OPPORTUNITIES AND IMPLICATIONS OF BRAIN-COMPUTER INTERFACE TECHNOLOGY

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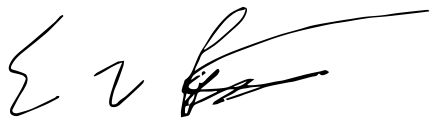
Foreword

It is my great pleasure to present another issue of The Wright Flyer Papers. Through this series, Air Command and Staff College presents a sampling of exemplary research produced by our resident and distance-learning students. This series has long showcased the kind of visionary thinking that drove the aspirations and activities of the earliest aviation pioneers. This year's selection of essays admirably extends that tradition. As the series title indicates, these papers aim to present cutting-edge, actionable knowledge—research that addresses some of the most complex security and defense challenges facing us today.

Recently, The Wright Flyer Papers transitioned to an exclusively electronic publication format. It is our hope that our migration from print editions to an electronic-only format will foster even greater intellectual debate among Airmen and fellow members of the profession of arms as the series reaches a growing global audience. By publishing these papers via the Air University Press website, ACSC hopes not only to reach more readers, but also to support Air Force–wide efforts to conserve resources. In this spirit, we invite you to peruse past and current issues of The Wright Flyer Papers at https://www.airuniversity.af.edu/AUPress/Wright-Flyers/.

Thank you for supporting The Wright Flyer Papers and our efforts to disseminate outstanding ACSC student research for the benefit of our Air Force and war fighters everywhere. We trust that what follows will stimulate thinking, invite debate, and further encourage today's air, space, and cyber war fighters in their continuing search for innovative and improved ways to defend our nation and way of life.



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Abstract

This paper examines the implications of a technological convergence of biotechnology and cybertechnology and how best to prepare for the exponential change triggered by this emerging field. This convergence, specifically brain-computer interface (BCI) technology, is enabling bidirectional communication between the brain and a computer. Clinical applications are significant, offering treatments for epilepsy, dementia, nervous system disorders, post-traumatic stress disorder, traumatic brain injury, as well as advanced prosthetics. In some cases, BCIs may be able to not just restore functionality but also augment it. New noninvasive techniques are now showing benefits to the point where healthy individuals may opt to have BCIs installed to augment their abilities. This paper will explore the opportunities this technology creates for the United States Air Force (USAF) to enhance combat capability, particularly in high-workload career fields, and the policy choices needed to prepare for the next 20 years. It concludes that in order to seize these opportunities, the USAF needs to act now on currently available technologies to foster a culture of increased experimentation and calculated risk-taking.*

* The author would like to thank the scientists and researchers from the United States Air Force Research Laboratory, 711th Human Performance Wing, Sandia and Los Alamos National Laboratories, the Defense Advanced Research Projects Agency (DARPA), and Charles Stark Draper Labs, Inc. The author would like to extend a special thanks to specific individuals who provided thoughtful insight and commentary. Among these are Col. John P. Geis II, Air War College, USAF retired, and Dr. Jessie Wheeler of Charles Stark Draper Labs. Their breadth of experience provided the foundation for understanding the challenges and opportunities BCIs will create for the USAF in the 2040 timeframe.

Scenario: 3 June 2040, Luzon Island, Philippines

A Penetrating Counter Air fighter with three BQ-58A "Valkyrie" loyal-wingman drones launches northwest on a classified maritime interdiction mission. Using a network of embedded biosensors, physiological and cognitive states are fed back to the pilot to improve situational awareness. Additionally, a fiber-optic brain-computer interface (BCI) connects the pilot's brain directly into the aircraft, fusing massive amounts of sensor data into a clear mental picture. Tasks for the loyal wingman are commanded not through voice or button pushes but through an onboard artificial intelligence (AI) decoding the pilot's intent. Three weeks before the mission, the pilot graduated from college, attended and completed undergraduate pilot training (UPT), then proceeded directly to his operational unit, a process that usually takes years. During college, the pilot had undergone regular neuromodulation sessions that helped pathways into his brain form faster and neurons fire more easily, enabling significant improvements in cognitive and physical abilities. During UPT, genetic modification through the use of a retrovirus modified the neurons in his brain to respond to both electricity and bursts of light from the fiber-optic BCI integrated into his brain. Using the interface, knowledge and experience from a cloud-based data repository were uploaded directly into the brain, eliminating the need for years of flight training.

Introduction

The convergence of cyber technology and biotechnology is creating opportunities for the USAF to enhance combat capability, particularly in the field of brain-computer interface (BCI) technology. Parallel advances are enabling this convergence in computing, genetic sequencing, medical sensors, and increased investment in neuroscience research. BCIs and related technologies have the potential to significantly change the way the Air Force employs airpower and trains individuals for high-workload career fields. Along with the multitude of clinical applications, including treatments for wounded warriors, this technology may enable rapid learning, enhanced cognitive and physical abilities, and the ability to interface the nervous system directly with a computer to improve performance and efficiency. These applications are of particular interest to the USAF as it seeks to meet challenging national security objectives for the next 20 years. The scenario above is based in 2040, but the BCI capabilities described are being enabled by advances in cyber technology and biotechnology today. The rapid convergence of cyber technology and biotechnology creates opportunities for the USAF to enhance combat capability, particularly in the fields of performance augmentation and training. However, we need to act now by integrating currently available technology to understand and gradually adjust to the policy changes that may be required.

Due to the technical nature of this subject, defining the technology under study, the intended audience, and the scope of the research upfront is important. A BCI is a bidirectional communication pathway between the brain and an external device, designed to acquire, analyze, and translate brain signals for a specific action.[1] The brain typically works by sending a signal to peripheral nerves and muscles to induce movement of a limb or to conduct a certain action. BCIs provide a new output channel for the brain to communicate with and ultimately control an external device. The external device could be an artificial limb, a simulated aircraft in flight, or anything that can be interfaced with a computer. BCI is also synonymous with brain-machine interface, neural-controlled interface, mind-machine interface, and direct neural interface, all of which are in other research. BCIs work by measuring and translating signals from the basic working unit of the brain, the neuron.

Neurons are a particular type of nerve cell in the brain designed to transmit and receive nerve impulses through an electrochemical reaction.[2] The intended audience for this paper is those without technical academic backgrounds but who still have a general understanding of modern technology. Considering this intended audience, effort was taken to reduce the neuroscience jargon, replacing technical terms with plain language when appropriate. The paper primarily explores the defense implications of BCI technologies in the 2040 time period, particularly performance augmentation and the policy choices that lay ahead for the USAF. Clinical applications are mentioned in brief, with the discussion of specifics limited to the treatment of wounded warriors.

The goal of this paper is to inform the reader of the current state, technical challenges, and future of BCI technology with a focus on USAF and Department of Defense (DOD) implications. Ultimately it will recommend actions that should be taken to prevent this inevitable outcome. First the paper summarizes background information on why this technology is on the fast track and the current state of investment. It then provides an overview of the technical challenges ahead and how they will guide USAF and DOD implementation. Next, the technological implications for the near, mid, and long term will be described. The analysis ultimately recommends that several currently available technologies should be tested in real-world scenarios. These include, noninvasive biosensors to improve situational awareness, neuromodulation to improve multitasking performance, and foveal eye-tracking to improve man-machine teaming. These technologies provide modest performance improvements and, if implemented now will help the USAF better cope with the policy choices that lie outside the near term.

Background

Why Is BCI Technology on the Fast Track?

In recent years, BCI development was put on the fast track because of parallel advances in multiple technology fields and interdisciplinary interaction. Other technology fields include the advancement of computing power, genetic sequencing, and medical sensor technology, to name a few. For example, computing power has seen a trillion-fold increase over the past 60 years.[3] Advances in computing power led to complete sequencing of human DNA structure in the early 2000s, a process that took nearly 13 years and $1 billion.[4] Today, a genome sequencing can be accomplished for a few thousand dollars and in about two days.[5] Parallel advances in medical sensors are enabling real-time measurement of brain activity, which helps researchers understand the brain's processes. Additionally, interdisciplinary interaction between neurologists, biologists, engineers, geneticists, psychologists, computer scientists, and mathematicians regarding BCIs has led to the integration of knowledge and methods. Improved technology and increased interaction are enabling the treatment of a multitude of different conditions through the use of BCIs.

Because BCIs enable a new output path for the brain to communicate, treatment of a wide variety of clinical conditions is now possible, subsequently driving increased investment and attention. These conditions include epilepsy, Parkinson's disease, dementia, amyotrophic lateral sclerosis (ALS), cerebral palsy, stroke, spinal cord injuries, and muscular dystrophies.[6] Increased attention has also been the result of some high-profile celebrity diagnoses including Christopher Reeve with spinal cord injury, Michael J. Fox with Parkinson's disease, and Stephen Hawking with ALS. BCI technology holds promise to be particularly helpful to people who are "locked-in," cognitively intact but without useful muscle function. BCIs would theoretically be able to restore communication abilities and neuromuscular function, significantly improving the quality of life for those individuals. This restoration of the brain's ability to communicate after neurological disease or injury is leading to applications that are of interest to the DOD.

The conflicts in Afghanistan, Iraq, and Syria over the past 20 years have led to a prevalence of post-traumatic stress disorder (PTSD), traumatic brain injury, and major limb amputation among our service members. This is driving increased attention and investment from the DOD into BCIs. Between 7 October 2001 and 28 July 2015, the Congressional Research Service estimated the following total US casualties from Afghanistan, Iraq, and Syria to be: 52,351 wounded in action with 1,645 major limb amputations, 138,197 diagnosed with PTSD, and 327,299 diagnosed with some form of TBI.[7] As a result, the US has a vested interest in investing in technologies that improve the quality of life for our wounded warriors. The Defense Advanced Research Projects Agency (DARPA) often heads research programs designed to specifically address the problems of TBI, PTSD, and limb amputation. In 2013, DARPA launched the Restore Active Memory (RAM) program with the goal to develop a "fully implantable, closed-loop neural interface capable of restoring normal memory function to military personnel suffering from the effects of brain injury or illness."[8] The Systems-Based Neurotechnology for Emerging Therapies (SUBNETS) program is also seeking to create an implant diagnostic and treatment system for the treatment of PTSD.[9] Finally, DARPA's Revolutionizing Prosthetics program aims to restore "near-natural hand and arm control to people living with the loss of an upper limb."[10] These programs represent efforts designed to improve the quality of life for wounded warriors but are also leading to opportunities to enhance the performance of healthy individuals.

Emerging from the clinical and wounded warrior applications of BCIs are opportunities to enhance human performance and hence combat capabilities. These upgraded combat capabilities have been highlighted by science fiction writers and Hollywood films for nearly a century, postulating the merging of cybernetics with organic tissue. There are technological advances in multiple fields leading to increasingly less invasive treatments. This could develop to the point where healthy individuals may elect to have procedures to augment their abilities. For example, the RAM program may lead to the ability to improve memory recall for a healthy brain. The SUBNETS program may lead to the ability to diagnose brain illness before the onset of symptoms. Advanced prosthetics are already moving beyond human abilities of dexterity and strength. With every significant advancement on the clinical side of BCIs comes an opportunity to apply technology to augment the performance of a healthy individual.

Current Investment in BCIs

BCI development and investment have seen explosive growth in recent years because of successes in clinical applications, with these successes now being applied to the improvement of human performance. BCI research is spread across a broad spectrum of efforts, and within this spectrum a variety of organizations conduct research, each with their own specific application for BCIs. Representing the bulk of the investment in BCIs are the applications for the treatment of clinical conditions, including the treatment of wounded warriors. This research is conducted by academia, commercial companies, US government laboratories, foreign governments, and research labs. These entities have an interest in BCIs because they may create therapies for previously incurable diseases and conditions. Because BCIs are becoming less invasive, commercial companies in addition to the DOD are now starting to research methods to apply these technologies to healthy individuals. This section will show that BCI technology is at a tipping point for exponential growth by describing the recent successes in academia, commercial companies, and the DOD for performance enhancement.

Within academia, recent breakthroughs in advanced prosthetics are increasing the possibility to improve performance. In 2012, these breakthroughs stemmed from Jan Scheuermann. Paralyzed from the neck down, she commanded a modular prosthetic limb with her mind to feed herself for the first time since becoming paralyzed. After two years of refining the technology, Jan was using the same interface to control the motion of an F-35 through the use of a simulator.[11] This breakthrough was widely publicized and culminated with a CBS *60-Minutes* special.[12] In 2018, Johnny Matheny used an updated MPL with haptic feedback to play the piano.[13] The haptic mechanism interfaced directly with nerve endings in his arm, creating a sense of touch in the artificial limb. The MPL was designed to provide human-like strength and dexterity.

These characteristics could be modified with new robotics and control algorithms to produce superhuman qualities. Additionally, solving the interface problem opens the door to a wide variety of applications, in which a human could theoretically control any large machine or weapon system. These advances are a direct result of government research grants into academia; the goal to improve wounded warriors' quality of life. However, revolutionary prosthetics merely scratch the surface to help those with and without disorders.

In the last few years, BCI research has gathered significant momentum with massive interest from several commercial companies looking to capitalize on BCI momentum to augment human performance. Facebook's Mark Zuckerberg recently revealed that company's research into BCIs. Zuckerberg sees the brain as the next big computing platform and is hoping to produce a BCI designed to allow people to type three times faster than traditional methods.[14] Elon Musk, the founder of SpaceX and Tesla, recently founded Neuralink. Musk aims to create a direct cortical interface with the brain via a product called neural lace, to help humanity better compete with AI.[15] A company called Kernal, headed by Bryan Johnson, is going big with an idea for "a [BCI] device that will allow us to learn faster, remember more, 'coevolve' with artificial intelligence, unlock the secrets of telepathy, and maybe even connect into group minds."[16] Charles Stark Draper Labs Inc. is also a leader in the field with several technologies on the horizon that may enhance human performance or man-machine teaming. His efforts include wirelessly connected implants for prosthetics, a live remote-controlled dragonfly with a BCI, and a field cap designed to read neural activity noninvasively.[17] This listing represents just a portion of the commercial products under development within the US. It was included to indicate that the technology is leading to a variety of different applications outside the clinical realm.

Based on recent successes and new ideas on how to adapt this technology for defense purposes, DOD has increased its investment and reorganized its efforts to lead in this field. DOD generally focuses on veterans' issues and making warriors whole. Through the years, their research has spanned a wide spectrum as technologies, threats, and societal sensibilities have changed. No longer is the US looking to create genetically modified cyborg super soldiers; instead DARPA focuses on the more modest and socially acceptable goals of restoring limb or brain function after injury and improving the performance of healthy individuals. Built on the success of the Human Genome Project, President Obama created a Brain Research through Advancing Innovative Neurotechnologies initiative in 2013.[18] This initiative split $100 million in fiscal year 14 between DARPA, the National Institutes of Health, and the National Science Foundation to improve our understanding of the human brain. In April 2014, recognizing this exploding field with new funding, DARPA stood up its Biological Technologies Office, which now heads at least 33 different research efforts in the biotechnology field.[19]

DARPA is currently funding several other initiatives designed to improve our understanding of the brain and create capabilities to improve US warfighting advantage. Some examples include the ability to improve healing (Electrical Prescription [ElectRx]) and boost learning through targeted neuromodulation (Targeted Neuroplasticity Training [TNT]). Several research efforts involve studying how to increase read and write memories directly into the brain and RAM/RAM-Replay (Neuro Function, Activity, Structure, and Technology [Neuro-FAST]).[20]

Additionally, DARPA funds efforts designed to improve signal resolution, bandwidth, and noninvasive techniques for BCIs, including Next-Generation Nonsurgical Neurotechnology (N3) and Neural Engineering System Design

(NESD).[21] The NESD program recently awarded $65 million to six different projects that focused on improving hardware, software, and neuroscience for BCIs.[22] Two of the six projects are researching the processes of speech and hearing, while the other four are examining the manipulation of vision. These programs represent a portion of DARPA efforts to improve our understanding of the brain, improve the quality of life for wounded warriors, and create opportunities to improve human performance. It should be clear by the successes with clinical applications, the interest by large commercial companies, and renewed investment and interest from the USG that BCI technology is an exponentially growing and potentially disruptive field.

The Way Ahead

Because BCIs and related technologies are creating opportunities to enhance human performance and war-fighting ability, they represent a potential threat to our military advantage, which requires a projection of where this technology is going. The question about disruptive technologies is not a new one. With the rapid changes brought on by the information revolution, disruptive technologies have become a regular occurrence. The 2018 *National Defense Strategy (NDS)* addresses the implications of new technologies by stating "we must anticipate the implications of new technologies on the battlefield, rigorously define the military problems anticipated in future conflict, and foster a culture of experimentation and calculated risk-taking. We must anticipate how competitors and adversaries will employ new operational concepts and technologies to attempt to defeat us, while developing operational concepts to sharpen our competitive advantages and enhance our lethality."[23]

Disruptive technologies can often be viewed as net neutral, offering opportunities and potential threats; we simply need to *anticipate the implications* per the 2018 *NDS*. One fairly recent in-depth look at the defense implications of BCIs was done in the fall 2016 edition of *Strategic Studies Quarterly* in Michael P. McLoughlin and Emelia S. Probasco's "Brain-Machine Interfaces: Realm of the Possible." In this article, they discuss the recent advances, challenges, and possibilities emerging from brain-machine interface technologies. However, they ultimately conclude that "it might be too soon to begin planning for brain-machine interface in everyday life."[24] The massive growth in this field in the past three years indicates that we may be closer than ever to seeing BCIs integrated into everyday life. Thus we need to start planning for the policy implications of BCIs and related technologies. Understanding the policy implications requires a road map for the future of this technology.

The first step in the projection of any disruptive technology is to understand the limitations of prediction. BCIs and related technology are not limited to one field but represent an interdisciplinary effort as described earlier. This interdisciplinary effort implies that advances in one field tend to influence other areas. Since these areas of study all seem to be growing exponentially, predicting where one domain will be in the next five, 10, or 20 years seems futile. While general technological trends can be extrapolated, the further from the present we get, the larger the uncertainty volume gets and therefore we have less predictability. This is particularly true concerning BCIs because the technology requires huge technological jumps in many different fields. According to its mission statement, DARPA is seeking technologies that create transformational change rather than incremental improvements. Their investments in basic research focus on "moonshot"-type problems, and as a result they often fail. Failure within BCI-related research may lead to massive shifts in technology. Since a large number of technical hurdles have been overcome in the past few years, considerable challenges still exist that may slow, stop, or divert the technology into something completely different from expectations. The next section introduces and describes four challenges that BCIs face. These challenges will guide how the DOD and USAF apply this technology.

Technical Hurdles

Before projecting where BCI technology may be in coming years and forecasting what is or is not possible, it is essential to understand the technical challenges involved. These technical challenges are not trivial and may significantly alter how the DOD and USAF use technology to enhance our war fighters. First, faulty metaphors and Hollywood hype have influenced our perception of the brain—an actual, complete understanding of the brain and its functions might still be decades away. Second, the body's immune system responds when subject to a foreign object. Third, achieving high signal resolution—while also ensuring safety with invasive methods—yields engineering challenges, including issues with power consumption, biosecurity, communications methods (wireless or wired), and decoder efficiency. Finally, ethical, social, and legal implications arise with BCI implants. These challenges, while not an all-encompassing list, represent the obstacles that will guide how the USAF and DOD apply these technologies in future efforts.

The first challenge highlights how far we have to go to gain a complete understanding of the brain. In the last decade, genetic sequencing technology and new tools for mapping the brain have led to an explosion in neuroscience research. Scientists can now use these tools to map neuronal firing patterns in an attempt to understand how different firing patterns lead to different actions. However, the brain contains between 80 and 100 billion neurons with each neuron having up to 10,000 connections to its surrounding neurons.[25] Scientists are still far from understanding the dynamics of the electrochemical interactions between the neurons and how those interactions are translated into memories, behaviors, perceptions, and actions. Often we seek the closest metaphor for the brain, comparing the brain to a digital computer and its subcomponents. While similarities exist (both are designed to process and store information), mechanisms for their processes and are quite different. In reality, when exposed to new experiences, the brain changes in an orderly way based on the existing, unique structure that each person has developed over a lifetime of experiences. Robert Epstein's article, "*The Empty Brain*," states there is no reason to believe that any two of us are changed the same way by the same experience."[26] For example, the firing patterns on the brains of two air battle managers (ABM) learning the same task would be dependent on their past experiences. This complicates the prospect of accurate memory prosthesis or the transferring of knowledge and experience from one person to another. The brain does indeed have a modular design, with certain areas designed for specific functions (i.e., movement planning, movement execution, aggression, attention, and so forth). This indicates that although the brain activity of the two ABMs will not be identical, they will likely be similar. There may be a quasi-transitive property within the brain like in mathematics (i.e., 5 x 6 = 6 x 5), where neurons are arranged differently but retain the same data. The first step in making an informed prediction about the future of BCIs is to temper our expectations. This can be accomplished by taking some time to understand what metaphors are valid and invalid depending on what is being compared.

The second challenge to BCIs is the body's natural immune response when subject to a foreign body. This is particularly important for invasive BCIs that reside under the skin. Invasive BCIs typically use an array of micro-electrodes in direct contact with specific neurons in the brain. Once the body recognizes the electrode as a foreign body, the immune system goes to work much like it would in the case of a splinter. The result is a process called tissue encapsulation, in which the electrode is surrounded by a fibrous capsule of tissue called a glial scar. The *Journal of Neuroscience Methods* article states the scar's purpose is believed to be separating "damaged neural tissue from the rest of the body to maintain the blood-brain barrier."[27] This capsule reduces the signal-recording ability of the electrodes and sometimes results in the death of the particular neuron, to the point where some BCIs become unusable after a few weeks. Worth noting are many research efforts attempting to solve the biocompatibility problem with tissue-response modifying drugs and advanced material coatings like hydrogels (which mimic soft body tissue).[28] However, bodily response represents the most significant challenge to achieving a chronic or long-term BCI in clinical patients. Today's BCIs are limited to clinical studies under the close care of physicians. The physicians have to not only work fast to gather data as the encapsulation takes place but also strictly monitor the patient for a brain infection. Until the biocompatibility of medical devices is improved, this challenge will likely limit the use of invasive BCIs to clinical populations for the next decade. Therefore, this pushes DOD and USAF near- and medium-term applications toward noninvasive methods.

The third challenge facing BCIs is overcoming engineering hurdles to achieve high signal resolution while also ensuring safety with invasive methods. The goal with any BCI is to produce a bidirectional communication with the brain. Often this is done via electrodes interfacing directly with neurons. The objective is to achieve high spatial and temporal resolution with the measurements. This means knowledge of where and when the measurement happened. The more electrodes that interface with the neurons, the higher the amount of data the researcher receives. Three research areas categorize BCIs today. The first is the insertion of an electrode that measures (or excites) a single neuron. Electrode methods are invasive, requiring an operation below the protective layer of skin that surrounds and protects the brain. Electrodes are subject to tissue encapsulation and infection. The second method involves taking measurements from the scalp using electroencephalographic (EEG) activity.[29] EEG methods are noninvasive but are typically characterized by low spatial and temporal resolution. The third method measures electrocorticographic (ECoG) activity from the surface of the brain rather than from inserting electrodes. An ECoG-mesh would likely measure populations of neurons firing. This method is also invasive but provides much higher measurement resolution than EEG methods. Additionally, ECoG methods are useful for avoiding some of the body's immune responses that create limitations for electrode methods.

In addition to resolution and safety, BCI engineering challenges also exist in power consumption, biosecurity, communications methods (wireless or wired), and decoder efficiency. Power consumption and biosecurity are fields that sometimes directly compete with each other.

Typically medical devices strive for low-power consumption to reduce battery size and prolong device lifespan. However, there is an inverse relationship between power requirements and efficient biosecurity measures, as protecting signals through encryption increases required computations, driving the power consumption up. Wireless communication methods are preferred over wired to reduce the chance of infection; however, they have their range limitations as the body is an excellent absorber of electromagnetic radiation. Decoders are also a significant engineering challenge, designed to accomplish the *analyze and translate* function of a BCI. This is because the brain is inherently plastic, meaning it can modify its structure and rewire itself as we age. As a result, the ability of a decoder to decipher the intent of neuronal firing patterns will degrade as the brain rewires.[30] The decoder needs to be able to understand and adapt to changes in the brain for the translate function to work correctly. Otherwise, the decoder would need to be retrained. These challenges are likely to be overcome as new methods for low-power biosecurity and decoding brain signals are developed. Additionally, advances in big data analytics and AI will help assist bringing BCIs closer to reality.

The fourth challenge involves consideration of the ethical, legal, and social implications (ELSI) of BCIs, which serves to slow the growth of this technology. The ELSI process began as a research program in the 1990s because of the HGP.[31] The goal is to have an independent assessment of the implications surrounding research. That way, we may venture into the gray areas of acceptability, whether ethically, socially, or legally. DARPA utilizes ELSI experts to help "proactively identify potential issues related to the use of neurotechnology."[32] These experts supplement the already cumbersome process provided by institutional review boards (IRB). For the USAF, the review is accomplished by the 711th Human Performance Wing's IRB out of Wright-Patterson AFB, Ohio. Their mission is to "facilitate excellence in human performance and technological research that advances war-fighting capabilities . . . by efficiently processing and professionally evaluating proposals for scientific validity and uncompromising protection of the rights and welfare of volunteer subjects."[33] Most would agree that the incorporation of a BCI to cure disease, treat brain injury, or regain use of a lost limb are altruistic efforts without ELSI concerns. These additional levels of review, though necessary, serve to slow the development of BCIs and may ultimately limit their applications when applied to healthy individuals.

The four challenges presented here represent hurdles that may slow, stop, or divert this technology into something completely different than expected. These hurdles also drive uncertainty in the prediction of where this technology will be in the next five, 10, or 20 years. Concerning the misconceptions surrounding the brain and our biases created by Hollywood or brain-computer metaphors, efforts need to be taken to inform decision makers what is within the realm of possibilities regarding BCIs.

The Future

Near Term, Zero–Five Years

Informed by the challenges that BCIs face, the USAF has an opportunity today to use BCI-related technology to help pave the way for more advanced concepts as they come online in the next five years. These opportunities include noninvasive biosensors and performance improvement methods, like neuromodulation and optical tracking techniques. These methods, while not BCIs by definition, may help streamline testing processes and address implications early as more advanced technologies come online. For the performance enhancement of healthy individuals, noninvasive methods are vital to ensuring that the rights and welfare of those that volunteer to test these technologies are not compromised. Additionally, they will ensure that volunteers can elect to have sensors removed or specify that the effects are only temporary. As stated in the 2018 *NDS*, the USAF is in a good position to create a "culture of experimentation and calculated risk-taking" by testing noninvasive methods in its high-workload career fields, particularly aircraft cockpits.[34]

The first step is to integrate noninvasive biosensors into the cockpit to provide feedback on the pilots' physiological and cognitive states. Such real-time feedback can improve situational awareness (SA) while also reducing some of the risks associated with flying. One recent example was Project Have Hope, executed out of the USAF Test Pilot School in 2017. The project incorporated a portable EEG and biofeedback display into the cockpit of an F-16 to monitor the pilot's heart rate (HR) and percentage heart rate reserve (%HRR). The goal was to improve SA by informing the pilots real-time of their physiological and cognitive states. The principal conclusion was that there should be a broader range of biosensors incorporated to define the operator physiological and cognitive state fully. However, Michael S. Fritts' work, Human Optimization and Performance Enhancement, states "there is hope in the future for an individualized, all-inclusive, and data-driven complex biofeedback algorithm."[35]

The ultimate goal is to nonintrusively integrate biofeedback into existing aircraft alerting systems, presenting only pertinent information to the pilot using a variety of aural, visual, and tactile cues. Additional sensors can be integrated to measure peripheral capillary oxygen saturation in the blood to aid in hypoxia detection. Also, an EEG skullcap could detect the precise moment of G-induced loss of consciousness (GLOC), directly interfacing with the aircraft to recover the pilot before hitting the ground. As GLOC and hypoxia-related incidents continue to occur within USAF—with the most recent aircraft loss in 2018—the operational utility should be obvious.[36] Improving safety and SA through the incorporation of noninvasive biosensors is an easy first step toward a better understanding of BCIs.

Another way that the USAF can get its foot in the door regarding the use of BCIs is by using neuromodulation technologies to improve operational abilities. Neuromodulation is the alteration—or modulation—of nerve activity by delivering electrical or pharmaceutical agents directly to a target area.[37] This technology has been around for nearly 50 years, designed for a variety of clinical applications. In the past decade, one technology called transcranial Direct Current Stimulation (tDCS) has advanced dramatically, and some studies have shown enhancement in cognitive and physical abilities resulting after treatment. The technology is highly safe, portable, affordable, and noninvasive.[38] A tDCS device is used to apply a small amount of electrical current to the surface of the scalp at a particular location based on the desired outcome. In essence, the electrical current pushes the neurons at the stimulated location closer to the threshold, making it easier for them to fire. For example, a company called Halo Neuro Inc. offers a commercially available headset that uses tDCS to apply a small current to the portion of the brain that controls movement.[39] They advertise that it helps build pathways in the brain faster, which enhances muscle memory for tasks like weight lifting or playing the piano. In 2018, the Air Force Research Laboratory released the results of its study into tDCS and found that the technology "significantly improves the participants' information processing capability, which results in improved performance compared to sham tDCS . . . . The findings in *Frontiers in Human Neuroscience* provided new evidence that tDCS has the ability to augment and enhance multitasking capability in a human operator."[40] Further research is required to fully understand the potential benefits and costs of tDCS, but it creates an opportunity to begin to understand how the USAF should address performance augmentation in its operators.

A third idea for the USAF to capitalize on BCI technology is to begin studying ways to improve man-machine teaming through noninvasive brain monitoring and foveal tracking. The effective interaction between man and machine is central to the USAF's ability to operate its major weapon system (MWS). This interaction can be improved by utilizing BCI-related technologies in concert with the MWS. For example, the designation of a target in a fighter aircraft is traditionally accomplished by using hands on throttle-and-stick switches to slew a cursor over the target on the radar screen and then designating with another button push, much like a mouse would be used to click a file. The incorporation of helmet-mounted cueing systems enabled pilots to look in the direction of the target and while pushing a button to designate, speeding up this process. This method involves precise cranial movements to place a fixed cursor over the target, which is quite tricky in dynamic high-G maneuvering and creates risks for the pilot's neck. A camera positioned within the helmet could track foveal movement to determine where the pilot was focusing in the field of view. Additionally, the aircraft could use that information to move a cursor on the multi-function displays. Coupled with an EEG skull-cap, the onboard computer could be trained to respond to specific neuronal firing patterns for simple tasks like designation.

Biosensors, neuromodulation technologies, and improved man-machine teaming are easy ways for the USAF to improve safety, SA, multitasking abilities, and the efficiency of its operators with the technology available today. These technologies, while not traditionally BCIs, rely on advances that have emerged in recent years from the increased focus on brain science. Getting a foot in the door is the first step to understanding what the costs, benefits, and implications of these technologies will be as technologies that create possibilities for more significant enhancement come online in the future. Furthermore, exploring these technologies first will help the USAF address the potential policy changes required for augmented individuals.

Medium Term, Five–20 Years

In the medium term, the increased investment in BCI technology will invariably lead to incremental improvements in biosensors, neuromodulation, and man-machine teaming. It may also lead to socially acceptable invasive methods, rapid learning, and remote animal control. Clinically, the expectation is that BCI technology will lead to the restoration or replacement of useful functions for those disabled by neuromuscular disorders. Additionally, basic neuroscience research funded by DARPA will lead to an increased understanding of the brain and may lead to applications that have not been considered. The purpose of this section is to forecast what the applications are for the USAF and DOD beyond the near term. These applications include implantable microchips, targeted neuromodulation for rapid learning, remotely piloted aircraft control, and animal control using BCIs.

Implantable microchips may lead to improvements in identification, information storage methods, biosensor technology, and security procedures. Animal "chipping" has been around for over 20 years, but recent news suggests that there may be a multitude of applications for human use as well. Beyond primary identification purposes, humans may be able to utilize these implanted microchips to open doors, pay for goods and services, hold emergency contact details, and store medical records. As of October 2018, more than 4,000 Swedes elected to have a microchip the size of a grain of rice inserted just above their thumb.[41] This microchip is designed to speed up their daily routine. It allows them to swipe their hand against an entry pad to access their office, home, or gym. The military could benefit from this technology and the same applications, including access to secure areas or computer terminals. The USAF should also consider the use of invasive microchips as biosensors to improve awareness of our physiological and cognitive states. While the effect of this technology will likely improve efficiency in our day-to-day lives and improve SA, the more significant impact is overcoming the societal stigma of self-modification (also known as "biohacking"). Since bio-hacking is becoming more mainstream, the USAF should now consider how to integrate bio-modified individuals into its ranks and if any restrictions are required based on the modification. Microchips are a reality for many individuals. However, because of an absence of testing and an understanding of the long-term effects, the opportunity is not in the near-term future for the USAF.

The second medium-term application for BCI-related technology is through formalized training using neuromodulation. Initial studies have indicated that targeted neuromodulation techniques like tDCS may not only produce slight improvements in multitasking abilities and memory performance but also may accelerate the learning process. As a service whose reliance on technology is embodied through the flight of aircraft, the USAF spends a significant portion of its budget training individuals to operate expensive weapon systems. Acceleration of the learning process should be of particular interest to the USAF and DOD to reduce the time required to train its service members. DARPA's TNT program is designed to achieve this challenge by investing in noninvasive technologies that boost the long-term retention of new cognitive skills. Dr. McClure-Begley states, "TNT technology would apply to a wide range of defense-relevant needs including foreign language learning, marksmanship, cryptography, target discrimination, and intelligence analysis, improving outcomes while reducing the cost and duration of the Defense Department's extensive training regimen."[42] Should this program yield its desired results, the implications will be significant with regards to education throughout the world. Beyond basic knowledge, neuromodulation technology integrated into pilot helmets is a possible and promising application by providing targeted and real-time electrical boosts to the brain for performance enhancement.

The third likely medium-term application of BCIs is the improvement of man-machine teaming through a combination of foveal tracking and brain monitoring. Jan Scheuermann demonstrated that the brain could be trained to control an F-35 in a simulator, which leads to the question of whether any robotic process automation (RPA) could be controlled with the mind. If so, is it more effective and efficient than previous hand-controlled methods? The Pentagon has a vision of a Soldier launching a drone on the battlefield and then using a BCI to control the drone in flight by feeding the drone's video feed directly into the optic nerve of the Soldier.[43] This vision for the future of the battlefield is likely at the far end of the medium-term as an interface with the optic nerve is still in its infancy. However, the control of a drone using noninvasive methods is within the realm of the next 20 years. After the USAF proves that fundamental man-machine teaming leads to increased efficiency like primary target designation using a noninvasive EEG cap, it should focus on exploring what other tasks could be accomplished using the same interface. Improvements could be in the form of control of a loyal wingman or RPA, new forms of communication, or ways of improving the efficiency of interaction between man and machine.

The incorporation of invasive BCIs into animals for defense purposes is another medium-term possibility. Medical testing on animals has long been the preferred method by the Food and Drug Administration (FDA) before any product goes forward to human trials. This applies to pharmaceuticals as well as medical devices like BCIs, for which the FDA has well-established processes for approval. BCI researchers are finding that some animal brains are much simpler to integrate BCIs into and allow for control of the animal or direct implantation of knowledge. In 2017, Draper Labs was able to control a dragonfly inflight using a BCI.[44] The dragonfly was genetically modified to accept optical commands from a BCI. This advancement is significant and differs from the commercially available remote-controlled cockroaches, which involves the spoofing of its antennae.[45]

Additionally, scientists have been able to locate specific memory locations in mice brains and encode them with false memories, which allows them to navigate a maze without prior knowledge.[46] These advances open a range of possibilities for increasing the use of animals in the military. Military applications include payload delivery, like the attempts during WWII to utilize pigeons and bats to deliver munitions, conduct reconnaissance and search and rescue, and detect explosives.[47]

The medium-term use of BCIs is likely to be informed and guided by the USAF's initial efforts to integrate noninvasive technologies into high-workload career fields. These initial efforts will help determine if invasive biosensors and microchips will be value-added for military applications. The incorporation of neuromodulation techniques, like tDCS, will help determine if the USAF should start including this technology into its formal training courses. The success of foveal tracking and noninvasive EEG caps in aircraft will lead to incremental improvements in man-machine teaming. Finally, the testing of BCIs in animals will likely lead to a variety of military applications.

Long Term, 20+ Years

The long-term implications of BCI-related technology are difficult to forecast because of the speed at which this field is advancing. Additionally, this technology is likely to be aided by other technological convergences in AI, big data analytics, nanotechnology, genetic modification, and 3-D printing. These fields also fall on the spectrum of exponentially advancing technologies, which means that BCIs are likely to evolve in multiple unpredictable directions. Given this fact, the only useful information that can be offered is that research efforts may overcome some of the major challenges presented above. For example, advances in nanotechnology and 3-D printing will lead to incremental improvements in microelectronic machine systems and sensors that will aid in engineering challenges. Advances in AI and big data analytics will help improve our ability to decode intent, which will improve man-machine teaming. Advances in gene manipulation will help with the biocompatibility problem. One particular field of genetic modification worth additional discussion that may enable some of the scenarios envisioned by Hollywood films is optogenetics.

Optogenetics is a field of study that enables brain cells to respond not just to electrical impulses but also to flashes of light from a fiber-optic cable. The idea for optogenetics originated from a 2005 paper written by Dr. Karl Deisseroth at Stanford University and has significantly advanced since then with support from the BRAIN initiative. It has been called "one of the most momentous developments in brain science in the past 160 years."[48] The process is extremely technical and involves the genetic modification of an individual's neurons to express various proteins when exposed to light.[49] The important implication is this field may overcome some of the significant challenges associated with electric BCIs. First, optical signals are less likely to be affected by the encapsulation problem that degrades electrical signals. Second, electrodes sometimes unintentionally activate the surrounding neurons of the target. Fiber-optic cables may have the ability to activate single neurons with a high-spatial and temporal resolution, a key to unlocking secrets the human brain still hides.

While optogenetics as a field is still in its infancy, it may lead to a chronic, implantable BCI that is both safe and efficient. It may allow individuals to fly an aircraft by just thinking of being in the cockpit or even remotely. Using this interface coupled with a decoder of the brain's intent, the pilot could direct loyal wingman or drones. A networked BCI may be able to directly interface with various parts of the brain to produce sensor overlays on the individual's visual field, enhance memory, control pain or emotions, or wirelessly transmit information to another individual. Targeted stimulation of various areas of the brain may also boost learning or physical capabilities. BCI and related technology are pushing humanity closer to the philosophy of Transhumanism, which seeks to enhance human intellect and physiology through the use of technology.[50] This philosophy may lead to a new definition of what it means to be human. These fundamental changes and impacts should be addressed through careful consideration of the ELSI concerns for each new technology. Within the military realm, the USAF and DOD should be the first to set the standards for the acceptable use of this technology and then apply those standards through international agreements. This will only be accomplished if we lead in the development and testing of BCIs.

Recommendations and Conclusion

> *How does one deal with technologies that merely enhance human performance, intellect, immunity, or capacity? While they provide distinct advantage, they do not necessarily present the kind of immediate threat of earlier weapons. Thus these will be more difficult to identify, control, restrict, and prevent.*
>
> —W. Michael Guillot
> "Emerging Technology," *Strategic Studies Quarterly*

Recommendations

Increasing the amount of experimentation conducted in this field will help determine the most likely direction and applications of the technology, while also allowing the US to set the standards for acceptable use. This increased experimentation will hopefully include a cultural shift within the USAF for increased risk-taking as recommended by the 2018 *NDS*. Three recommendations are made on how the USAF can get its foot in the door regarding BCIs. These recommendations are:

- **Integrate wearable biosensors** for pilots in the cockpit or for high-workload career fields. These biosensors may improve safety and increase SA by providing feedback on the individual's physiological and cognitive states.

- **Begin testing neuromodulation techniques** like tDCS in real-world scenarios to improve multitasking performance and memory. Additionally, the USAF should investigate the prospects of accelerated learning when studying the long-term effects of neuromodulation.
- **Increase investment of man-machine teaming** studies, like foveal tracking algorithms and noninvasive EEG sensors, by integrating into pilot helmets to reduce workload and improve efficiency.

The 711th Human Performance Wing (HPW) at Wright-Patterson AFB, Ohio, in conjunction with the Air Force Test Center (AFTC) at Edwards AFB, California, should be the primary organizations responsible for these recommendations. The 711 HPW has the expertise required to ensure testing efforts are planned with a high standard of clinical rigor, the test subject's rights are protected, and tests meet USAF military utility. The AFTC has the expertise to ensure technologies meet technical adequacy and military utility and are conducted with a high degree of safety. These BCI-related technologies are available today and have already been tested in a limited fashion by the USAF. It is time to move these technologies outside the lab into controlled real-world environments. Accomplishing these efforts will help the USAF address policy implications early, ultimately preventing large shocks to the system.

Conclusion

A Black Swan is an unpredictable event with extreme consequences. In contrast, a Gray Rhino is a "highly probable, high-impact threat: something we ought to see coming."[51] A Gray Rhino could take the form of an extreme weather event, climate change, the 2008 housing bubble, the collapse of the Soviet Union, or new disruptive technologies. These events often have clear warning signs or visible evidence that indicates change may happen. Michele Wucker, the author of *The Gray Rhino*, describes a specific type as "unidentified . . . as one that contains uncertainty over the nature of the danger and/or the situation." These Gray Rhinos are typically technologies that have the potential for explosive growth with unknown consequences. She recommends testing various scenarios in hopes of identifying the most likely result and remaining alert and flexible as sometimes technologies may not be what they seem to be.

This paper explored the convergence of biotechnology and cyber technology, which is in the form of an unidentified Gray Rhino. Addressing this Gray Rhino requires continued investment and experimentation in the neuroscience field. Leading in advancement will ensure that the DOD maintains its war-fighting advantage, assuming that this technology will bring about the enhancements it promises. Additionally, leading will also guide the technology on the international stage by closely integrating ELSI experts during development. The US should keep its research open and continually engage with the international community to ensure that technology complies with international ethical, legal, and societal norms.

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. Shih, Krusienski, and Wolpaw, "Brain Computer Interfaces in Medicine," 268.
2. Merriam-Webster Collegiate Dictionary, "Neuron."
3. Experts-Exchange, "Processing Power Compared."
4. National Human Genome Research Institute, "Human Genome Project."
5. Lewis, "Human Genome Project."
6. Mak and Wolpaw, "Brain-Computer Interfaces," 187–199.
7. Fischer, "A Guide to US Military Casualty Statistics," 1–6.
8. Defense Advanced Research Projects Agency (DARPA) Public Affairs, "Progress Human Memory Prosthesis."
9. Sanchez, "Systems-Based Neurotechnology for Emerging Therapies (SUBNETS)."
10. Sanchez, "Revolutionizing Prosthetics."
11. Stockton, "Woman Controls a Fighter Jet Using Her Mind."
12. Cetta and Pelley, "60 Minutes-Breakthrough: Robotic," CBS News.
13. Gohd, "Florida Man Lives with Robotic Arm."
14. Metz, "Facebook's Race to Link Your Brain to a Computer."
15. Metz, "Elon Musk Computerize Your Brain."
16. Richardson, "Race to Hack the Human Brain."
17. Draper, "A Tiny Neural Implant" and "DragonflEye Has Liftoff."
18. Office of the White House Press Secretary, "BRAIN Initiative."
19. DARPA Public Affairs, "Biological Technologies Office."
20. Gieson, "Electrical Prescriptions (ElectRx)." ElectRx is a DARPA program designed to "exploit and supplement the body's natural ability to quickly and effectively heal itself, intervening when required to correct or bolster nervous system activity." This program may lead to rapid, in the field "treatments for pain, general inflammation, post-traumatic stress, severe anxiety, and trauma." McClure-Begley, "Targeted Neuroplasticity Training (TNT)." TNT is a DARPA program that "supports improved, accelerated training of military personnel in multifaceted and complex task. The program is investigating the use of noninvasive neurotechnology in combination with training to boost the neurochemical signaling in the brain that mediates neural plas-

ticity and facilitates long-term retention of new cognitive skills." Sanchez, "Neuro Function, Activity, Structure, and Technology (Neuro-FAST)." Neuro-FAST is a DARPA program that applies a multidisciplinary approach that combines data processing, mathematical modeling, and novel optical interfaces, the program seeks to open new pathways for understanding and treating brain injury, enable unprecedented visualization and decoding of brain activity, and build sophisticated tools for communicating with the brain. Sanchez, Restoring Active Memory (RAM). RAM is a DARPA program, which aims to mitigate the effects of traumatic brain injury (TBI) in military Service members by developing neurotechnologies to facilitate memory formation and recall in the injured brain. RAM-Replay is a companion program to RAM, with the goal of developing new closed-loop, non-invasive systems that leverage the role of neural replay in the formation and recall of memory to help individuals better remember specific episodic events and learned skills.

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22. Haridy, "DARPA Backs 6 Brain-Computer Interface Projects."

23. Department of Defense, "National Defense Strategy for the US," 7.

24. McLoughlin, Brain-Machine Interface–Realm of the Possible, 17.

25. Mastin, "Human Memory: What It Is, How It Works, and How It Can Go Wrong." In current publications, there is a large disparity concerning the number of neurons contained within the brain and the number of connections that each neuron typically has. Most agree that the human brain contains between 80-100 billion neurons with many indicating that 86 billion is the typical average. The number of connections per neuron is widely varied depending on the location in the brain and the age of the person. On the low end, some estimate 1,000 per neuron while others estimate up to 40,000 possible connections. Most research has settled on around 10,000 connections per neuron, which leads to the widely quoted total of 1,000 trillion synaptic connections within the brain.

26. Epstein, "The Empty Brain."

27. Polikov, Tresco, and Reichart, "Response of Brain Tissue," 7.

28. Morais, Papadimitrakopoulos, and Burgess, "Biomaterials/Tissue Interactions," 188–196.

29. Schalk, "Can Electrocorticography (ECoG)," 1–9.

30. Banks, "What Is Brain Plasticity and Why Is It So Important."

31. National Human Genome Research Institute, "The Ethical, Legal, Social Implications (ELSI) Research Program." The ELSI Research Program focused on several

possible consequences of genomic research: (1) privacy and fairness in the use of genetic information, including the potential for genetic discrimination in employment and insurance; (2) the integration of new genetic technologies, such as genetic testing, into the practice of clinical medicine; (3) ethical issues surrounding the design and conduct of genetic research with people, including the process of informed consent; and (4) the education of healthcare professionals, policy makers, students, and the public about genetics and the complex issues that result from genetic research.

32. McClure-Begley, "Targeted Neuroplasticity Training (TNT)."

33. USAF Fact Sheet, "Review Board."

34. Department of Defense, "National Defense Strategy for the US," 7.

35. Fritts, "Project HAVE HOPE," v.

36. Losey, "Report: Thunderbirds Pilot Killed in Crash."

37. International Neuromodulation Society, "About Neuromodulation."

38. The Brain Stimulator, Inc., "tDCS FAQ's."

39. Halo Neuroscience, Inc., "Neuroscience Explained."

40. Nelson, McKinley, Phillips, McIntire, Goodyear, Kreiner, and Monforton, "The Effects of Transcranial Direct Current Stimulation (tDCS)."

41. Savage, "Microchips."

42. McClure-Begley, Targeted Neuroplasticity Training (TNT).

43. Axe, "Pentagon's Wild Plan for Mind-Controlled Drones."

44. Ackerman, "Cyborg DragonflEYE Takes Flight."

45. Condliffe, "Cyborg Cockroach's Nervous System."

46. Noonan, "Implanted a False Memory into a Mouse."

47. Mizokami, "That Time the US Tried to Steer Bombs with Pigeons."

48. Colapinto, "Lighting the Brain."

49. Adams, "Keio Prize in Medicine."

50. Bostrom, "A History of Transhumanist Thought."

51. Wucker, *The Gray Rhino*, 18.

Abbreviations

%HRR	percentage heart rate reserve
ABM	air battle manager
AFRL	Air Force Research Laboratory
AFTC	Air Force Test Center
ECoG	electrocorticographic
ELSI	ethical, legal, and social implications
FDA	Food and Drug Administration
GLOC	G-induced loss of consciousness
HPW	Human Performance Wing
MWS	major weapon system
NDS	National Defense Strategy
NESD	Neural Engineering System Design
PTSD	post-traumatic stress disorder
RPA	robotic process automation
SA	situational awareness

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