researchers to ask different questions and develop new explanatory frameworks about humans at work in the real world and in relation to modern automated systems and machines. Better understanding of brain function can, for example, provide important guidelines and constraints for theories of information presentation and task design, optimization of alerting and warning signals, development of neural prostheses, and the design of robots.

As an interdisciplinary endeavor, neuroergonomics will continue to benefit from and grow alongside developments in neuroscience, psychology, engineering, and other fields. This ongoing synthesis will significantly advance our understanding of brain function underlying human performance of complex, real-world tasks. The basic enterprise of HF/E – how humans design, interact with, and use technology – can be considerably enriched if we also consider the human brain that makes such activities possible. There already have been considerable achievements in basic research and application in neuroergonomics. The future is likely to yield more such advances.

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