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THE SHAPE OF THINGS TO COME: THE MILITARY BENEFITS OF THE BRAIN-COMPUTER INTERFACE IN 2040

by

Patrick A. Cutter, Major, USAF, MT(ASCP)
MSc, Clinical Laboratory Science

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Advisors: Major Reid J. Wynans and Major Thomas E. Kiesling

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Abstract

By 2040, advanced brain-computer interfaces (BCIs) will provide the American warfighter with remarkable advantages. As the role of robots and incredibly advanced computer systems permeate throughout the military infrastructure, BCI will provide the means to realize maximum performance from human-computer collaboration enhancing both human and software performance; providing the needed ability to solve and adapt to growing battlespace complexities. Current BCI technology already demonstrates the ability to directly interpret and influence neural activity related to sensory information, as well as the intention to perform motor functions, human cognitive ability, and physiological regulation. Based upon a conservative projection of technological advancement, the impact of portable BCI technology in 2040 will have significant military benefits to include: heightened situational awareness, enhanced autonomous system management, human cognitive enhancement beyond natural abilities, synthetic telepathy, augmented reality/response, improved training techniques and reduced casualty rates with improved medical outcomes. It will be the bidirectional type of BCI, providing two-way communication and influence between brain and computer, which will open the full potential to exploit the powerful communicative and human-machine performance boosting opportunities offered by this technology. The Department of Defense should capitalize on this emerging technology. It should specifically foster the development of bidirectional BCI and pursue the technological or non-technologic means to increase human sensitivity to BCI methods.

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Introduction

By 2040, advanced brain-computer interfaces (BCIs) will provide the American warfighter with remarkable advantages. BCIs allow for direct neural communication between machine and brain bypassing both the peripheral nervous system and sensory organs. Soon, this technology will reach well beyond rehabilitative medical use and provide significant human and machine enhancement opportunities. Current brain interface technology has already demonstrated the ability to read and interpret sensory information, the 'inner voice', and the intention to perform motor functions. Remarkably, this same technology has been used to artificially stimulate neurons to convey sensory information, control motor functions, improve cognitive ability and enable rudimentary brain to brain communication.

Advancements in materials technology, computer processing and neuroscience will accelerate the development of safe, practical and robust BCI capability. Bidirectional interfaces with the ability to influence specific neural groups will not only revolutionize health-care, but transform how the average individual interacts with others and their networked environment. This will revolutionize communication. Business forecasts indicate that the first commercially available Apple or Google thought controlled messaging devices will be on the market within 10 years and that the brain-computer style interface could become the most common computer interface by the early 2030s.[1] As with any game-changing communication technological innovation, direct brain to computer interaction will be commercially profitable and its presence will spread rapidly throughout the global marketplace.

The 'genie is out of the bottle'. No one military will have a monopoly on BCI technology. BCI research is prevalent throughout the European Union, Asia and the United States at over 30 major research centers.[2] Last year, it was a multinational research team that achieved BCI facilitated direct brain-to-brain communication between two humans.[3] Counter BCI technology proliferation would be extremely difficult and impractical.

The focus of this paper is the potential transformative influence that this advanced BCI technology will have on the Department of Defense and its ability to prepare for and fight in conflicts twenty-five years from now. The forecasts for BCI capability in 2040 are based upon proven and published results available in 2015 and a conservative projection of technological advancement in associated computer and materials technology. *These trends indicate that BCIs will further enhance human-computer collaboration allowing for a more encompassing approach to enhanced human operator and computer performance, sensor fusion, data transfer, plus more efficient autonomous system management. The militaries that explore methods to develop and embrace robust BCI will gain significant advantages over those who do not.*

Human-Computer Collaboration – Why Is It Important?

In 2040, warfare will be much more complex than it is today. Regional powers will continue to adopt improved and novel warfighting technology in an attempt to counter and deny US military power projection.[4] Strengthening near-peers are striving to close existing technological gaps. As the US suffers from budgetary restraints adversely affecting military technological and scientific development, these rising nations will continue to increase their own research investments and will enjoy a corresponding surge of active scientists and engineers within their own defense establishments.[5] As the playing field is leveled, the nation best able to adapt to this complex environment and overwhelm their adversaries' capability to do so will be better equipped to achieve their own military goals. Human-computer collaboration offers a means to expand American ability to manage that complexity.

Brain to computer interfacing will be a powerful component in strengthening Department of Defense human-computer systems, boosting the ability for human-machine teams to deal with increasingly complicated defense problems. An example of human-computer cooperation achieving performance levels surpassing the abilities of both the human and computer components can be seen with software aided Advanced Chess. Sometimes known as Freestyle Chess, this game variant is one in which human players are encouraged to use computer assistance during the course of the match.[6] Typically, the humans are not 'grandmaster' level players and the computers are of typical commercial laptop quality. The famous Russian grandmaster Garry Kasparov has sponsored Advanced Chess tournaments with interesting results; the average players with their average computers were consistently winning against unassisted high level players.[7] Even more astonishingly, the computer-assisted 'average' players were even successful against very powerful and expensive computer systems.[8]

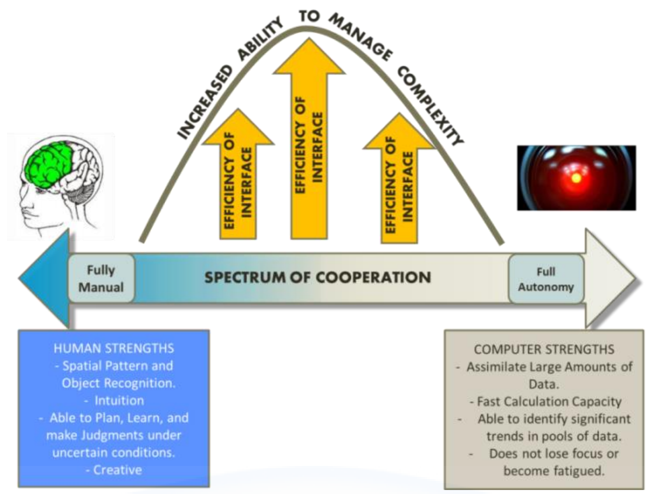
Recent software-assisted sonar-based object identification studies demonstrate another example of synergistic human-computer collaboration. In one study, conducted by NATO's Science and Technology Organization, human-computer system teams together analyzed large amounts of sonar data. Through man-machine cooperation, the rate of data analysis occurred at a much greater rate and vastly diminished the misidentification of undersea anomalies which plagued autonomous object identification. The study concluded "it has been experimentally demonstrated that fusing the skill of a human (or multiple humans) and computers can significantly improve performance beyond that which is achievable with one type of operator."[9]

Human-computer collaboration has also met success in the field of molecular biology. FOLDIT, a protein modeling program, works in tandem with human operators to determine the functional structure of difficult to model proteins. Computers provide the enormous computational power to calculate the interactions amongst the differing components of the molecule while the human intuitively manipulates the 3D-digital model into what they see as a good 'fit'.[10] The teams are able to solve such complex research endeavors in a matter of days or weeks; compared to the potential years that it would take a sole mainframe computer to solve such challenges. In some instances, the FOLDIT human-computer team was able to determine protein structures so complex they were absolutely unsolvable with current computer technology.[11]

It is the greatly different abilities of the human and computer that make these teams successful. The brain's ability to process computational data is dwarfed by a relatively simple computer. The human may be superior at several forms of spatial and object recognition; but for rapid and complex computational power, the human is no match to software. Our brains, billions of networked neurons, are more suited to conducting a myriad of crucial parallel functions simultaneously. The human brain regulates thousands of critical body functions, receives sensory input, translates that input, and directs our interaction within the environment. It also remembers these interactions and learns from them. The brain holds the difficult to define human consciousness and builds our internal 'world-view' in which we build assumptions that we base our behavior upon. Intuition and creativity are powerful and important qualities that human beings bring to the team. Both characteristics are impossible to mimic on a computer system today and may be just as difficult even in 2040.

The human-computer cooperation relationship demonstrates an increased ability to deal with complexity, allowing for an overall greater level of potential human and software performance. The efficiency of the interface is a significant factor influencing the potential advantage which can be extracted from that relationship. *In 2040, the most efficient method to* *realize maximum performance from human-computer teams could be the brain-computer interface.*

Figure 1. Human-Machine Cooperation Spectrum - Increased Ability to Manage Complexity.



<u>Overview of Brain Computer Interface (BCI) Technology</u>

A BCI device is simply a direct artificial conduit allowing for the transfer of information or stimulation between a brain and computer. It allows nearly seamless interaction. The core of the concept involves software translating and or manipulating neural activity. The neural signals or lack thereof can be implemented as program input. As with any type of input, say a command typed from a keyboard, software translated brain activity could be encoded to be utilized in any intended manner; whether it is stored, transmitted, and or used as an input or trigger for yet other programs.

Practical and successful BCI implementation traces back to 1973 with a National Science Foundation grant to the University of California Los Angeles to investigate the feasibility of detecting discrete electrical potentials within the human brain using an electroencephalograph. The study determined that impulses from the brain could be used as program input. The project lead, Dr. Jacques Vidal, posed the question back then “Can these observable 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?"[12] Four decades later, in regard to prosthetic devices, we can answer his question with a resounding 'yes'. Since then, prolific study has provided a better understanding of brain function and the basis of cognitive neural communication. Improved neurological mapping has revealed not only the intricate structures of the human brain, but the relationships and influences between cerebral neural groups. Endeavors such as the National Institutes of Health's Human Connectome Project are currently charting the complex connections amongst the eighty-three cortical regions of the brain.[13]

BCI devices can be categorized into three differing types; those that possess only the ability to detect and translate brain activity, devices that solely provide stimulation to the brain, and bidirectional BCIs which have the capability to both read and stimulate neural activity. *Unidirectional BCIs are useful; however, it is the bidirectional device that opens the potential for the Department of Defense to fully realize and exploit powerful communicative and human-machine performance-boosting opportunities.*

Currently, several non-invasive and invasive methods to perform 'brain' reading and stimulation exist; each with their own distinct limitations and advantages. The greatest attainment of high signal quality and precise neuronal stimulation has been through animal studies involving surgery; building a physical direct connection between neural tissue and the computer to directly read neural signaling and generate deep brain stimulation.[14] Such drastic invasive techniques are wholly inappropriate for human application and are not considered in this paper. Suitable, and safer, non-invasive techniques are available and have proven capability despite potential signal diffusion effects caused by the centimeters of skull and tissue transmitted through.[15]

Detecting and Measuring Neural Activity

One non-invasive method, Electroencephalography (EEG), is the most common and inexpensive means of measuring brain activity. EEG measures the average postsynaptic voltage variations amongst synchronized neuron groups through sensors, sensitive electrodes, attached to the subject's head.[16] EEG precision is dependent on the number of electrodes used in the measuring process. Currently, EEG is limited to detecting brain waves associated with the most superficial regions of cerebral tissue.[17]

As a health-care tool, EEG is used to assess comprehensive brain function; determining the effectiveness of anesthetics, pinpointing the brain region source of seizure, and ascertaining brain death.[18] However, it has certain constraints that make it a relatively imprecise BCI method. Besides the inability for EEG-devices to read most areas of the brain, there is a great amount of operator time investment to train on individual devices to achieve optimal results. Nonetheless, many of the early BCIs are based upon the EEG methodology due to low cost and ease of manufacture. The first commercially available BCIs are based on EEG technology. As of February 2015, EEG interfaces for personal computer use are available for purchase with a cost of less than $500.00 per unit (Figure 2).[19]

Figure 2. A commercially available EEG-type unidirectional BCI. Image source: Emotiv. "Emotiv EEG Systems: Introducing New Epoc+." http://emotiv.com/.

Another method of brain neuron impulse detection is through a means known as functional magnetic resonance imaging (fMRI). The fMRI technique uses high strength magnetic fields to indirectly detect regions of neuron group activation by measuring changes in proximate blood flow using a method referred to as blood-oxygen-level contrast (BOLD).[20, 21] The hemodynamic responses are an indication of increased demand of glucose and oxygen requirements in nearby cerebral tissue. This non-invasive method is precise since signal resolution is not impaired by intact skull or tissue.[22] The fMRI/BOLD process is a safe and approved medical procedure.[23] Short or long term adverse effects have not been reported in both human and animal studies.

One key disadvantage to fMRI/BOLD is that since the basis of measurement is the indirect detection of blood flow, a lag exists between initial neural activity and the detection of the hemodynamic response. This time period can sometimes be measured in seconds.[24] To mitigate this drawback, the fMRI method is sometimes recommended to be used in conjunction with other methods when speed is desired. Practical fMRI/BOLD BCI use is also limited due to the size of the required equipment. A majority of MRI-capable devices are immobile and require a considerable amount of power. These devices are designed with the primary intent of whole body imaging for ascertaining medical diagnoses. However, it is not unreasonable to conclude that a portable brain reading fMRI apparatus could be constructed within the next 25 years. Recently, hand-held fMRI hand-held battery-powered analytic devices have been developed and used, on a small scale, for the examination of Antarctic ice cores.[25]

One non-invasive brain 'reading' method, magnetoencephalography (MEG), directly measures neural activity. MEG-capable devices detect the minute magnetic fields produced by electrical currents passing through distinctive neuron groups. In one aspect, this methodology is superior to fMRI/BOLD due to its ability to identify neural stimulation within a few milliseconds of initial activity.[26] For reference, this is faster than the typical human reaction time, which can be measured in the hundreds of milliseconds.[27] As with fMRI, MEG is proven safe; it is a medically acceptable method for delicate procedures such as measuring fetal and infant cerebral development.[28] As with fMRI capable-devices, MEG equipment is also large and bulky. Additionally, as with research-level fMRI devices, smaller and portable MEG device construction is feasible; though the design needs to include significant shielding to address the extreme sensitivity the MEG method has to ambient electrical and magnetic interference.[29]

Influencing Neural Activity

Transcranial magnetic stimulation (TMS) is a medically approved method for influencing neural regions by activating or deactivating neurons through electromagnetic induction. This is accomplished by an electrical coil, situated close to the head, discharging targeted fields of magnetic flux into regions up to 6 cm deep into the brain.[30] The limitation to this technique is the range and strength of the magnetic flux. Applied TMS is approved by the US Food and Drug Administration (FDA) for the treatment of migraines and those forms of depression disorders in which drug-therapy has proven to be ineffective.[31] Though extremely rare, repetitive TMS has been implicated in causing seizures and TMS candidates are required to be screened for family history plus any physical indicators suggesting a high propensity to epileptic episodes.[32]

In research, TMS has been effective at generating artificial sensory responses bypassing the peripheral nervous system altogether.[33] It has even been effective in transmitting sensory information into the mind of patients suffering from conditions where sensory organs may be entirely lacking or nonfunctional. As long as the related sensory neural groups within the specific sensory cortex are undamaged, information can be conveyed into and processed by the individual's brain.[34]

TMS and fMRI can and have been used in tandem to both 'read' and stimulate neural groups. Used together, these two methods have been used to identify appropriate brain cell targets, stimulate the neurons to generate synthetically perceived sensory input, measure any resulting neural response, and then improve precision through retargeting if necessary.[35] Software modulation of controlled fMRI use and TMS bursts is effective in ensuring that these two magnetic processes do not interfere with each another.[36]

Very recent advances have been made in non-invasively using acoustic energy to precisely regulate neural activity; a method termed transcranial focused ultrasound (FUS). FUS can be applied at regular and frequent pulses at localized brain regions to generate very controlled and refined responses. The precision is at levels that FUS holds the potential to create very complex synthetic sensory stimulus. Besides stimulating the sensory cortices, FUS can elicit complex and involuntary motor responses through neural stimulation. In one FUS study, neural signals from one human brain was recorded and transmitted into another's to trigger motor responses. [37]

Advanced material technology will create the potential for the development of acceptable minimally-invasive brain interfacing methods. These are processes which may achieve the high signal strength and precision seen in the more severe invasive techniques, while avoiding unacceptable surgical exposure and manipulation of human brain tissue. In January 2015, a research group at the Massachusetts Institute of Technology published a study describing an innovative microscopically thin, flexible, multifunctional polymer fiber which may serve to be the basis of a highly effective bidirectional BCI device which could be emplaced without physically harming the surrounding tissue.[38] This microfiber is capable of concurrently stimulating neurons while serving as a sensitive detection device. It also holds the capability to deliver drugs to specific areas within the brain.

Looking ahead to 2040, improvements in nanotechnology may lead to the creation of even more advanced fibers or distributed nodes of wirelessly connected intra-cranially distributed networks that communicate with thousands of 'neural reading & stimulating' devices that could be safely inserted within a human brain. Such tiny apparatuses could conceivably be delivered through the subject's vascular system. Small glucose fuel cells powered by easily available nutrients have already been developed and could be used to power such devices.[39] If small enough, even the computers in which the interface is interacting with could be located or dispersed within the cranium. Such advances into enhanced and safe methods for creating brain-computer communication systems will greatly deepen the impact of BCI applications while also making them more robust, practical, and easily upgradeable.

BCI Capability & Research – 2015

What can be accomplished with BCI is already truly astounding. However it is a fairly young technology whose majority of use is in the health-care field due to the prohibitive cost of quality equipment for truly effective BCI. Besides its use as an analytical tool to assess brain injury, BCIs enhance a patient's quality of life. For example, the cochlear implant, developed in 1976, can be seen as an early type of simple BCI. The cochlear implant restores or improves hearing in the deaf or hearing impaired who possess intact auditory nerve architecture.[40] This achievement is made possible by stimulation-providing electrodes coiled around the cochlea.[41] These electrodes excite nerves within the tympanic duct transmitting stimulus to the primary auditory cortex located within the temporal lobe where it is processed just as if it was natural sound stimulus.

Bidirectional BCIs are also used for treating migraines and controlling seizures. In the case of seizure, the device detects the onset of an episode within the patient's brain and delivers stimulation to key areas disrupting the epileptogenic potential. Such treatment is highly effective with a 92-99% success rate.[42]

Stimulation of the visual cortex has been shown to produce artificial sensory stimulus of controlled shape and size in animal studies.[43] Artificial sight through BCI is still in the early research phase and will become more practical as technology allows for greater resolution. Interestingly enough, data can also be read from the visual cortex. In 2011, an interface reading the activity of 177 feline vision associated neurons was able to generate an image based on the stimulus that the animal's visual cortex was receiving from its own sensory organs (Figure 3).[44] Similar success has been achieved through non-invasive methods with humans at the Neuroscience Institute at the University of California. According to Nishimoto, "this modeling framework might also permit reconstruction of dynamic mental content such as continuous natural visual imagery."[45] Furthermore, the study explains that even imagined images or scenes, such as dreams or hallucinations, could be decoded through their BCI method.[46]

Figure 3. Comparison of true images (top) and images constructed from software-translated neural data from a feline visual cortex. Image source: http://news.bbc.co.uk/olmedia/470000/images/_471786_catimage1300.jpg.

BCIs have also read stimulus from the motor cortex and translated these signals into intended movement. Since the nineties, this technology has allowed patients suffering from 'locked-in' syndrome, a form of complete paralysis, to operate a computer cursor.[47] In the last decade, research into prosthetic thought-controlled hands has shown that these signals can be used to operate complex prosthetics with remarkable articulation.[48] Interestingly, in cases involving amputation, BCI-controlled prosthetics have shown to be a reasonable therapeutic approach to alleviate associated phantom-pain.[49] Stanford University is currently recruiting patients for an advanced study that will employ the wireless control of thought driven prosthetics.[50] Thought controlled locomotion via wheelchair has been demonstrated, however BCI driven walking proves to be difficult. Multiple projects in this area have shown that even small signal translation errors of intended movement over elevation transitions, such as steps, can cause unrecoverable disturbances in the prosthesis' and patient's stride.[51] There is much research in this field and several centers have even shown that it is possible to transmit haptic sensation to the brain and thereby possibly greatly increase the functionality of the prosthetic and the overall quality of the synthetic limb for the user.[52]

BCIs have also been used for controlling robots and other apparatuses besides prosthetics or medical rehabilitative devices. For example, several commercial companies have developed thought controlled aerial drones in which the movements of the machine are associated with the operator's intent to move their own limbs. In March 2015, a DARPA research team demonstrated that a quadriplegic could operate a simulated Joint Strike Fighter through thought alone.[53] BCI operated vehicles currently operate at a low level of performance and control as compared to the similar devices piloted through more conventional means; however, this capability continues to improve.[54]

Certain current capabilities seem to border on the realm of science fiction. One 2012 study, by the Neuroscience Program at Michigan State University, indicates that BCIs can be used to regain impaired or even damaged somatosensory and cognitive function.[55] A different project showed that primates working with a program through a BCI interface that targeted and stimulated the neurons associated with decision-making were still able to maintain adequate cognitive performance levels despite being under the influence of a strong narcotic.[56] Such studies open the door to potentially improving human cognitive abilities beyond natural performance.

Networked BCI also allow for direct messaging between brains, a form of computer assisted telepathy. Practical direct brain to brain communication currently exists at a simple 'morse-code' level. It has been demonstrated that a subject using a non-invasive BCI can transmit thought generated stimulus over the internet into a second BCI-using operator, where the data is translated into stimulus projected into that subject's visual cortex. In one experiment, the data was interpreted by the receiver as flashes of light within the peripheral vision. The first operator could control the transmissions and successfully sent messages to the second through this method.[57] Other civilian institutions have shown that not only intended speech, but covert speech or 'the inner voice', could also be detected by BCI, and be translated by software.[58] Other projects have been conducted to determine the possibility of ascertaining information such as passwords and PIN codes directly from the human brain.[59] The potential for this research is the development of the capability to transmit high quality complex data and ideas at a rapid rate and directly to the receiver's mind. Synthetic telepathy may prove to be a revolutionary step in communications well before 2040.

Experiments in direct brain-to-brain communication have also shown that stimulus for intended motor function can also be transmitted successfully. In one trial, two subjects cooperatively played a video game where one BCI operator observed the screen and the second in a different location operated the game controller. The first operator controlled the hand movements of the second in order to interact with the game, and achieved successful signal transmission-to-motor response levels of up to 83%.[60] Thought control over another's motor functions has also been shown to be able cross species. One experiment showed a 94% accuracy rate of transmitting a BCI-signal from a human brain to a rat in order to control the animal's tail movements.[61]

Even at this nascent stage, BCI research has demonstrated direct brain to brain communication, mind-controlled prosthetics, and vehicles controlled by thought. These capabilities are no longer fiction. In 2015, BCI studies pull the veil aside to show that human performance enhancement including heightened cognitive abilities is attainable. As the technology matures over the next twenty five years, militaries that vigorously explore these advantages and apply bidirectional BCI will yield significant operational advantages such as cognitive dominance, improved battlespace awareness, enhanced management of autonomous systems, and improved medical outcomes for the wounded.

BCI Capability – Some Assumptions in Looking Forward to 2040

Extrapolating trends in BCI capability over the next 25 years shows that the greatest benefits that this technology has to offer goes beyond just doing better what is capable today. The true advantages offered to the American warfighter will be seen in the integration of BCI technology to enhance human-computer systems. However, as with any type of prediction, certain assumptions must be made. For this analysis, I assume that advances within the following fields will occur: computer engineering, materials science, neurophysiology, psychology, network development and communications.

Please note that these predictions are not reliant upon the development of human-equivalent artificial computer intelligence. These forecasts are based upon the expectation that computer processing power will continue to grow at the same approximate pace, doubling every two years, that it has done for the last 50 years. This trend, known as Moore's Law, indicates that computer systems in 2040 will be considerably more capable than those existing today.[62]

I also make the assumption that subsequent BCI device models will be subsequently cheaper, smaller, and lighter while possessing stronger and safer brain reading and neural activation ability. These are based upon the hypothesis that there will be a commercial market for BCI enhancements that will drive continued research and development. Investigation into the potential adverse short and long term physical and mental effects will be conducted in order to make BCI safe. I am not suggesting that BCI enabled technology will be ubiquitous; however it will be relatively common and not considered a novelty. I posit that the children and teenagers of the 2030s will be familiar and comfortable with mind-interacting technology.

Another assumption is that continued research will be made concerning the ability of the human brain to adapt to this transformative communicative method and mode of enhancement. The plasticity of the brain is amazing. Neurons alter their structure to become more sensitive to new stimulus.[63] Repetitive stimulus fosters long-term neural changes and a resulting increase in available synapses. Frequent BCI use may structurally alter the operator's brain to become more sensitive to the interaction. Operators will gradually become better receivers and possess an enhanced ability to process information via interface. Studies have shown that animal brains adapt to the BCI and adjust to the additional neural stimulation brought on by the introduction of signals from exogenous sensory data and supernumerary prosthetic limbs.[64]

Learning the bounds of the brain's flexibility will most likely define the limitations of full BCI associated capabilities. Potentially, the DoD may find methods to enhance an operator's ability to exploit the full benefits of a BCI. For example, meditation may be a valuable component of BCI training programs. Several clinical studies have shown that this esoteric method enhances brain plasticity.[65]

Technology that has the potential to alter the informational state of the brain will generate ethical, legal and religious concerns. I am confident that some groups will consider bidirectional BCI capability as unethical and see it as an instrument that challenges the concept of self and the integrity of the human soul. Such discussions are beyond the scope of this paper. I assume that despite such deliberations, that in 2040 the Department of Defense will not be limited in employing safe BCI technology.

BCI Capability – Military Relevant Applications in 2040

For the purpose of this discussion, the predicted BCI capabilities will be categorized into the following four differing groups (Table 1).

Table 1. BCI types by function with relevant military application and corresponding operational significance.

Type	Function	Relevant Military Applications	Overall Operational Significance
Type 1	Interaction with Sensory Cortices	Shared sensory data. Human or other organism sensory data incorporated into sensor fusion. New senses and expansion of natural sensory perception beyond natural limits. Enhanced data management and ability to data-mine. Ability to record innate sensory data. Augmented reality applications. Enhanced operator training / computer system programming.	Heighten situational awareness. Provide advanced capacity to quickly resolve battlespace problems. Improve data and trend-analysis ability.

Type 2	Interaction with Motor Cortex	Enhanced autonomous system management/operation. Exoskeleton/supernumerary limb operation. Augmented response. Enhance operator's task performance and expand range of manual tasks that the operator may be considered competent to perform. Enhanced operator training / computer system programming.	Increase operator's scope of control in quality and quantity of systems. Reduce number of personnel required to achieve desired effects. Reduce casualty rates.
Type 3	Interaction with Cognition	Cognitive enhancement beyond natural ability. Synthetic Telepathy / Shared Consciousness Recover impaired cognitive ability and maintain operator's cognitive performance levels despite adverse conditions. Improved ability to allocate human or computer oversight (Scalable autonomy/consciousness). Communication of complex concepts such as operator's intent to autonomous system	Achieve Cognitive Dominance. Enhance communication.
Type 4	Interaction with Autonomous Nervous System plus Medical Intervention	Mimic physiological states typically associated with pharmaceuticals. Regulate awake-sleep states. Induce meditative cycles. Improve operator's sensitivity to BCI methods. Monitoring operator's medical condition. Neural tissue sustainment / improved medical outcomes.	Extend operator peak performance time. Maintain operator's performance levels despite adverse conditions. Improve casualty medical outcomes.

<u>Type 1 – Interaction with Sensory Cortices:</u>

Type 1 BCI capability will offer the ability to increase a human-computer system's situational awareness giving an improved ability to react and adapt to a quickly changing environment. Furthermore, the power to directly read and influence the sensory cortex offers sensory data for future analysis and offers a way to perform that analysis.

In twenty-five years, advanced portable Type 1 BCI capability offers a new element to sensor fusion where shared sensory data from humans or other organisms may be part of a computer sensor system. Visual and auditory data from multiple warfighters could be integrated and compiled to create a more holistic real-time picture of the environment. Bidirectional capability may also provide the option to project data into the mind's eye of a combatant, such as a pilot. This may convey knowledge of what the software and linked humans believe to be important within the surroundings. Extreme situational awareness at this level could possibly enhance human-computer team ability to execute complex battlefield interactions such as close air support (CAS) conducted by humans or semi-autonomous robotic wingmen.

Sensory data from animals with natural ability beyond humans could be accessed and prove to be significant in the warzone. For example, olfactory data retrieved from the brain of a trained canine could not only prove to be a powerful chemical sensing system but could be integrated with software that can refer to a database and translate the canine sensory stimulus into actual chemical identification. This animal-computer system could potentially bolster base chemical defense through the capability to detect substances at extremely low densities since the BCI may be able to read sensory stimulus that is at sufficient levels to trigger a response in a few neural groups, but not at the level necessary to actually trigger the animal's awareness to the chemical's presence.

Humans may obtain new or modified sense data that is beyond their own natural ability through BCI. Potentially, personnel could be trained to interpret radar or sonar fed directly into a sensory cortex. This technique may also be used to allow an operator an innate 'sense' of elements or interactions within cyberspace. As shown with the current research, the scope of these new senses could be vast. Potentially a drone operator could be trained to be able to have sensory data of multiple craft fed into their brain, interpret it, and use that information to effectively guide a swarm. Visual data from sensors mounted on an aircraft could provide the pilot with a real-time complete 360 degree spherical view of the plane's environment in his or her 'mind's eye', providing the user with omni-directional sight.

A benefit of integrated natural sensory data is that it could be recorded. Such data could possible by reviewed later by a human-computer team. Potentially, a BCI-coupled analyst may benefit from the natural intuition of the human and the powerful linear computational power of the computer to ascertain what the significant factors or trends are within the data-pile.

Another method in which Type 1 BCI could provide increased situational awareness for the warfighter could be seen with a form of augmented reality. Just as Google Glasses can provide a form of mediated reality by showing icons or text within its display in order to convey information regarding items within the user's vision, a BCI device could perform the same effect. The computer interfacing with the human can gain the advantage that it could possibly use data provided by the human's brain to identify objects and people within the operator's sight. The computer may also be able to identify a threat, even at the periphery of vision, that is not noticed by the user and bring the user's attention to it through a visual cue.

Furthermore, a BCI-based augmented reality application can be used to guide the user through processes such as equipment operation or repair. Medics in the field could be provided with possible visual and auditory cues giving guidance on performing complex medical procedures. This method could also enhance training in several fields by providing those sensory clues to the operator and recording their responses for assessment.

Type 2 – Interaction with Motor Cortex

Advanced Type 2 BCI's will have a powerful impact on the quality and amount of tasks that the individual operator can perform. Augmented operator response could potentially have a greater impact on the battlefield than augmented reality. At the operational level, this may translate into requiring a smaller footprint in an area to achieve the same level of desired effect.

Type 2 BCI will permit the human motor cortex to be influenced by software that modifies or enhances the operator's physical response; allowing the operator to achieve results greater than the human operator's natural ability. This type of human-machine collaboration has roots in robotic-assisted surgery. One present day medical marvel, the DaVinci robotic surgical system, uses mixed autonomy to perform computer-assisted invasive surgical procedures.[66] While the surgeon is guiding the robot's surgical instruments manually, the computer system improves the human's performance by factoring out natural hand tremors from the surgeon's input. The system also does not allow the human to make certain mistakes.[67]

Just as a Type 1 BCI offers augmented reality, Type 2 could provide augmented response. Employing both this Type 1 sensory capability with a Type 2 motor cortex stimulating process, the computer intelligence or second user operating via telepresence, could help assist in the procedure by guiding the receiver's hand motions. Likewise, if the human-computer system perceives a potential threat the BCI may also help to enhance reaction time by stimulating reflexes through the motor cortex. With a precise BCI, the software could use the human's limbs to manipulate tools and perform tasks. Essentially, the operator-computer team could complete tasks that the software was familiar with but the operator was not.

In this manner the Type 2 BCI could also prove to be a valuable training tool; interacting with the neuron's associated with the task function in order to enhance the operator's ability to perform the task enhancing the development of muscle memory. Furthermore, motor cortex stimulus from an individual adept at wanted skills could be recorded and transmitted via BCI to activate the neural pathways of a trainee in order to stimulate similar neural pathway growth.

One clear use of BCI technology is to control the operation of devices or vehicles such as unmanned drones, artificial limbs, or even overlying exoskeleton apparatuses by translating the intent of movement stimulus from an operator's brain through a Type 2 interface. For a vehicle in which the BCI-user is occupying, there is probably no practical benefit to operating the vehicle with a BCI over conventional means. The brain to computer interface could better serve as an effective method for directing autonomous devices, such as an unmanned vehicle, instead. Through the ability to enhance operator information management ability and streamline the human-decision making-response time, BCI could serve as a means to allow an operator to effectively manage multiple craft; whereas routine operations of the craft may be handled autonomously by online software itself.

The Type 2 BCI interface may be an effective manner to instruct, i.e. program, computer systems in the 2040's. One proposed innovative method for programming automated systems is to teach the robot practically in the same fashion as you would train a human; you show it what you want it to do. Teaching by demonstration has been sought after as a means to program manufacturing robots without hand-typing massive lines of code.[68] The program or instruction through this method may be of higher quality if the device can see the actual movements of the programmer and also receive data from the human's brain on the intended movement. During this programming or teaching process, automated systems could gain a greater inventory of identified objects from human trainers through a Type 3 (cognitive) interface. There may be a time in the near future in which the keyboard based computer programming field emerges into a career field that can be more aptly seen as a teacher of machine-intelligence.

Type 3 – Interaction with Cognition

The U.S. Army's 2014 *The Human Dimension White Paper* suggests that future cerebral enhancements of personnel could lead to a cognitive advantage or dominance over our adversaries.[69] Significant cognitive enhancement through Type 3 BCI could boost the ability of tactical warfighters, operational planners, and strategic thinkers having impact across the full spectrum of preparing for and conducting war. Technical cognitive augmentation would provide future commanders and operators with methods to adapt quickly to complex battlespace conditions and develop the needed suitable solutions to complex problems.

One Air Force Research Laboratory (AFRL) 2007 proposal suggests that TMS can "enhance speed and accuracy of decision-making" and that the "operator's mental abilities may be expanded and become less of a limiting factor." The report proposed that applied BCI primes the neurons associated with cognitive abilities and enhances their function. Within it, Dr. Jeremy Nelson states that this technology offers a method to improve operator learning and memory.[70] He predicts that BCIs will be able to produce savant-like qualities; greatly improving human information processing ability. The report also suggests that TMS can aid the user in maintaining adequate performance levels while sleep deprived and improve their awareness levels.[71]

A shared consciousness linked through multiple networked BCIs would allow for the rapid transfer of complex concepts between planners or problem-solvers. This would be an advanced form of the synthetic telepathy allowing for direct knowledge sharing and linkages between the decision-making areas of multiple individuals. Situations or problems could possibly be solved with a greater understanding of all aspects of the problem(s) as seen through the lens of multiple personnel. This level of integration seems far-fetched, yet brain-networks such as these are predicted to be available within the next two decades.[72]

This level of integration could also allow for human intervention or awareness could scaled into unmanned vehicle operation depending on the system's demands or needs based on the complexity of the environment that it is facing. The BCI-linked human operator could also decide which system functions could be placed under human supervision and those that can be allocated to autonomous control. Once again, the DaVinci robotic surgical system demonstrates an example of shared and scalable human-computer control; where during the course of an invasive surgical operation, certain procedures such as suturing can be allocated to the robot's software and performed autonomously while the surgeon focuses on other aspects of the operation.[73]

Type 4 – Interaction with Autonomous Nervous System plus Medical Intervention

Type 4 BCIs will extend operator peak performance time while also allowing them to maintain that performance despite adverse conditions. The interface's influence could also trigger brain-saving or life saving measures reducing potential casualty rates and improving final medical outcomes for certain injuries.

Whereas Type 2 BCIs can influence motor function, Type 4 will provide a method to physically affect other internal physiological processes. The brain as the major component of the central nervous system regulates numerous biological processes, such as the regulation of hormones like adrenaline, and the manipulation of the brain's management of those systems could produce beneficial physiological states. These interfaces could offer the means to duplicate effects typically associated with pharmaceuticals. For example, BCI technology has already demonstrated the ability to disrupt the sense of pain.[74] This could have practical applications as an electronic anesthetic.

In twenty-five years, instead of using stimulants a pilot may be able to replicate the desired awake state through BCI generated neural activity without the side effects or risk of developing a psychological or physical chemical dependence. This technique could place a pilot into a resting recuperative state in which they could be roused from rather quickly; thereby regulating awake-rest cycles. Controlling the awake-rest cycle of the BCI integrated user could help ration and harness periods of consciousness and peak performance for when it is necessary. Meditative states could also be induced which would also offer the advantage of providing a manner of increasing the operator's sensitivity to the BCI neural stimulation method or methods.

The Type 4 BCI could also monitor the operator's medical condition through either measurement of neural activity associated with physiological processes or by interacting with ancillary devices that directly measure key analytes within proximal tissues or the bloodstream. When trauma or a threatening medical state is detected, the Type 4 BCI would then be able to initiate an intervention or treatment response. Furthermore, it could communicate with a networked system and initiate programmed alternatives for when the operator was determined to be incapacitated. For example, if the BCI-operator was a pilot, the interface could trigger the aircraft's software to go into a fully autonomous mode if the BCI determined that the pilot was cognitively or physically unable to control the plane.

The multi-functional intra-cranial fibers, developed by the MIT research group, possess the ability to deliver drugs directly to neural tissue. Advanced forms of these fibers could transport glucose and oxygen from internal infusion-pumps when triggered by life-threatening conditions such as cardiovascular failure or trauma. A dispersed network supplying essential substances and facilitating perfusion into neural tissue could theoretically delay the onset of ischemic injury and eventual cell death. Obviously, postponing brain death through an automated neuron saving treatment would have a considerably profound effect on the operator's ability to recover and to do so with a reduced amount of brain damage.

If pursued and employed, small and advanced BCI devices will create significant military benefits by enhancing the sensory, physical, and cognitive capabilities of the American warfighter.

Recommendations

Bidirectional BCI interfaces and the material technology to achieve portable BCI should be the two main focuses of further BCI-related government and industry partner research. The BCI offers real operational benefits. Some applications, such as augmented response and cognitive enhancement, are of such significance that senior leaders and planners need to start thinking now as to how the benefits could best be exploited by and integrated into the armed services.

The bounds of the human brain's flexibility will most likely define the limitations of the BCI-assisted human-computer relationship. More should be done to learn brain plasticity limits and sensitivity to BCI methods. Technological, or as mentioned in this paper, non-technological, solutions could possibly enhance operator sensitivity to the interface. Since brain interfaces will most likely be widely available in the 2040s, the militaries that possess effective methods to increase human sensitivity to BCI methods will gain an edge over those who do not.

This paper did not address the offensive capabilities of BCI technology; whereas direct brain influencing methods could be used upon an adversary in order to 'read' or degrade their cognitive, motor, or sensory neural ability. Furthermore, the cyber aspect of directly networked organisms was not addressed. There is very little information available on these subjects. As the technology matures, the DoD should not turn a blind eye to such issues and investigate the potential for offensive BCI, possible defenses, and the role of BCI-related cyber.

Conclusion

BCI technology has already achieved marvels that even today sound like science fiction. By 2040 as the role of robots and incredibly advanced computer systems permeate throughout the military infrastructure, advanced BCI will provide the means to achieve the most gain from human-computer collaboration. As the technological playing field is flattened, those nations best able to develop strong human-computer systems will gain an edge towards achieving cognitive dominance over their enemy and the enhanced ability to adapt to complex battlespace conditions.

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