Cognitive Science and Technology

Chang S. Nam *Editor*

Neuroergonomics

Principles and Practice

Springer

Cognitive Science and Technology

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ISSN 2195-3988 ISSN 2195-3996 (electronic)
Cognitive Science and Technology
ISBN 978-3-030-34783-3 ISBN 978-3-030-34784-0 (eBook)
https://doi.org/10.1007/978-3-030-34784-0

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Foreword

Passion runs deep in the hearts of researchers who strive to understand the connections between people and the systems around them. This passion spans a wide range of scientific fields and has not only shaped our understanding of the interactions between people and the world, but it has also changed the ways we live our lives. Chang S. Nam and his colleagues share this passion, and their research in Neuroergonomics clearly demonstrates this passion. Another thread that runs across time and connects many of these passionate researchers is their desire to understand and solve problems in order to help individuals and society. ***Neuroergonomics: Principles and Practice*** is a publication that seeks to do this for the scientific community and the general reader who is interested in better understanding how Neuroergonomics, and its application, can shape everyday life and emerging applications. As one explores this publication, it is useful to look at some related history and examine some common elements.

In 1959, Charles Darwin showcased his passion in the groundbreaking publication, ***On the Origin of Species***. He outlined natural selection and advanced both the scientific community's and nonspecialist readers' understanding of the interaction between the environment and living organisms. Darwin's work was foundational in advancing our understanding of how changes in the characteristics of a species occur over several generations via the process of natural selection. Understanding evolution has been, and is, helping people solve problems that impact their lives. Evolution is the root of human behavior and is inseparable from the system, the environment, that shapes species.

In 1938, B. F. Skinner showcased his passion in the groundbreaking publication, ***The Behavior of Organisms***, where he advanced a new science based on selection by consequences as the mechanism through which behavior changes during the lifetime of the individual. He outlined the science of behavior and advanced our understanding that behavior is determined by its consequences, be they reinforcements or punishments, which make it more or less likely that the behavior will occur again. Skinner's work has successfully been applied widely in real-world applications because he explored the connection between the environment and individual behavior. Understanding the science of behavior has been, and is, helping people solve problems that impact their lives because most of society's problems involve human behavior. Behavior is the root of human interaction and is inseparable from the system, the environment, that shapes the individual.

In 1960, J. C. R. Licklider showcased his passion in the quintessential publication, ***Man-Computer Symbiosis***, where he put forth the novel notion that a cooperative interaction between people and computers was possible via a new symbiotic partnership paradigm. He outlined how the close coupling of people and electronic partners would enable a partnership that could far exceed the capabilities that a human or computational system could achieve individually. His work set people on the quest to tightly couple human brains and computing machines, so that the resulting partnership could process information that no human brain is capable of alone and process data in a way that no computer is capable of alone. Understanding the symbiotic relationship between people and computers has been, and is, enabling the creation of better decision-making capabilities and is a key component in enabling individuals to more effectively solve complex and fast-paced challenges. Interaction is the root of human–machine symbiosis and is inseparable from the system, the environment, that shapes individuals' brain and behavior.

Today's human–machine symbiotic systems can now be developed at a much deeper level than simply observable behavior between humans and machines. Modern human–machine symbiotic systems can now exploit our understanding of the brain and the associated behavioral correlate. Neuroergonomics is the study of brain and behavior at work and is the combination of the fields of neuroscience and ergonomics. In 2019, 160 years after the publication of Darwin's original publication, Chang S. Nam and his colleagues are showcasing their passion in ***Neuroergonomics: Principles and Practice***, where they seek to solidify the application of neuroscience to ergonomics. Like Charles Darwin, Chang S. Nam and his colleagues are advancing our understanding by explaining Neuroergonomics in a manner that speaks to both the scientific community and nonspecialist readers. Like B. F. Skinner, Chang S. Nam and his colleagues articulate a path forward that will result in the production of real-world applications. Like J. C. R. Licklider, Chang S. Nam and his colleagues put forth ideas and a future direction for the field of Neuroergonomics that will support the design of safer and more efficient systems. Chang S. Nam and his colleagues are advancing our understanding of the relationship between brain function and performance in real-world tasks. Like all of these prior contributors, Chang S. Nam and his colleagues pursue these goals to better help people solve problems that impact their lives.

Neuroergonomics: Principles and Practice has a rich history and is a milestone in the field of Neuroergonomics. In the late 1990s, Raja Parasuraman coined the term Neuroergonomics and spent his career defining and advancing the field. This was driven by his passion to study how humans interact with machines and his passion for cognitive neuroscience. During this same time period, I coined the term Augmented Cognition, and I spent my career defining and advancing this related field. This was driven by my passion to advance the frontier between human–computer interaction, psychology, ergonomics, and neuroscience, with the aim of creating revolutionary human–computer interactions. Therefore, it seems only natural to me that Neuroergonomics and Augmented Cognition have remained tightly coupled. The tight connection was further deepened in 2010 when Raja Parasuraman, the *Father of Neuroergonomics*, accepted the Human Factors and Ergonomics Society's Augmented Cognition Technical Group's Spirit of Innovation Award. Today, Chang S. Nam and his colleagues are providing us this essential publication at a time when the seeds planted over the last few decades have ripened. This publication builds upon this history and is helping to carry the field of Neuroergonomics forward.

For me, it is a wonderful coincidence that I originally met Chang S. Nam while attending the same Human Factors and Ergonomics Society's Augmented Cognition Technical Group that had previously celebrated the *Father of Neuroergonomics*. When I met Chang S. Nam at this conference, our passion for basic and applied research in human factors and ergonomics engineering to advance the science of Human–Computer Interaction quickly drew us together. A key element of that connection was our common, broad perspective on the application of systems and information engineering to human-centered technologies, including brain–computer interfaces and Augmented Cognition-Based Systems. Additionally, our passion for real-world application, particularly in the application of challenges facing operational military personnel, provided the thread to connect our thoughts. Operational military challenges are often particularly useful in tying together innovation, science, and immediate problems that need solving. Today, I particularly resonate with Chang S. Nam and his colleagues who worked on this publication because they address fundamental human factor issues and they emphasize the role of the human nervous system. This work is a key element of Augmented Cognition-Based Systems that sense a multitude of brain states, combined with other behavior and modeling techniques and adapt to users in real time, providing a true symbiosis between the human and computational systems.

It is important to remember that Neuroergonomics is helping to enable practitioners to leverage basic knowledge from brain–computer interfaces and neuroscience to achieve more effective human–systems integration. Neuroergonomics provides practitioners with more effective tools and systems to build Augmented Cognition Systems. The work in this publication details scientific developments that were necessary to create optimal systems, explains the sensors necessary for success, and includes many lessons learned regarding integration into existing and new applications. This knowledge provides the reader with useful information that is beneficial in understanding how to select adaptation strategies and manage adaptation processes. The optimal design of adaptive strategies can significantly enhance human performance and enable the development of effective Augmented Cognition Systems.

Passion is contained throughout this publication and its contents will enable readers to understand the connections between people and the systems around them at a level of detail that cannot readily be found elsewhere. This passion and its associated contents will change the ways we live our lives. Keeping in mind the past, and with hope for the future, enjoy exploring this publication today.

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Preface

Neuroergonomics is a combination of the Greek words neuro, meaning “relating to nerves or the nervous system,” and ergonomics, meaning “the study of work”—the study of brain and behavior at work. Neuroergonomics is an emerging area whose meaning is collectively defined as the study of the human brain function and behavior in relation to behavioral performance in natural environments and everyday settings. The domains impacted by neuroergonomics are varied; research has been conducted in the military, health, workplace, education settings, and so on. Thus, the impact of neuroergonomics is large; however, there are currently few books to provide students, practitioners, and researchers, including those outside of academia, with a single, go-to source containing state-of-the-science information about neuroergonomics. This book provides up-to-date coverage for researchers, students, and practitioners, including those with no formal training in neuroergonomics, to be able to grapple with a synopsis of key findings and theoretical and technical advances from neuroergonomics-related fields.

This book is organized into an introductory chapter with an emphasis on the evolution of neuroergonomics, five main parts, and a conclusion chapter. First part, consisting of four chapters, opens with an introduction to the fundamental components of neuroanatomy and brain function, as well as brain processes neuroergonomists need to understand (chapter “An Introduction to Neuroergonomics: From Brains at Work to Human-Swarm Teaming”). Chapter “Brain Basics in Neuroergonomics” provides a brief overview of some of the aspects of EEG-based experiments that will serve as an entry point and guide to researchers, including those who are new to the field. In addition, two other guides are intended to provide the necessary information for neuroergonomists to be able to understand the effects and usages of two other common neuroimaging methods—functional near-infrared spectroscopy or fNIRS (chapter “The EEG Cookbook: A Practical Guide to Neuroergonomics Research”) and transcranial direct current stimulation or tDCS (chapter “Functional Near-Infrared Spectroscopy (fNIRS) in Neuroergonomics”) on the brain. Second part introduces three computational approaches applicable to neuroergonomics, such as adaptive control of thought-rational (ACT-R, chapter "Transcranial Direct Current Stimulation (tDCS): A Beginner's Guide for Neuroergonomists"), deep learning techniques (chapter "Adaptive Control of Thought-Rational (ACT-R): Applying a Cognitive Architecture to Neuroergonomics"), and dynamic causal modeling (DCM, chapter "Deep Learning Techniques in Neuroergonomics"), where the history of advancements, its concepts, and applications in neuroergonomics research are described. Third part presents six chapters that discuss various neuroergonomics assessments of cognitive and physical performance in the areas of physical activity and sedentary behavior (chapter "Dynamic Causal Modeling (DCM) for EEG Approach to Neuroergonomics"), psychophysiology (chapter "Physical Activity and Sedentary Behavior Influences on Executive Function in Daily Living"), emotion (chapter "Neuroergonomics and Its Relation to Psychophysiology"), motor skill (chapter ""Hello Computer, How Am I Feeling?", Case Studies of Neural Technology to Measure Emotions"), training (chapter "The Neural Basis of Cognitive Efficiency in Motor Skill Performance from Early Learning to Automatic Stages"), and music proficiency and performance (chapter "Approaches for Inserting Neurodynamics into the Training of Healthcare Teams"). Fourth part illustrates how two emerging fields of brain–computer interface (BCI) and neuroergonomics can be brought together to add tremendous insight to an important issue—enhancing the quality of life for people with severe disabilities, through the design, development, and implementation of a hybrid EEG-functional transcranial Doppler ultrasound (fTCD) BCI (chapter "The Neuroergonomics of Music Proficiency and Performance"), BCI for spinal cord injury rehabilitation (chapter "Hybrid EEG–fTCD Brain–Computer Interfaces"), and BCI-controlled functional electrical stimulation (FES) for handgrasp rehabilitation (chapter "Brain–Computer Interfaces for Spinal Cord Injury Rehabilitation"). Fifth part presents everyday and emerging applications of neuroergonomics in the areas of car driving (chapter "A Sensorimotor Rhythm-Based Brain–Computer Interface Controlled Functional Electrical Stimulation for Handgrasp Rehabilitation"), driving and navigation (chapter "Neuroergonomics Behind the Wheel: Neural Correlates of Driving"), augmented reality (AR) and virtual reality (VR) (chapter "Fundamentals and Emerging Trends of Neuroergonomic Applications to Driving and Navigation"), information visualization (chapter "Neuroergonomic Solutions in AR and VR Applications"), and trust (chapter "Neuroergonomic Applications in Information Visualization"). This book ends with a series of reflections on the future of, which suggests where to go from here.

This book was motivated by the desire many neuroergonomists have had to further understand the neurocognitive mechanisms and correlates related to perception, memory, attention, and the planning and execution of actions in a variety of contexts. Thus, we hope that our readers will find the information presented in this book timely and useful in guiding their research.

On behalf of the editorial team, I would sincerely like to thank the contributing authors for their professionalism as well as their commitment to the success of this book.

Raleigh, USA Chang S. Nam

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Editor and Contributors

About the Editor

Chang S. Nam is a Professor of Edward P. Fitts Industrial and Systems Engineering at North Carolina State University, USA. He is also an Associate Professor of the UNC/NCSU Joint Department of Biomedical Engineering as well as the Department of Psychology. He received a Ph.D. from the Grado Department of Industrial and Systems Engineering at Virginia Tech in 2003.

Dr. Nam is the author or co-author of more than 100 research publications including journal articles, edited books, book chapters, and conference proceedings. Dr. Nam's research interests center around neuroergonomics, brain–computer interface (BCI) and rehabilitation, neuroadaptive automation in large-scale unmanned aerial vehicles, hyperscanning, cognitive neuroscience, and trust in human–robot interaction. His research has been supported by federal agencies including the National Science Foundation (NSF), the Air Force Research Laboratory (AFRL), and the National Security Agency. Dr. Nam has received the US Air Force Summer Faculty Fellowship Program (AFSFFP) Award, NSF CAREER Award, Outstanding Researcher Award, and Best Teacher Award. He is the Editor of two BCI books—*Brain–Computer Interfaces Handbook: Technological and Theoretical Advances* and *Mobile Brain–Body Imaging and the Neuroscience of Art, Innovation and Creativity*—and is currently working on an edition of *Trust in Human-Robot Interaction: Research and Applications.* Currently, Dr. Nam serves as the Editor-in-Chief of the journal Brain–Computer Interfaces.

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Introduction

An Introduction to Neuroergonomics: From Brains at Work to Human-Swarm Teaming

Hussein A. Abbass

Abstract The field of Neuroergonomics sits at the interface between humans' brains and humans' working environment with an aim to improve the work humans do. In this chapter, I will review the scientific journey that led to the birth of Neuroergonomics. The journey starts from the Biocybernetics and Brain–Computer Interfaces projects in 1960s, followed by work on adaptive aiding in 1970s, and all the way to early 2000s with work on Augmented Cognition and Neuroergonomics. An extension to Neuroergonomics gave birth to Cognitive-Cyber Symbiosis, whereby Neuroergonomics is augmented with artificial intelligence agents that act as relationship managers between the human brain and the information-centric work environment. Some challenges facing these fields today are then discussed using a human-swarm teaming lens.

1 Introduction

Neuroergonomics is the study of the human brain in relation to its contributions to the human's efficiency in a working environment (Parasuraman & Wilson, 2008). The field has grown over decades with foundations that could be traced back to 1960s. The evolution of the field has witnessed a series of concepts and terminologies that started with what appeared to be morphologically different, but equally similar at their foundational cores, dimensions of the field. This chapter will explore these dimensions, starting with Licklider's work.

In his seminal paper "Man-Machine Symbiosis" (Licklider, 1960), Licklider wrote: "A multidisciplinary study group, examining future research and development problems of the Air Force, estimated that it would be 1980 before developments in artificial intelligence make it possible for machines alone to do much thinking or problem-solving of military significance. That would leave, say, five years to develop man-computer symbiosis and 15 years to use it. The 15 may be 10 or 500, but those years should be intellectually the most creative and exciting in the history

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C. S. Nam (ed.), *Neuroergonomics*, Cognitive Science and Technology,
https://doi.org/10.1007/978-3-030-34784-0_1

of mankind.” Licklider had a vision that humans and machines will work together in harmony. The enabling technology for this vision is artificial intelligence (AI). Today, we have started to live the years that Licklider labeled as “intellectually the most creative”. Before we delve into some of these creative ideas and how they are reshaping human’s efficiency at work, we will first offer a glimpse of selected history that led to neuroergonomics as we know it today.

2 Before and After Neuroergonomics

The inception of neuroergonomics could be traced back to two ambitious projects: Biocybernetics (Wiener & Schadé, 1964) and Brain–Computer Interfaces (Vidal, 1973) or BCI. Both projects had the intriguing idea of using physiological responses as objective metrics to assess a human’s mental load and processing. As stated in the concluding report of the Biocybernetics project: “the objective in the DARPA Biocybernetics Program was to investigate the use of pupillary responses in assessing attentional demands on operators of complex man-machine systems. The results of this project were strongly positive: the task-evoked pupillary response has emerged as an excellent physiological indicator of mental workload.” (Beatty, 1979, 1).

The BCI project, led by Vidal, focused on the identification of signal responses in the brain to external stimuli and the opportunity this offers to design a communication channel between the human brain and the work environment. Vidal in his seminal paper asked: “Can these observable electrical brain signals be put to work as carriers of information in man-computer communication or for the purpose of controlling such external apparatus as prosthetic devices or spaceships? Even on the sole basis of the present states of the art of computer science and neurophysiology, one may suggest that such a feat is potentially around the corner.” (Vidal, 1973, 157).

Biocybernetics and BCI offered evidence to strengthen the hypothesis that objective indicators could be extracted from human signals, whether they are signals due to brain/cognitive functions or behavioral responses, and could be interpreted into actionable knowledge. Encoding the information residing within these signals offered the missing key to open a door of opportunities to connect humans and machines. It then did not take much time for the work to evolve to a different level of ambitious. A level whereby automation adapts in response to human mental states.

Adaptive Aiding (Rouse, 1988) is a program of research that started in 1974; almost straight after the Biocybernetics and BCI projects. Rouse explains that in a complex system, there are many components interacting. At one point of time, automating one component is essential and useful, while at another point of time, this automation may not be that useful. As the task demands change, the level of aiding and the strategy needed to define the way human and machine interact should also change. He defined three requirements for adaptive aiding:

- As task demands increase, the level of aiding should increase.
- As task demands increase, the interaction between human and machine should be streamlined.
- Variations of aiding and mode of interaction should be initiated by the aiding/automation tool.

These simple rules laid out the foundations for an intertwined journey in three streams of research that need to come together to deliver on the ambitious aim. One stream focuses on collection and interpretation of signals from humans. The second pays attention to the design of metrics to analyze the complexity of a task. The third is centered on algorithmic design of the adaptive logic that uses the actionable information from the first two streams to decide when, what, and how to switch functions or subtasks between humans and machines.

While brain imaging offered insights into the functional topology of the brain, real-time data analysis required more temporal resolution and flexibility in the sensors used to collect the data that other brain imaging techniques such as functional magnetic resonance imaging (fMRI) could not offer. Electroencephalography (EEG) offered more opportunities in this direction with the air traffic control (ATC) domain offering the perfect problem due to the mentally demanding tasks an air traffic controller does. Other techniques in the literature include: functional near-infrared spectroscopy (fNIRS) and transcranial Doppler (TCD), where both sense brain activities, while transcranial direct current stimulation (tDCS) delivers a low electric current of one to two milliamperes for neuromodulation.

Brookings, Wilson, and Swain (1996) conducted one of the early studies in this area, albeit with a small sample size of eight subjects. They experimented with three ATC scenarios that varied traffic volume, traffic complexity, and time criticality. They used 19 EEG channels according to the 10–20 electrode system and analyzed five bands: delta (1.1–3.9 Hz), theta (4.3–7.8 Hz), alpha (8.3–11.9 Hz), beta 1 (12.3–15.8 Hz), and beta 2 (16.2–24.9 Hz). Results for power spectral band values were calculated as the percentage of the total power between 1.1 and 24.9 Hz. They concluded the study with a number of findings including: the percent theta power at central, parietal, one frontal, and one temporal site significantly increased as task difficulty increased, the beta 1 band was sensitive to the traffic conditions at F3, Fz, F4, Cz, T4, and the interaction between traffic and difficulty manipulations was reflected in delta activity sites F3, Fz, F4, and T3. The study demonstrated the differential sensitivity of a variety of workload measures in complex tasks.

By early 2000, sufficient literature demonstrated the plausibility of the premise that EEG measured from the human scalp reveals mental processing information that could be leveraged to adapt automation to the human. However, the reliance on off-line post-analysis meant that the findings are mere academic ones. It was only meaningful to take a step to transform these findings into real-time systems to have any practical significance.

The above motivation gave birth to Augmented Cognition (AugCog) program (Schmorrow & Kruse, 2002). The aim of AugCog was to develop mental-state measurements and tracking technologies. As described by Schmorrow and Kruse (2002), the plan was "In FY 2002, the AugCog program is developing robust, noninvasive, real-time, cognitive state detection technology for measuring the cognitive processing state of the user. In FY 2003, AugCog will be developing and testing integrated multi-sensor interface technologies that will permit human state manipulation." (Schmorrow & Kruse, 2002, 7). Along with a similar timeframe, the literature saw the birth of Neuroergonomics. Probably the first use of the term was in Parasuraman's paper (Parasuraman, 1998), but the real impact and use of the term were more influential in his 2003 paper (Parasuraman, 2003). In that paper, Parasuraman defined neuroergonomics as "the study of brain and behaviour at work." (Parasuraman, 2003, 5).

Interestingly, despite the revolutionary concept of AugCog, the significant majority of research that has been done in the last two decades remained on the course of either off-line analysis or real-time BCI for medical applications (Nam & Nijholt, 2018). Only a few studies looked at real-time EEG analysis using realistically complex operational scenarios (Abbass, Tang, Amin, Ellejmi, & Kirby, 2014). To put it simply, AugCog and Neuroergonomics remain today a largely unexplored territory with significant missed—opportunities that practitioners could easily leverage. The working environment, in practice, has seen few attempts to use real-time EEG-based indicators to influence and shape the environment, let alone the potential for a two-way communication between the human brain and the task the human is operating on. This has been due to some challenging factors; some technological, while others are social.

On the technological level, factors ranged from the lack of robust sensors that could be used in an operational environment without imposing significant discomfort on the human from long usages, to the difficulties in generalizing EEG indicators across subjects. While trends in the EEG signals were consistent, at least among the majority of subjects, each subject requires different parameterizations of their models, let alone that the EEG signal for the same subject could be significantly impacted with caffeine, alcohol, and even time of the day. Social factors included the ethical implications of continuous assessments of the mental states of an operator in a work environment and the lack of compelling business cases to use what some would consider a "fancy" technology that may only be well-needed in safety-critical domains.

The above challenges called for new ways to think about how to transform the experimental results obtained in carefully conditioned environments to operational settings. The complexity of real-time calibration of the models to the human operator, contextual analysis, understanding and assessment of the task, and the level of sophistication required to create a truly symbiotic relationship between the human and the machine, called for a level of sophistication in the design of artificial intelligence (AI) beyond simple forms of adaptive logic.

The Cognitive-Cyber Symbiosis (CoCyS) concept (Abbass, Petraki, Merrick, Harvey, & Barlow, 2016) was then introduced to design this AI agent. CoCyS "revolutionised the adaptation process from a machine adapting to a human to smart adaptive agents (called 'ecookies') that act as autonomous relationship managers between humans and machines." (Abbass, 2019, 163). CoCyS leverages the revolution in AI to reduce the technological challenges faced in Neuroergonomics by automating the process to a sufficient level of autonomy that enables a plug and play environment. Such automation will allow massive productions of the technologies that will ease the financial burdens to create the business case for it. In simple terms, CoCyS is a bridge for AugCog and Neuroergonomics to make the visions created by visionaries and innovators, such as Schmorrow and Parasuraman, over the last 60 years an economically viable reality.

3 Where to from Here?

Neuroergonomics has evolved over the years as being discussed above. With the levels of sophistication seen today in sensor technologies, the complexity of the tasks expected from humans, and the advances made in artificial intelligence, the field needs to start tackling unprecedented challenges. In this section, the author will use his current research to lay out some of the most pertinent challenges in Neuroergonomics. To start with, Fig. 1 depicts the bigger picture of the author's research program in cognitive-Cyber Symbiosis for Human-Swarm Teaming (CoCyS-HST).

HST is one of the tasks that is expected to be most demanding on the human. An air traffic controller would normally be handling 7–9 aircraft at any point of time. In HST, the human could be teaming with other humans and one or more swarms of autonomous vehicles, each consisting of tens of vehicles, if not more.

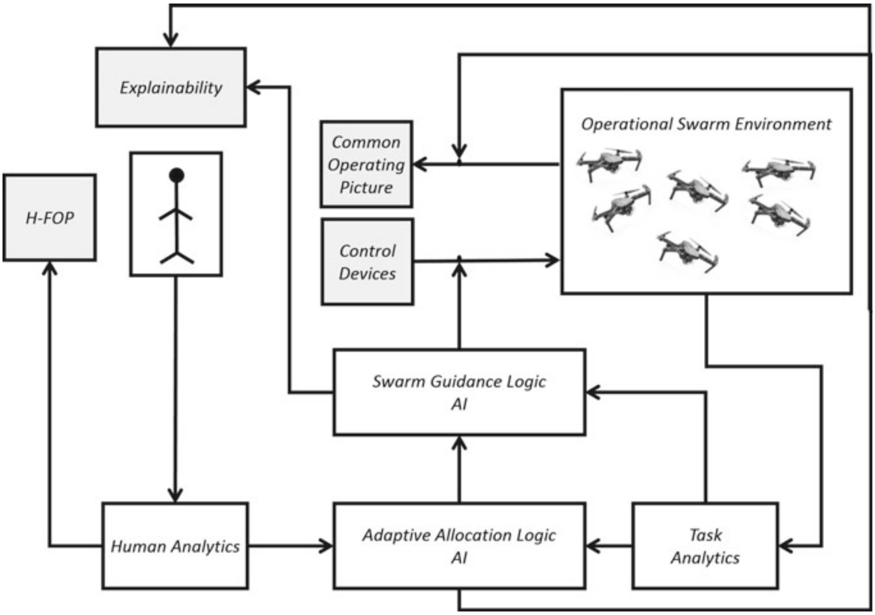

Fig. 1 Cognitive cyber symbiosis for human-swarm teaming

This level of complexity is unlikely to be manageable by a human. The situation calls for an AI to assist the human in managing the complexity and automate swarm guidance. This swarm guidance AI (SGAI) is responsible for autonomous guidance of the swarm in support of the human operator. The level of autonomy in SGAI is controlled by another AI, the adaptive allocation logic AI (AAL-AI), that relies on real-time analytics of the task and the human mental states to determine the optimal allocation of functions between the humans and the SGAI. Such allocations of functions are then communicated directly to SGAI to adapt its level of autonomy, and to the human through the interface depicting the common operating picture of the swarm to adjust human's situation awareness and actions.

To integrate the dynamic allocation of functions between the human and SGAI with the human, both AAL-AI and SGAI need to offer a level of explanation to the human. These explanations are necessary for many reasons. First, they are more likely to improve human's trust in the system. Second, they assist the human to maintain their situation awareness; especially when SGAI changes its level of autonomy which may cause the human to disorient. For example, if SGAI decides to reduce the level of autonomy due to a high-risk decision that needs to be made, the human is suddenly required to integrate more information to make a decision. Take for example a self-driving car that decides to hand control back to the human in a high-risk situation, the human needs to be quick in forming and/or updating the human's situation awareness picture.

The human factors operational picture (H-FOP) is a concept introduced in Ma-Wyatt, Fidock, and Abbass (2018), whereby a human analytic AI offers real-time assessments of human's mental states from a multitude of heterogenous data modalities including EEG, galvanic skin conductance, heart rate, and behavioral data such as facial expressions, mouse movements, and keystrokes.

The neuroergonomics challenges in the above system reside mainly in the H-FOP, human analytic, task analytic, and AAL-AI components. There are classic challenges with significant literature to address them. For example, the first challenge is related to the question of which indicators are useful in this task to evaluate human's attention level, situation awareness, mental load, level of engagement, and fatigue. With reliance on data from different modalities, each modality could contribute some indicators. For example, both EEG and heart rate variability could offer indicators of mental load. The second challenge is related to the design of appropriate fusion functions to integrate information from these diverse modalities. A third challenge revolves around similar lines but for the task itself; that is, how to characterize and assess the complexity of a situation as the task evolves?

We need to switch focus to challenges that have not been discussed sufficiently in the literature. The first of these is real-time calibration of the models based on EEG indicators. This is possibly one of the main obstacles in taking EEG from the lab environment to the real-world. In simple terms, if the system is plug and play, any human should be able to join the system and the system should work with this new human autonomously and with ease.

This form of calibration is very difficult but not impossible. Possible ways to achieve it include the following. One could calibrate against moments of subject relaxation. That is, if the operator needs to take rest every two or three hours, in the rest break, the operator could get trained to spend 2 min with their eyes closed and attempting to relax, for the system to calibrate. A second way is to calibrate against events in the task. The task analytic agent monitors the task in real time and is able to identify certain events such as the sudden appearance of an obstacle. These events could be used for calibration as they are expected to be followed by event-related potentials. A third possibility is to collect data from significantly large number of operators in a variety of task contexts, time of day, with different impacts of different beverages, and sufficient diversity to represent the population of operators. This later case seems possible, and may generalize well on a particular targeted subpopulation, but seems to run a hidden risk if the system maps a subject to the wrong behavior in a critical moment due to a bias in the sample.

Calibration within a subject own experience seems to be the most reliable approach to follow as it is subject centric and does not assume a single parameterization fits-all model. Moreover, a human who is using the same system on a daily basis may not require continuous calibrations as per the suggestions above. The system would have collected enough data to generalize and work well for that particular human.

A second challenge that does not get discussed sufficiently in the literature is the AAL-AI. Most of the literature assumes a very simple rule-based AI taking the form of a recommender system. However, the AAL-AI in complex tasks need to be far more sophisticated (Abbass, 2019). It first needs to be contextually aware of the human, the particular situation the human is faced with, and the overall mission. Second, the AAL-AI needs to anticipate the impact of each decision on human's situation awareness to decide an appropriate protocol for switching functions between the human(s) and SGAI.

Acknowledgements The author would like to acknowledge funding from the Australian Research Council Discovery Grant number DP160102037.

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Brain Basics in Neuroergonomics

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Abstract This chapter provides an introduction to (1) the fundamental components of neuroanatomy and brain function, (2) how brain processes give rise to behaviors that are relevant to study from a neuroergonomic perspective, and (3) how these brain processes can be detected and investigated with neuroimaging methods typically employed in neuroergonomics.

1 Introduction

The brain sits at the center of the human nervous system and is involved in regulating or executing almost every action that the human body produces. It is therefore difficult to overstate the importance of this organ with regards to our physiological functions. Studying the function of human action or thought will ultimately and inevitably lead to the brain. Neuroergonomics is well positioned to facilitate an understanding of this link between mental processes (such as actions or thoughts) and brain function. In order to make this link, however, an understanding must begin at both ends of the process, both with how the action is completed, and the processes that underlie the action. Knowledge of the workings of the brain helps us understand the processes before and during the action. This chapter aims to provide such knowledge, so that the output and the links between them can be understood and discerned with greater precision.

The brain has been studied extensively, particularly in recent history as neuroimaging and molecular methods have both improved and become easier to implement. This has allowed for many breakthroughs to be made and we now have a clearer idea of what the brain is, what it consists of, how it works, develops, and how it learns. An introduction to the current state of understanding of each of these areas will be introduced below. It should, however, be made clear—while great progress has been made (and continues to be made), we are still far from a true, holistic, and complete understanding of brain function.

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C. S. Nam (ed.), *Neuroergonomics*, Cognitive Science and Technology,
https://doi.org/10.1007/978-3-030-34784-0_2

The brain in anatomical terms consists of the cerebrum, the cerebellum, and the brain stem. The cerebrum is usually what is pictured when considering the brain—the two-hemisphere structure with multiple folds. The cerebellum is located at the back of the head and outwardly shows multiple fine grooves and furrows. The brain stem consists of several structures that reside within the cerebrum, and is the link between the cerebrum and the spinal cord. Below, we will go through the functioning of each of these structures, and highlight areas that have particular relevance to neuroergonomics.

2 An Introduction to Neuroanatomy

2.1 The Cerebrum

In broadest terms, the cerebrum consists of six brain areas that span two hemispheres. Four of these areas can be seen from the external view of the brain—the frontal, parietal, occipital, and temporal lobes. Two other lobes, the limbic and insular lobes, are found within the cerebrum. Each of these lobes can be said to be the site of exclusive functions, although there is also considerable overlap.

On the outermost point of the cerebrum sits the cerebral cortex (often, and herewith referred to as the cortex), a sheet of neurons roughly 1.5–3 mm thick. The cortex is finely wrinkled, creating the gyri (ridges) and sulci (furrows) that are seen on the surface of the brain. This wrinkling dramatically increases the surface area of the cortex, allowing for many more neurons to reside within this space. Various other areas constitute the remainder of the cerebrum, including the basal ganglia, hippocampus, and the olfactory bulb, among others (Martin, Radzyner, & Leonard, 2012) (Fig. 1).

2.2 The Cortex

The cortex is where the majority of neuronal processing takes place before that signal is transmitted to subcortical areas (and beyond). This is evidenced by the approximately 77 billion neurons (Azevedo et al., 2009) that reside in the cortex. The cortex itself is composed of multiple columns of neurons (Defelipe, Markram, & Rockland, 2012) that contain multiple layers. There are six layers within the column, although the exact composition of the neurons within the layers differs depending on where it is situated. This will be returned to within Sect. 2.1.

Initial processing of visual information is carried out within the cortex, in the occipital lobe (at the back of the head). As light enters the retina, it activates photoreceptors (a sensor of light within the eye) that trigger a cascade of signals that are sent to the visual cortex. Around 50% of the signal is sent in a contralateral fashion (i.e.,