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BRAIN-COMPUTER INTERFACES

U.S. MILITARY APPLICATIONS AND IMPLICATIONS

AN INITIAL ASSESSMENT

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Summary

Brain-computer interface (BCI) represents an emerging and potentially disruptive area of technology that, to date, has received minimal public discussion in the defense and national security policy communities. This research considered key areas in which future BCI technologies might be relevant for the warfighters of tomorrow. It sought to explore the operational value of current and future developments regarding man-machine neural communication, the associated vulnerabilities and risks, and the policy levers that should be in place before the technology is deployed.

The project drew from reviews of relevant technical and security literature and discussions with subject-matter experts to develop a July 2018 game convening technical and operational experts. The game tested the potential utility of a functional "BCI toolbox" against two future tactical urban operations vignettes. Game results indicated that BCI technologies are likely to have practical use on a future battlefield, particularly as the pace and volume of human-machine interaction intensify. Within the vignettes, participants anticipated that BCI capabilities could enhance the speed of communication, improve common situational awareness, and allow operators to control multiple technological platforms simultaneously. Participants noted that the pragmatic utility of each BCI capability would depend largely on its fidelity and reliability during combat. Of the capabilities assessed in the game, direct brain-to-brain communication facilitated by BCI appeared to offer the most transformative applications for operational use but also carried the most significant operational and institutional risks.

Our analysis also explored possible areas of risk associated with the development and application of BCI combat capabilities. As with many new technological developments, BCI may create new military operational vulnerabilities, new areas of ethical and legal risk, and potentially profound implications for existing military organizational structures. In particular, the report highlights potential operational vulnerabilities associated with the development and adoption of BCI technologies by the U.S. Department of Defense (DoD), including the potential for new points of failure, adversary access to new information, and new areas of exposure to harm or avenues of influence of service members. It also underscores institutional vulnerabilities that may arise, including challenges surrounding a deficit of trust in BCI technologies, as well as the potential erosion of unit cohesion, unit leadership, and other critical interpersonal military relationships. Finally, we consider potential future U.S. government ethical and legal responsibilities to an individual BCI operator, as well as the implications that BCI technologies might have on the ethical and legal responsibilities of that individual. These considerations should be incorporated into research and development (R&D) efforts early in the process and may warrant dedicated a departmentwide oversight mechanism as the technologies continue to mature.

Overall, our findings suggest that as the U.S. military increasingly incorporates artificial intelligence (AI) and semiautonomous systems into its operations, BCI could offer an important means to expand and improve human-machine teaming. However, precautions will need to be taken to mitigate vulnerabilities to DoD operations and institutions and to reduce potential ethical and legal risks associated with DoD's development and adoption of BCI technologies. Specifically, we recommend that DoD

- **expand analysis to illuminate operational relevance and risks.** This research developed a systematic approach to evaluating potential operational applications of BCI by pairing operational experience with technological expertise and incorporating a disruptive and creative Red team of RAND Corporation experts. New analytical approaches such as this could supplement existing internal exercises to help ensure that operational needs and risks, rather than just technical opportunities, drive BCI development and identify new adversary threats.
- **address the trust deficit.** The game and associated research highlighted the extent to which cultural barriers to BCI, particularly among infantry service members, are likely to be high. Trust barriers could be mitigated through heavy vetting and testing in

noncombat scenarios, introduction to service members that already rely on machine technologies, and an initial focus on noninvasive measures and medical applications.
- **collaborate and anticipate.** Our research highlighted examples of where DoD seed funding yielded successful BCI breakthroughs, and examples of emerging private-sector innovation. Where possible, future collaboration could leverage private-sector advances to the benefit of the U.S. military and, if carefully pursued, could improve trust gaps within the military. As the commercial market develops BCI technologies, this will help establish its capabilities and shortcomings. Although BCI applications are currently still in the basic-research phase, development of other technologies by the military, including robotics, AI, and big data analysis, will need to consider the eventual availability of BCI.
- **plan ahead for institutional implications.** As the U.S. government prepares to incorporate BCI technologies into future military capabilities, it will require institutional innovations to address new ethical and policy issues at each stage of the process, from R&D to operational application to veteran care.

Abbreviations

AI	artificial intelligence
ARL	Army Research Laboratory
BCI	brain-computer interface
BMI	brain-machine interface
BRAIN	Brain Research through Advancing Innovative Neurotechnologies
CaN CTA	Cognition and Neuroergonomics Collaborative Technology Alliance
DARPA	Defense Advanced Research Projects Agency
DNI	direct neural interface
DoD	U.S. Department of Defense
EEG	electroencephalogram
EW	electronic warfare
FDA	U.S. Food and Drug Administration
HCI	human-computer interaction
IoT	Internet of Things
MMI	mind-machine interface
MOUT	*Military Operations in Urban Terrain*
N^3	Next-Generation Nonsurgical Neurotechnology
NCI	neural-control interface
NESD	Neural Engineering System Design
NIH	National Institutes of Health
OODA	observe, orient, decide, act
R&D	research and development
tDCS	transcranial direct current stimulation
TNT	Targeted Neuroplasticity Training
TTX	table-top exercise

Introduction

The 86 billion neurons of the human brain represent humankind's primary evolutionary advantage and, perhaps, an area of untapped potential. Currently, our brains interact with the world through our bodies, sending electrical currents through the nervous system to vocalize with our mouths, to type—or swipe—with our fingers, or to move bipedally through space. What will happen when human brains are freed of their corporeal confines and can control machines directly? Neurotechnological advances have already given quadriplegics the ability to perform basic operations in an F-35 simulator with their thoughts[1] and have given scientists the ability to decode speech that subjects are imagining in their minds—albeit imperfectly. Eventually, our physical bodies might become a constraint that could be circumvented with appropriate neurotechnology.[2] The technical means for this brain-body bypass are BCIs, defined as methods and systems for providing a direct communication pathway between an enhanced or wired brain and an external device, with bidirectional information flow (between the brain and a device).[3] Their potential impact is broad and far reaching, and policies on how to develop and manage such technology should be proactive, not reactive.

BCI technology is progressing. Such progress highlights the need to assess current and potential applications, and to ensure that the technology responds to actual needs in addition to the intentions of developers. As BCI transitions from basic research to more operational and commercial applications, it will be important to devote early attention to the broader implications, to consider what policies and guidelines might maximize its benefits while mitigating potential downsides. Developing such technologies as AI, data analytics, and robotics have captured headlines and fostered public discussion regarding potential benefits and risks. Limited comparable conversation has, as of yet, evolved for BCI. When compared to other prominent emerging technologies, BCI is relatively immature; few capabilities have been deployed commercially. However, it has the potential to be no less influential. With profound potential implications in fields from defense and national security to health and wellness, BCI may represent a highly disruptive technology that, to date, has received insufficient analysis.

This report offers an initial assessment of what viable applications BCI may have in U.S. military operations, and what risks and vulnerabilities may be associated with its development and deployment. The authors describe the current state of the art and possible areas of technology development and growth for BCI military applications and investigate key questions associated with the use of BCI capabilities in a future combat scenario. Fundamentally, we ask, (1) what is the potential operational significance of current and future developments regarding BCI, and (2) what are the policy considerations necessary for effective management of the technology with an understanding of its potential impact on the warfighter of the future?

Human-Machine Teaming

The research views BCI in the context of the anticipated future of warfare, including increases in human-machine teaming. The analysis begins from the premise that human-machine teaming will play a major role in future combat and that BCI may provide a competitive advantage in future warfare. Former Deputy Secretary of Defense Robert Work, who led DoD's *3rd offset*, a catalyst for defense-sector technology development focused on human-machine teaming, summarized trends with military technology as follows:

> The coin of the realm during the Cold War was armored brigades, mechanized infantry brigades, multiple launch rocket system battalions, self-propelled artillery battalions, tactical fighter squadrons, among others. Now, the coin of the realm is going to be learning machines and human-machine collaborations, which allows machines to allow humans to make better decisions; assisted human operations, which means bringing the power of the network to the individual; human-machine combat teaming; and the autonomous network.[4]

Although DoD R&D efforts include many dimensions of technology, certain aspects are particularly relevant to potential work with BCI. In particular, there is an increasing focus on human-machine collaboration for improved decisionmaking, including human-computer interaction (HCI) and cognitive teaming, assisted-human operations, and advanced manned and unmanned combat teaming.[5] Defense officials discussing the "centaur" model—collaborative human and AI teams—have highlighted the relative advantages of the U.S. civilian and military workforce in developing and operating human-machine teaming technologies.[6] Human-machine teaming technologies that effectively leverage the unique cultural strengths of the American warfighter, including critical thinking and creative problem-solving, represent an area of particular value to the future U.S. military.[7] Technology development programs within DoD have thus focused on human-machine collaboration.[8] In fact, the Defense Advanced Research Projects Agency

Ultimately, humans and machines could collaborate cognitively and seamlessly—to think together.

(DARPA) has suggested that "smart systems will significantly impact how our troops operate in the future, and now is the time to be thinking about what human-machine teaming will actually look like and how it might be accomplished. . . ."[9]

Future developments with human-machine teaming have the potential to prompt far-reaching defense policy debates.[10] Technological advances, such as BCI, that allow humans to connect increasingly closely with machines on the battlefield may yield fundamental strategic and operational changes within each of the U.S. service branches and will undoubtedly raise ethical and organizational questions across the U.S. defense community. Thus, as DoD pursues a forward-looking vision for human-machine teaming, ambitious planning should prompt similarly far-reaching defense policy debates.[11]

In preparation for a future world in which human-machine teams represent the "coin of the realm," DoD has already invested in the development of technologies that can permit the human brain to communicate directly with machines, including the development of implantable neural interfaces that are capable of transferring data between the human brain and the digital world.[12] On the future battlefield, human thoughts may well be channeled to AI software or to robots, with information transferred back from sensors and machines directly to the human brain.[13] Ultimately, humans and machines could collaborate cognitively and seamlessly—to think together.

Approach

This analysis is structured to explore the operational implications of BCI technology. It pilots a repeatable process for systematically exploring the relevance and implications of emerging technologies in the context of military operations. Mapping technological capabilities to practical applications—and understanding not just the state of the art but the state of the practical uses—can present a significant challenge for assessments of emerging technology. Our process addresses that challenge by parsing the technology into operationally relevant capabilities, testing their operational relevance with a table-top exercise (TTX), and then exploring implications, risks, and risk-mitigation strategies. The process is itemized as follows:

1. Through literature review and discussions with subject-matter experts, we summarize the technology and identify key areas of developmental effort.
2. Specific topics of technology development are used as a catalyst for discussions with military experts to identify potential military applications in theater.
3. We aggregate the results of the analysis concerning technology development and operational relevance to provide a general assessment of whether BCI could potentially be valuable in a military setting and, if so, how. This preliminary finding becomes the overarching guide for a TTX.
4. Based on the technical and operational assessments, we derive a set of projected BCI capabilities—a future BCI toolbox.
5. The BCI toolbox is used in a table-top game based on exemplary scenarios involving tactical urban operations. This game explores more extensively the anticipated viability and relevance of BCI in theater.
6. Throughout this process, we explore vulnerabilities, risks, and risk-mitigation strategies associated with BCIs across three dimensions: technological, institutional, and legal/ethical.

Technology Summary

Introduction

Although a comprehensive review of the field of BCI would be beyond the report's scope, and although the literature on the topic is extensive enough to support handbooks,[14] dedicated societies,[15] and dedicated journals,[16] this section highlights prominent work, themes, and organizations to inform the assessment of potential military applications. By drawing on technical and popular literature, as well as discussions with subject-matter experts, we segment the topic into distinct areas of work, clarifying what exactly BCI entails and what kind of research is active. The section ends with a discussion of future trends and potential directions and summarizes primary technical challenges and risks.

While we adopt the term *BCI* based on its prevalence in the literature, a variety of related terms are used to describe similar capabilities: neural-control interface (NCI), mind-machine interface (MMI), direct neural interface (DNI), and brain–machine interface (BMI).

Although there is some debate regarding the precise nature of signals that are transmitted within the human brain, BCIs generally involve monitoring or affecting those signals.[17] Different BCI tools allow users to access and to use these signals with various levels of accuracy and invasiveness. In short, a BCI enables a bidirectional communication between a brain and an external device, and there is a broad range of ongoing work on this topic. In this context, bidirectional generally includes direct neural readout and feedback and direct neural write-in.

As reflected by the aforementioned definition and by the alternate terms, the focus is often on human-machine teaming, which aligns with needs stemming from trends in warfare. Practically, BCI provides a mechanism for blending human strengths and computer strengths, and much of the ongoing work strives to link these two sets of capabilities and yield synergistic advantages. The efficiency of the interface between humans and machines—whether facilitating communication by screens, text, or another form—is a significant factor in allowing humans to manage increasingly complex systems and information. BCI can improve such efficiency.

Although human-machine teaming can be useful, it is just a subset of BCI applications. The literature regarding ongoing R&D and potential applications extends beyond human-machine teaming, and BCIs need not just link humans and machine to provide value. More generally, BCIs provide a method to connect to the human brain. They provide more data. This connection can then be tied to a machine, to software, to another human, or simply to an output system for assessment. In fact, while human-machine teaming remains a cornerstone of developing technology for warfare, the broader advantages of BCIs point toward not just integrating humans and machines but leveraging human capabilities in general.

Review

While the practical significance of BCI has just recently become more visible, work in this field has been ongoing for nearly a century. In fact, work with the first human electroencephalogram (EEG)—a device for tracking and recording brain wave patterns—was published in 1929.[18] Jacques Vidal coined the term *brain-computer interface* in 1973, and research in this field has continued since.[19]

Work with BCI tends to fall into the following categories, which provide a framework for our investigations of operational relevance and applied capabilities in subsequent sections:

- data transfer *from* the brain
- direct system control
- prosthetics and paralysis treatment
- cortically coupled AI (for training or running AI systems)
- data transfer *to* the brain, and brain-to-brain communication.

Each of these topics can be segmented further into work involving invasive systems and noninvasive systems. Invasive systems involve implanting electronic devices beneath the human skull, inside the brain. The surgery allows practitioners to place the implant exactly where desired to monitor precise sets of neurons that govern specific neurological functions, but it carries health risks. Alternatively, noninvasive systems sit outside the skull. While this reduces risk to the user, the skull essentially acts as a filter and muffles the electrical signal.[20] The signals picked up by external electrodes are less clear, and it is more difficult to ascertain which neurons are firing.

A key effort in fueling most of these topics has been the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) initiative at the National Institutes of Health (NIH). This effort is broadly aimed at "revolutionizing our understanding of the human brain."[21] BRAIN partners include the National Science Foundation, DARPA, the U.S. Food and Drug Administration (FDA), and the Intelligence Advanced Research Projects Agency (IARPA), as well as foundations, institutes, universities, and industries. NIH allocated $46 million in 2014 and $81.4 million in 2015, reflecting growing interest in the topic.[22] Overall, DARPA has invested "hundreds of millions of dollars" transitioning *neuroscience* into *neurotechnology* since the early 2000s.[23]

With regard to the topic of *transferring data from the human*, a primary goal is assessing cognitive performance. To this end, the Army Research Laboratory (ARL) is using 3-D printing to create helmets that fit perfectly to each user and then incorporate EEG sensors to monitor brain activity.[24] The Air Force is also pursuing a camera-based comprehensive cognitive monitoring system built into a pilot's helmet to monitor cognitive workload and stress.[25] The helmets can adapt displays based on the pilot's unique physical and mental conditions. Separate research sponsored by ARL has investigated deep learning solutions for predicting drowsy and alert states based on EEG readings, and DARPA-sponsored teams have tested "closed-loop" brain implants that use algorithms to detect patterns associated with mood disorders.[26] BCI devices to monitor performance and even emotional spikes related to depression, anxiety, or rage are increasingly prevalent in China, where uses include factories, public transport, state-owned companies, and the military.[27]

Related to systems for extracting data from the human brain for assessment are methods for *direct system control*, whereby users control machines wirelessly with brain activity. In one well-publicized example, DARPA, APL, and the University of Pittsburgh used a BCI implant to permit a quadriplegic woman to operate flight simulators.[28] Researchers have also corrected robot mistakes through noninvasive measurement of EEG signals.[29]

Other research projects focus on drone control. With funding from DARPA and the U.S. Army, researchers at the Human-Oriented Robotics and Control laboratory enable a user to control a swarm of drones.[30] The lab's researchers suggest the technology could be used practically in the military within five to ten years. Applications also include delivery of medical help, search and rescue, and exploration, all in remote or inaccessible environments. Finally, using commercial hardware, researchers at the University of Florida have constructed, and demonstrated the use of, a low-cost system that is capable of wirelessly controlling common small drones.[31]

Beyond military applications, the health-care sector has advanced significant work with BCI direct control, especially involving invasive systems. Work at Stanford University enables paraplegic patients to control a computer mouse and computer software with their thoughts.[32] Dr. Krishna Shenoy, one of the principal investigators, suggests, "The day will come—closer to five than 10 years from now—when a self-calibrating, fully implanted wireless system can be used without caregiver assistance, has no cosmetic impact and can be used around the clock."[33]

The integration of *prosthetics*, which is essentially a subset of the work with direct systems control, has direct applications in the health-care sector. Much of this work involves invasive systems, primarily because of the necessity to target specific sets of neurons with relatively high accuracy. Perhaps the most complex prosthetic, conceptually, is the spinal cord. Researchers have used electrodes to reconnect the motor cortex and the spinal cord in monkeys and rats, restoring the ability to walk.[34] Case Western Reserve University used a similar procedure, called *functional electrical stimulation*, to enable arm and hand movement by bypassing the spinal cord and directly inducing muscle stimulation.[35] As part of the Revolutionizing Prosthetics program, DARPA and APL have pursued research concerning BCI-enabled prosthetic hands and arms that use intracortical microstimulation to provide feedback to the user (directly to the brain) and evoke sensations that the user perceived as coming from his/her own hand.[36] APL extended this work to study how BCI users could interpret external artificially provided intracortical microstimulation, even if the type of information being provided varied from what a brain region would normally have been processing. They then used this approach to provide a BCI user with navigation information from a simulated Mooney Bravo aircraft.[37]

Data (or information) from a human brain can be used not only to inform assessment tools or to drive systems but also to inform software with *cortically coupled AI*. Rather than using brain signals to *control* a computer or a system, a "cortically coupled computer system opportunistically senses the brain state, capturing a user's implicit or explicit computation, and then communicates this information to a traditional computer system via a neural interface."[38] This information can then potentially help train an AI system. This use of BCI represents a heightened level of human-machine teaming, allowing a human to *think with* a machine (or a computer) or, more specifically, integrate human thoughts or data into a process conducted by machine. Real-time BCI interaction could negate the current requirement for predetermined computer codes to transfer information, addressing one of the key bottlenecks of traditional human-machine integration.[39] Such teaming is of particular interest to members of the AI community who are exploring methods and approaches for managing and "controlling" AI. BCI may be able to provide this tool. Elon Musk, the founder of Neuralink, a relatively new company focused on integrating humans with AI, suggests, "Some high bandwidth interface to the brain will be something that helps achieve a symbiosis between human and machine intelligence and maybe solves the control problem and the usefulness problem. . . ."[40]

In addition to the extraction of data from the brain, there is also work exploring the ability to implant or *transfer information to the brain* itself. A significant challenge in enabling efficient system and prosthetic control is feedback to the user, providing information about the system being controlled. Although patients in a lab setting may be able to control a prosthetic hand using a BCI, for example, they will not necessarily realize where their prosthetic hand is without seeing it, unless they can look directly at it to obtain visual feedback.

Noninvasive transcranial direct currents can be used to treat depression and strokes, to increase focus and attention, to shorten training time, and, potentially, to improve physical training.

Research at Wake Forest Baptist Medical Center and the University of Southern California, funded by DARPA's Restoring Active Memory program, has shown initial success improving memory using surgically implanted electrodes, a strand of research with promise for treating Alzheimer's disease, strokes, and head injuries.[41] By reinforcing recorded neural patterns from a patient's experience (i.e., seeing a particular image), researchers were able to improve episodic memory, which is the most common type of memory loss in people with Alzheimer's disease, stroke, and head injury. Researchers saw a 35-percent improvement in subjects' baseline short-term memory.[42] Researchers noted, "This is the first time scientists have been able to identify a patient's own brain cell code or pattern for memory and, in essence, 'write in' that code to make existing memory work better, an important first step in potentially restoring memory loss. . . ." While this work focused on improving existing memory skills, future work might enhance the ability to retain specific memories as memory skill begins to fail. Noninvasive transcranial direct currents can be used to treat depression and strokes, to increase focus and attention, to shorten training time, and, potentially, to improve physical training (with a focus on the motor cortex).[43]

A natural extension from research that aims to read brain signals and to send or implant information in the brain is brain-to-brain communication.

The DARPA Neural Engineering System Design (NESD) program is developing invasive systems that can communicate clearly and individually with any of up to one million neurons in a given region of the brain, and this includes the ability both to transmit to the brain and read from the brain with some neurons.[44] While current invasive devices may incorporate something on the order of 100 channels, this project strives to read 10^6 neurons, write to 10^5 neurons, and interact with 10^3 neurons full-duplex, a far greater scale than is possible with existing neurotechnology.[45] Another DARPA program, the Next-Generation Nonsurgical Neurotechnology (N^3) program involves a noninvasive system capable of reading from and writing to multiple points in the brain at once.[46]

A natural extension from research that aims to read brain signals and to send or implant information in the brain is *brain-to-brain communication*. With funding from the ARL, researchers at the University of Washington conducted a pilot study for a noninvasive system that uses EEG to read basic brain signals, transmit them over the internet, and then transfer motor responses to a second user using transcranial magnetic stimulation.[47] The signals represent very basic actions in the context of a simple video game, such as *move left* or *right*. Nonetheless, especially given that these signals are transferred over the internet, the potential to send even basic thoughts across the internet inherently presents many opportunities and many risks concerning security and ethics. The authors extend this effort to involve five groups of three individuals.[48] Two individuals sent information, and the third person received information, with all three collectively playing a Tetris-like game. The work follows earlier experiments in transferring signals between rats[49] and from a human to a rat.[50]

Development Directions and Technical Challenges

Development Directions

In general, the direction with most BCI work concerns the amount and quality of data being transferred. The fidelity with which data can be extracted and transferred from the human brain will likely increase.[51] Signal bandwidth will likely improve. DARPA's NESD program, for example, has invested in research on implantable neural interfaces for sensory restoration that may engage up to one million neurons at once.[52] As of July 2019, one of the grant recipients, led by Brown University, presented 0.25-square-millimeter implants, called "neurograins," that permit wireless bidirectional communication with an external device with an uplink rate of up to 10 megabits per second.[53] As of January 2020, another grantee, Paradromics, had announced a new high–data rate implantable BCI that can process and transmit neural data at 60-times-lower power dissipation than existing approaches, allowing transfer of more data at lower risk of overheating the brain.[54]

Although no proof-of-concept currently exists for this technology, one potential frontier in transferring data from the human brain may be long-distance standoff wireless assessments. These might allow commanders to assess their soldiers' state or even the enemy's state from long distances. Similarly, BCI might find use in aggregating the assessment of a group. For example, BCI could be used to monitor the cognitive workload of a squad. For direct system control, more work will be needed to transfer complex manipulations or strategies with resistance to distractions.

With respect to prosthetics, the next step is establishing new neurological connections. Currently, BCI efforts regarding prosthetics involve reconnecting existing neurons to physical systems. It is more challenging to provide the ability to control a prosthetic (and associated neurons) that never existed. In addition, more work is also needed to provide proprioceptive feedback directly to the brain to improve bidirectional BCI control of prosthetic limbs. For data transfer to the brain, the ultimate goal is to provide the brain with direct, high-fidelity information (e.g., isolated memory implants). Like long-distance standoff assessments, this capability is not yet feasible but nonetheless remains a target for the BCI field.

A particularly interesting prospect for BCI is its integration with the Internet of Things (IoT), which connects systems via the internet. DoD believes IoT can contribute to improved readiness by allowing one to monitor the status of materiel and weapons systems in real time, and it is thus becoming pervasive.[55] IoT has tactical applications, including giving warfighters access to sensors and data, and BCI could enhance this ability.[56]

Some argue that, ultimately, the direction of this technology will follow the market.[57] With the increasing focus on entrepreneurship, researchers and academicians may likely spin off new technology, and commercial entities will drive development based on market demand. To be sure, companies like Kernel,[58] Neuralink,[59] Paradromics,[60] and Facebook[61] are actively pursuing BCI capabilities. A scenario whereby commercial industry dominates this space can have two modes. Industry can, of course, respond to needs that pull the technology, but industry may also push technology according to anticipated profitability. It may be advantageous to have the relevant policy in place *before* the marketplace drives the technology.

Technical Challenges and Risks

Despite the exciting and dynamic future that BCIs may uncover, there are, of course, technological challenges and risks. Perhaps the most significant technological challenge in BCI development is the trade-off between signal clarity and the ability to target specific neurons provided by invasive systems, and the ease of use with noninvasive systems.[62] DARPA's N^3 program is currently seeking to address some of these challenges by developing a portable noninvasive system capable of reading from and writing to multiple points in the brain at once.[63]

Invasive systems, which provide higher-fidelity signals, carry risks associated with any surgery, including hemorrhaging, infection, or brain damage. Electrodes can also induce infections and can degrade with time. Scarring and exhaustion (when neural substrates stop reacting) reduce signal strength. Biocompatibility is also a significant limitation. Furthermore, all current implants corrode and, thus, limit the duration for which they are useful. Sensors for most implanted BCIs currently last only about two to five years, although some primate work involves sensors receiving signals for as long as seven to eight years. Reducing the sensor rigidity, size, and tendency for deterioration while retaining signal quality remains a persistent challenge. Developing sensors with additional channels to improve accuracy and minimizing sensor power usage, which can cause tissue damage, are additional challenges. Precise placement of sensors on the brain is also challenging. In general, the hardware necessary for BCI (amplifiers, cables, sensors, etc.) is still too large for practical use outside a lab.

With both invasive and noninvasive systems, the data gathered from neurons are then analyzed, and accurate decoding presents another challenge with the advancement of BCI. This decoding often involves some form of machine learning for performance assessment, which breaks down if the individual, task, or time frame changes. Furthermore, decoding algorithms are unstable and require regular recalibration, in part because the position of neurons relative to electrodes changes, and firing patterns naturally change. To be sure, machine learning is an active area of research, including methods for generalizing results such that an algorithm trained on one set of data may be used with acceptable accuracy on a new, slightly different set of input data.

Despite the aforementioned technical risks that must be addressed, the applications and underlying capabilities currently being explored with BCI suggest that BCI *may* have viable uses for warfare. Subsequent sections thus consider operational repercussions of using BCIs in a military setting.

Operational Considerations

Introduction

Military theorists and practitioners have long lauded the human mind as a critical determinant of military success. Could direct linkage between the brain and an external device improve a warfighter's performance? Building on the overview of emergent BCI technologies in the previous section, the following section begins to explore how BCI technologies might be applied within a military context.

Two lenses frame the discussion. The first considers relevant features of the future warfighter experience to extrapolate potential applications for BCI. The second draws from open-source material from U.S. military research organizations and discussions with subject-matter experts to identify existing concepts for how BCI might be applied even in today's operational environment. This analysis informs the introduction of a BCI toolbox, which serves as the conceptual cornerstone for the RAND Corporation's BCI TTX.

BCI and the Future Warfighter

In his work on the history of the future of war, British scholar Sir Lawrence Freedman notes that "there is no longer a dominant model for future war, but instead a blurred concept and a range of speculative possibilities."[64] His work does identify a few recent strategic themes addressed in the literature on future wars, including an increased prevalence of hybrid wars, cyberwar, use of robots and drones, and the advent of megacities and climate change as sites and catalysts for future wars.[65] A 2019 RAND Perspective further projects several broad strategic trends for the future of war: increased competition for regional hegemony, difficulty defending isolated countries and domains, a decline of American qualitative and quantitative military edge, blurred lines between war and peace, and continued war on terrorism.[66] Additionally, increased focus on inter-state strategic competition and the potential for conflicts with near-peer adversaries also raises the possibility that future adversaries may wield more resources and sophisticated technological capabilities than have those of recent decades. However, as a 2019 Royal United Services Institute report on the future operational environment concludes, counter-Western strategies are "dynamic and evolving" and "differ depending on the context, means, ways, and ground."[67]

At the operational level, the character of warfare and combat experiences of the human warfighter may be driven in large part by rapid advances in military technological innovation.[68] As both the United States and potential adversaries develop and deploy new battlefield technologies, collaborative relationships between humans and machines are likely to evolve and place new requirements on the cognitive workload for a future warfighter. Regarding the potential application of BCI, the future warfighter is likely to have increased requirements to

- digest and synthesize large amounts of data from an extensive network of humans and machines
- make decisions more rapidly due to advances in AI, enhanced connectivity, and autonomous weaponry
- oversee a greater number and types of robotics, including swarms.

One recurring theme in discussions of cognition and future combat is that decisionmaking is likely to be complicated by the synthesis of enormous amounts of information.[69] During ground combat, for example, information sources might include such tools as acoustic sensor networks, which could provide the location of distant gunfire, or drone trackers to detect swarming robots.[70] In a future battlefield defined by the IoT, smart devices, soldier-worn sensors, and unmanned aircraft may flood service members with actionable data.[71] Extensive data and new sources of information may improve future situational awareness but could also complicate considerations for operational decisionmakers to process. Enhanced connectivity will expand the sources and speed of information transferred between humans or between humans and machines. Such information could range from networked connections between an F-35 and fourth-generation counterparts during an operation to real-time readiness status updates of ground-based materiel and weapon systems.[72]

Unsurprisingly, services are already pursuing ways to facilitate rapid and extensive flow data between warfighters and decisionmakers to improve the smooth functioning of interconnected military systems.[73] BCI systems could serve as a potential future tool support this endeavor, allowing human analysts and operator to monitor and exploit larger amounts of information more effectively.[74]

To address the potential for information overload, future service members are likely to engage more extensively with AI. On the future battlefield, AI tools may help human operators assess an environment, curate data, and ultimately allow operators to digest greater volumes of information.[75] Already, the U.S. Army has sought to leverage AI to "lighten the cognitive load" on future warfighters as a core capability objective of its 2017 Robotic and Autonomous Systems strategy.[76]

As AI and rapid connectivity are increasingly incorporated into military operations, the pace of warfare will continue to accelerate.[77] Thus the speed at which decisions need to be made will also accelerate. In the coming decades, the United States and near-peer competitors are likely to seek out new ways to speed up decision cycles.[78]

Finally, the future human warfighter may need to oversee and interact with a larger number of autonomous and semiautonomous systems.[79] Drone swarms may be incorporated at the tactical and operational levels in complex urban environments.[80] Future ground operations will incorporate robotics into supply and logistics chains.[81] Already, service members can look to uninhabited aircraft flying above the combat zone for ISR and close air support. Additional combat applications for machines could include, for example, a robot that would be the first to enter a building and take fire, currently one of the deadliest roles in urban warfare.

Potential BCI Applications in Future Combat

Within the context of these technological and operational trends for military environments, this section summarizes potential relevant applications, based on the literature and feedback from subject-matter experts. In general, BCI could theoretically be applied to help future warfighters make more informed decisions within a shorter timetable or to more effectively engage with more robotic systems than their current counterparts.

Laboratory studies indicate that BCIs may be able to enhance both the speed and accuracy of human decisionmaking.[82] In a future BCI team, AI could theoretically transfer initial data analysis from a plane or drone directly to the relevant centers of an operator's brain to further reduce cognitive load.[83] In combat, BCI could thus accelerate an operator's observe, orient, decide, act (OODA) loop, through new ways of presenting information and bypassing physical senses.[84] Thus, DARPA cites the potential ability of military personnel to "facilitate multitasking at the speed of thought" and "interface with smart decision aids" as two rationales for its investment in noninvasive or minutely invasive BCI technologies.[85]

BCI could also be used for more efficient engagement with AI to help maintain human oversight over operational decisions within a compressed time frame. Some scholars have hypothesized that an AI-enabled battlefield could lead to a phase shift in warfare in which the tempo of operations outpaces the speed of human decisionmaking. Some Chinese scholars have referred to this as a *battlefield singularity*.[86] Some U.S. scholars have referred to this concept as *hyperwar*.[87]

If this hypothesis about the role of AI and automation in warfare is accurate, it may be the case that BCI is the only way to have humans remain

To address the potential for information overload, future service members are likely to engage more extensively with AI.

effectively engaged in decisionmaking in war and keep pace with machines. In this world, adopting BCI and effectively integrating humans with machines is not merely a tactical advantage but the central strategic advantage in warfare. BCI systems could facilitate *centaur* warfighting, leveraging "the precision and reliability of automation without sacrificing the robustness and flexibility of human intelligence."[88] On the battlefield, one critical question would be whether BCI would permit humans to make meaningful decisions within future AI-driven operations tempos.

Additionally, BCI could yield potential advantages for human operators seeking to manage future robotics machines, or groups of machines, in combat. As former DARPA program manager Al Emondi has suggested, "As we approach a future in which increasingly autonomous systems will play a greater role in military operations, neural interface technology can help warfighters build a more intuitive interaction with these systems."[89] As a practical matter, the ability to achieve hands-free control of a vehicle, robot, or a drone swarm though BCI could allow operators to use their hands for other tasks, such as carrying a traditional weapon. BCI could also potentially allow operators to do more with a swarm than manual operation would permit. One 2009 North Atlantic Treaty Organization study concluded that the goal of having a single human operator control multiple vehicles was "at best, very ambitious, and, at worst, improbable to achieve."[90] Current work on brain-swarm interface posits that brain-computer technologies may be able to improve this challenge.[91]

Existing Concepts for BCI Combat Applications

Even today, BCI technologies, if they were available and more readily deployed, could yield specific operational benefits because of the direct access they permit to the human brain. Some DoD research programs publicly identify potential military operational applications of BCI that could be relevant in the existing operational environment. The following section draws from these themes, as well as insights from subject-matter experts, to discuss additional potential applications for BCI during combat

One area where BCI technology could potentially prove useful for today's military personnel would be *synthetic telepathy* among human operators.[92] In 2009, DARPA's "Silent Talk" program awarded grants to research institutions to "allow user-to-user communication on the battlefield without the use of vocalized speech through analysis of neural signals," an application that could greatly facilitate covert communication.[93] An external analysis highlights the potential use of BCI technology to develop shared consciousness within and across units, improve collective awareness of combat challenges, and provide combatants with insights into perspectives and internal deliberations of multiple operators.[94]

Direct access to the human brain could also help commanders improve the understanding of the cognitive and psychological states of their forces. As early as 2008, the Air Force investigated battlefield command-and-control systems that used EEG and eye movements to "assess the operator's actual cognitive state" in an effort to "avoid cognitive bottlenecks before they occur" and eventually to "anticipate future mission state and operator functional state ahead of time."[95] In its vision statement, the ARL's Cognition and Neuroergonomics Collaborative Technology Alliance (CaN CTA) makes the case for developing the capacity to continually monitor operator neurocognitive behavior, including depth, distribution, and shifting of human attention, appraisal of information, the emotional context of actions, and the impact of physiological state—fatigue, stress, arousal—on cognitive and motor performance.[96] This type of function could plausibly identify and facilitate operations for extremely fatigued convoy drivers, or perhaps for gunners or tankers operating in complex environments for whom mistakes could prove deadly.[97] At a more complex level, a technology that could provide insights into the emotional state of a soldier might provide red flags as to whether and when the soldier might "break" psychologically, when a soldier might have psychotic tendencies, or perhaps when a soldier is shooting to miss. One study on the use of functional magnetic resonance imaging to identify falsehoods suggests that the ability to detect whether a subject is concealing information may be of particular interest to counterterrorism and counterinsurgency missions.[98]

DoD has also explored the application of BCI technologies to improve cognitive performance during or in preparation for combat.[99] Potential military applications offered by enhanced cognitive abilities of service members, through electrical or chemical stimulation, might include improved memory of battle assignments or storage of large amounts of information by a fighter pilot.[100] Caffeine has been used as a cognitive stimulant by the U.S. military for over a century.[101] More recently, researchers from the Air Force Research Laboratory have highlighted cognitive challenges associated with high-level multitasking environments as an impetus for applied research on transcranial direct current stimulation (tDCS) in the military context.[102] DoD has also invested in efforts to accelerate military training through the use of BCI.[103] As DARPA's Targeted Neuroplasticity Training program description observes, service members often need specialized skills demanding perceptual acuity, rapid and accurate judgment, and effective planning and execution of complex actions. The existing training for these can be time consuming and require high aptitude.[104] Thus, DoD perceives utility in pursuing technologies that could reduce the time, investment, and innate aptitude required for the acquisition of these specialized skills.

Beyond cognitive enhancement, BCI could also be used to reduce pain or to regulate such other emotions as fear. As one analyst with military medical experience has observed, BCI capabilities that can physically manipulate the central nervous system and disrupt pain could offer "practical applications as an electronic anesthetic." DARPA's Electrical Prescriptions (ElectRx) program seeks to support military operational readiness by developing nonpharmacological treatments for pain, general inflammation, posttraumatic stress, severe anxiety, and other challenges through the stimulation of the peripheral nervous system.[105] Commanding officers have long grappled with how best to manage fear on the battlefield as warfighters make individual or collective decisions to fight or not fight when fearing death.[106] Application of BCI to improve management could plausibly be of use, though there are

Beyond cognitive enhancement, BCI could also be used to reduce pain or to regulate such other emotions as fear.

also arguably positive products of strong emotion in combat, including an increase in adrenaline that improves physical capability.[107]

In the future, BCI that improves human sensors—eyes that could see in different spectra or ears that could hear sounds outside the usual human range—might improve situational awareness in infantry operations. As former DARPA program manager and former Army infantry officer Geoffrey Ling has observed, "If I gave you a third eye, and the eye can see in the ultraviolet, that would be incorporated into everything that you do. . . . If you can see at night, you're better than the person who can't see at night."[108]

Testing BCI Capabilities Through National Security Gaming

Can BCIs support national security and future warfare? If so, how? When applied to the anticipated future of warfare, the technology summary for BCI suggests there may, in fact, be operational benefits. To test this further, the RAND team conducted a TTX—a national security game—centered around a toolbox of projected future BCI capabilities. The game brought together experts with technical and operational experience and challenged them to make choices about what BCI technology they would employ and why across tactical vignettes. The game reinforced some preliminary hypotheses about the appeal of specific BCI tools and clarified potential use cases in an operational environment where the value of BCI was disputed. Importantly, the game also provided insights into potential vulnerabilities and risks, detailed in the next section.

A Projected BCI Toolbox

Drawing from the technology summary and consideration of future operational requirements, we projected a toolbox of six future sets of BCI capabilities. The first three capabilities generally relate to connectivity between humans, and between humans and machines. The second three relate to human performance and training. These capabilities served as the core for the July 2018 BCI TTX—in effect, they served as our hypotheses about which BCI technologies will be most relevant to tactical military units. They are listed as follows:

Human-machine decisionmaking involves transferring data *to the human brain* from sensor input and from the brain to machines. It might help users aggregate and transfer information and assessments. For example, a computer might sort and display information in an easily digestible form for quick and accurate response. Alternatively, with cortically coupled AI, data can be provided *from the human brain* to a computer. This kind of tool allows a warfighter to digest more information faster, to be used, for example, with theater assessment or risk and threat assessment. Warfighters ultimately can increase overall reaction time, thus collapsing the OODA loop.

Human-machine direct system control involves allowing warfighters to control systems with their thoughts wirelessly, as well as to supervise semiautonomous and AI systems, including robots, drones, drone swarms, or jets. It might, for example, enable an immediate system shutdown or weapons launch simply by exercising a thought. This, in turn, provides the warfighter increased situational awareness and again helps collapse the OODA loop.

Human-to-human communication and management entails wirelessly transmitting commands or basic ideas among warfighters and commanders, lightening the load of communications systems. It could facilitate immediate and silent communication of plans or tactics on the battlefield, or improve communication with headquarters to enhance commanders' awareness of in-theater conditions.

Monitoring performance would enable awareness of group or individual emotional, cognitive, and physical states. It could permit monitoring neural and cognitive state, thus detecting when a person is fatigued, paying attention, has high or low cognitive workload, or is significantly stressed. It might also help a commander to better understand aggregated squad or platoon cognitive state and fatigue.

Enhancement of cognitive and physical performance includes improving a warfighter's cognitive and physical states on the battlefield. Cognitively, it could yield enhanced focus and alertness for rapid and improved situational awareness and decision-making. The warfighter would also be afforded an enhanced emotional state that could, for example, disrupt fear and mitigate stress. It could also enhance cognitive skills training, per DARPA's Targeted Neuroplasticity Training (TNT) program.[109]

With regard to physical performance, it might include regulating or enhancing a warfighter's psychological state.[110] It could enhance sensory capabilities through stimulation of the peripheral nervous systems and possibly specific cortices (i.e., visual or audio). It could also enable the mitigation of pain via pharmaceutical distribution. Finally, this tool could also include improved strength through more efficient integration with mechanical exoskeletons,[111] which are natural extensions of the work on prosthetics.

The *Training* BCI tool could improve operator learning and memory processing, allowing warfighters to retain more information. It could also enable accelerated training, including deployable training devices for rapid training in theater. It could allow for adaptive (and more effective) personalized mission-specific training. BCI could provide more effective feedback during training and—someday—could enable implanted knowledge sets for immediate "training."

Figure 1 lists the capabilities of a BCI toolbox that may be available in a relatively near time frame, as well as longer-term projections. These capabilities are grouped with respect to the tools discussed above. In general, the long-term capabilities reflect

FIGURE 1

BCI Toolbox for National Security Game

BCI tool (2030 → 2040 → 2050)	Near-term capabilities	Long-term capabilities
1) Human-machine decisionmaking	• Immediate transfer of operational risk • Faster decisions to deploy weapons • Shorter preparation cycle with faster feedback from occurrences in battlespace (collapse OODA loop) • Increased speed and accuracy of targeting	• Transfer of risk and threats (increased bandwidth) • Augmented AI systems
2) Human-machine direct system control	• Transfer basic commands to systems • Increase situational awareness and reaction • Collapse OODA loop	• Transfer of complex manipulations (increased bandwidth and degrees of freedom) • Resistance to distraction (use in dynamic environments) • More specific commands and control
3) Human-to-human communication/ management	• Transfer basic commands between individuals • Reduce (radio) weight	• Transfer complex strategies involving commanders/headquarters (increased bandwidth)
4) Monitor performance	• Monitor state • Monitor individual and group cognitive workload, stress, breaking point	• Long-distance standoff assessment • Monitoring of adversary emotional and cognitive states • Archived dynamic cognitive profiles
5) Enhance cognitive performance	• Regulate emotional state (i.e., stress) • Increase focus and alertness	• Modulate emotional state
6) Enhance physical performance	• Improved strength augmentation • Improved sensory capabilities	• Implanted auto pharmaceutical distribution • Pain disruption
7) Training	• Increased learning retention • Deployable training devices • Adaptive individualized training • More immediate and effective assessment	• Implanted knowledge sets

NOTE: This framework was used to support game play but does not reflect a technical maturity assessment.

an improvement in the complexity and bandwidth of data being transferred. Regarding direct system control, in addition to transferring more complex manipulations of a system, long-term capabilities may also reduce the sensitivity of BCI systems to user distractions. Long-term capabilities related to monitoring performance will allow organizations to archive cognitive performance and profiles over time.

Testing the Operational Relevance of BCI Capabilities

To provide an initial test of the utility of the seven BCI toolbox areas to tactical military operations, we ran a one-day game in which we convened experts to make decisions about which, if any, of the BCI toolbox technologies they would utilize in two urban ground combat missions. This event allowed us to better understand (1) whether players perceived any BCI technology as useful in a complex context, (2) the perceived relative advantage of different technologies for different tasks, and (3) the rationales for why players did or did not opt to use different technologies, helping to unpack advantages and limitations of the tools.

Our BCI TTX convened a small group of players from diverse military and technical backgrounds to drive conversation and elicit a broad range of insights. The primary intent was to explore the relevance of BCI capabilities in a military setting and

Urban infantry operations presented a "most challenging" use case, with target users who have traditionally been skeptical of the utility of technological advances.

discuss the nuances of how such capabilities might be used. On the technical side, players included researchers and managers with expertise in neuroscience, military technology, and human-machine teaming. A second set of players was drawn from current and prior-service officers and experts on military affairs, many with experience in urban operations. The group was asked to represent U.S. forces as a whole in the vignettes. Two RAND analysts who study disruptive technology took on the role of the adversary during the last stage of the game.

Players were asked to apply and weight the utility of each of the six BCI capabilities from the BCI toolbox in the context of two tactical urban operations and across the six warfighter functions: mission command, intelligence, fires, movement and maneuver, force protection, and sustainment. This process allowed us to compare the players' assessment of the utility of different technologies for different functions across two different missions.

Urban infantry operations presented a "most challenging" use case, with target users who have traditionally been skeptical of the utility of technological advances. As a former Assistant Secretary of Defense for International Security Affairs and combat Marine, Bing West once bluntly suggested, "Urban battle will remain a slugfest, with the basic ingredient remaining heavy doses of high explosives. No technology is emerging to replace that."[112] We drew two mission vignettes from doctrine for urban operations to allow players to drill down into common tasks: clearing a building and responding to an ambush. Both vignettes included complex subtasks that could address the range of warfighter functions.

Additional details of the game design and execution are included in the appendix.

Insights on the Use of BCI from Game Play

The game provided several types of insights to help us understand the utility of BCI in urban operations. First, we collected data about which BCI capabilities players opted to leverage to tackle which functional areas. We used this information to understand which capabilities were seen as more useful to support complex ground operations. Second, we collected data on the players' discussion of why they saw specific technologies as promising or risky. In this section, we discuss which technologies players opted to use, and what they saw as the advantages. These findings generally align with our initial hypothesis that BCI has uses even in complex environments but showed that players did not see the six capabilities as equally helpful. Beyond the potential promise for BCI that was supported by game play, we also noted many important limitations and risks introduced by using BCI. These findings are addressed in the next section.

Our initial insight from the game is that BCI capabilities can, in fact, be useful on the urban battlefield, supporting the team's initial hypothesis. All BCI tools were used multiple times by a player, and all warfighting functions had a majority of tools applied at least once. When given a choice between using BCI technologies or not, players often decided to use a BCI technology to confront the challenges of the tactical vignettes.[113] More specifically, the game provided evidence about the relative frequency at which BCI tools were selected to support different warfighting functions, which suggests the perceived relative utility of different technology baskets. Overall, human-machine decisionmaking, direct systems control, and enhanced physical performance were noticeably more popular than other tools. Perhaps not surprisingly, these tools were most often used to support mission command, intelligence, fires, and force protection tasks. Enhanced cognitive performance and training were rarely used, but that may have been due to the tactical nature of the problem sets, which could have made long-term issues like training less pressing. All of these results were in line with our initial projections, but the independent support from game players provides additional evidence for the utility of BCI for specific operational tasks.

The game also underscored the need for further analysis of the future technical capabilities of BCI-related military applications. Participants noted that the pragmatic utility of each BCI tool would depend largely on its fidelity and reliability during combat. A human-to-human communication tool permitting fully shared situational awareness would be of greater use than more rudimentary communication, which could be as easily transmitted over a traditional short-wave radio. A BCI device overseeing the operation of drone swarms is only as useful as it is dependable in maintaining control during unfavorable conditions. Additionally, the incorporation of adversary automated lethal systems into the game raised technical questions about the future ability of BCI to overcome time constraints associated with human decisionmaking. One player commented that some of the capabilities presented in the BCI toolbox did not feel sufficiently concrete to make an operational determination, which may have contributed to some players' decisions. The next section further explores some of the key vulnerabilities and risks identified during game play, which must be given further thought before BCI can be productively fielded in combat environments.

Vignette 1: Clearing a Building

The first vignette, clearing a building, was drawn directly from Marine Corps Warfighting Publication *Military Operations in Urban Terrain* (MOUT).[114] In response to the vignette, players cited locating civilians and killing the enemy as two critical subtasks. Communication, control of forces through multiple rooms, and ensuring situational awareness were derivative subtasks. Overall, players identified the key problem as one of information collection and human management and thus were more invested in BCI solutions that aided communication and decisionmaking.

Drawing from the identified subtasks, participants underscored the need to communicate clearly and make swift and accurate decisions under conditions with limited line of sight, visibility, and hearing. As a result, players focused their discussion on BCI tools that could assist with command and control, communication, and intelligence. As one player suggested, BCI potentially offers the "totality of information, getting voices and images together" while also providing tools to help make sense of otherwise disorienting conditions.

Speed of decisionmaking and enhanced common awareness were repeatedly mentioned as key qualities of BCI tools that would be important in improving current communication, command and control, and intelligence. As one player observed, a unit leader clearing a building would "need to know who is really scared, or dead, and would need to know that without spending time to talk."

Even for such functions as movement and maneuver, player discussion focused on the need to communicate the location of other service members and the status of different areas of the building instantaneously, although there was some debate about the additional value of BCI for this task beyond the use of a traditional radio.

Players also selected tools that provided a commander with more refined information on which to base decisions. To the extent that BCI could enhance a commander's ability to rapidly cull information from front-line soldiers, sort that information, and make decisions on targeting and human management, it would potentially be useful in accomplishing the task.

Control over robotics and physical enhancements were also mentioned but discussed far less, and they seemed to be less central to players' conception of the vignette's challenges. For example, many of the operators stressed that, in these types of conditions, the Blue shooter would still be a human wielding a rifle, because the extra degree of judgment and accountability would be necessary. The lack of emphasis on controlling such emerging technologies as drone swarms and battlefield robotics may also have been due in part to the fact that players were asked to consider only current levels of non-BCI technology.

Vignette 2: Ambush and Casualty Evacuation

The second vignette adapted an ambush description from MOUT to include a casualty evacuation described in a firsthand account of the battle of Fallujah.[115] This vignette also explicitly incorporated future non-BCI technologies projected to be available to the United States and near-peer adversaries in the 2040 time frame, including autonomous lethal AI; air- and water-based swarming unmanned vehicles; advanced electronic warfare (EW); integrated intelligence, surveillance, and reconnaissance; situational awareness; and fires support.[116]

In this vignette, the focus shifted from communication to control over multiple platforms and medical support. The additional consideration of plausible future military technologies highlighted new areas for potential human-machine interaction. While players did identify similar BCI technology as helping with command and control and intelligence, as in the first vignette, these warfighting functions were far less prominent in discussion. Instead, players placed more emphasis on the multiple platforms that needed to be coordinated to provide situational awareness, fire support, and medical evacuation capabilities. Players also noted that the more-open lines of sight in the vignette made air support and ground-based robots more useful, making direct control a more attractive option.

The presence of an active casualty moved applications of BCI to providing and monitoring medical care to a central focus. Building from a firsthand observation that "time is critical" when addressing urgent casualties, participants considered ways that BCI could improve response time.[117] One player suggested that transfer of advanced medical expertise through BCI could transform any combat medic into a surgeon, potentially reducing transport time to critical care. Players paid particular attention to using human-machine decisionmaking to support the correct allocation of resources—for example, determining how much service member time should be spent providing medical care, or allocating unmanned systems to different tasks.

Additional Use Cases

Players also noted several additional areas where BCI would be helpful beyond the confines of the vignettes. For example, players discussed the utility of providing BCI to a mechanic, who could then draw on either machine learning–based diagnostics or the experience of a more senior technician when making repairs. Players felt that this would enable more capable support functions that, while not depicted directly in the vignette, would be key to maintaining forces over longer operations. Similarly, players mentioned that if there had been allies or partners operating alongside the vignette forces, BCI could be helpful in overcoming the language barrier to smooth communications. The short duration of the vignettes also minimized the role of cognitive and physical fatigue in player decisions. Players noted that potential offensive applications of BCI were not included in the toolbox but could be useful. Players also noted that the opportunities for BCI in the operational management of the fight would likely be extensive but would be quite different from the tactical applications that the game focused on.

It is important to caveat that, while players felt BCI would be useful in the urban environment, they were quick to note that it would not be a panacea. In addition to the potential of BCI, the exercise also highlighted possible vulnerabilities, challenges, and risks created by the use of BCI. These are captured in detail in the following section.

Summary of Game Findings

While the insights of a single game should not be overstated, our BCI TTX contributed to an emergent discussion on BCI by identifying and considering tangible ways in which future BCI capabilities might contribute to combat operations. Participants chose BCI tools over traditional military approaches for tasks across the spectrum of warfighter functions. Of the seven BCI capabilities identified in the study, participants found the most uses across the two vignettes for three. First, participants prioritized BCI support to human-machine decisionmaking, anticipating the benefits from the integration of information from many sources during a chaotic battle or the acceleration of decisionmaking during combat.

Second, direct systems control through BCI could offer combatants hands-free control of semiautonomous systems and drone swarms. Third, enhanced physical performance would offer improved auditory and visual capabilities, or more fluid control of exoskeletons. Participants noted that utility of this function may become particularly pronounced once technology for military applications of AI and robotics develops further, improving the fidelity and reliability of BCI tools, and once adversaries have access to these capabilities. Further analysis of these three capabilities could further refine their uses and associated risks.

Our participants noted that future direct brain-to-brain communication among service members, while requiring more advanced technology than may be available in the 2040 time frame, could be revolutionary in allowing a team to coordinate actions while clearing a building. The discussion also suggested that the technologies might pose increased risks of adversary exploitation and would have the greatest impact on current military organizational structures, depending on whether the capability can be turned off and used selectively. Many of the challenges identified in the game highlighted the likely future amplification of cybersecurity risks by the use of BCI. Our Red team underscored the potential vulnerabilities associated with hacking, denial of service, and EW.

Potential Risks

Analysts of emerging military innovation often note the need for caution surrounding the capability-vulnerability paradox, whereby new advantages can introduce new vulnerabilities.[118] The introduction of any new technology may present new challenges, risks, and vulnerabilities. Thus, in addition to considering the operational utility of future BCI technologies in combat, this project sought to consider how the unique attributes of BCI might present new considerations for DoD and to identify core areas for further examination. Some of these considerations were derived from existing literature; most were drawn from discussions that were held in preparation for and during the BCI TTX, including insights from a Red team dedicated to identifying BCI-related vulnerabilities. While the game confirmed the potential usefulness of BCI technologies on the battlefield, it also highlighted potential risks. With respect to policy, the value proposition certainly suggests continued investment and development, but the risks highlight key areas where policymakers should be proactive. This section considers potential operational vulnerabilities, institutional vulnerabilities, and ethical and legal risks, all associated with combat applications of BCI technologies.

Analysts of emerging military innovation often note the need for caution surrounding the capability-vulnerability paradox, whereby new advantages can introduce new vulnerabilities.

Operational Vulnerabilities

A Red team analysis of game-player decisions helped identify ways in which BCI technology could create new vulnerabilities for the future warfighter. To scope the analysis, game facilitators sought to distinguish between new vulnerabilities specifically associated with future BCI capabilities and those associated with greater future reliance on technology in general. Participants generally agreed that within each new area of vulnerability, the extent of the vulnerability would depend on both the reliance on BCI technology and specific features of the technology itself.

New Potential Points of Failure

One major area of vulnerability was that reliance on BCI use could present new ways for an adversary to deny access to the technology, potentially rendering a unit less effective. A 2014 examination of synthetic telepathy concludes that "brain-to-brain communication over the Internet may never be the best solution for the battlefield, despite the millions of dollars of Pentagon research money that's gone into exploring it."[119] This may be due in part to the potential for service denial. The security of the network among brains, or between brains and machines—and network vulnerability to electromagnetic pulse—would thus be of paramount importance as EW attacks began. In fact, this issue arises outside the field of BCI as interests in secure networked communication on the battlefield increase.

Overreliance on new mediums of transmission could be problematic for any new technology, including future battlefields driven by the IoT, and maintaining communication channels is likely to be a priority. However, BCI could present a particular vulnerability because of its technical reliance on detecting very weak electrical signals. In a battlefield situation, these weak signals could potentially be jammed. As one Red team member noted, Russia has significant EW capabilities embedded even at the lowest tactical level. Mitigation options could include helmets or masks that create a Faraday cage, shielding the user from jamming attempts. However, the increased weight and the reduced visibility that might result from use of such equipment could make this a problematic option.

Adversary Access to New Information

In addition to the risk of having signals jammed, there is a risk of adversaries intercepting and using signals. Technologies that provide access to an operator's emotional or cognitive states could potentially be a treasure trove for adversary intelligence collection. Russia has reportedly targeted NATO soldier smartphones for information on operations and troop strength, while the Chinese government has reportedly hacked military contractor computers to extract highly sensitive data about future submarine warfare.[120] BCI technologies that permit direct access to the brains of service members could plausibly provide near-peer competitors with valuable information regarding the U.S. disposition of forces, organizational frictions, and vulnerabilities among individual service members themselves. The degree of vulnerability of operators' brains would likely depend on the fidelity of the BCI technology employed, the amount of sensitive information that operators had access to, and the robustness of physical and behavior countermeasures designed to thwart adversary hacking attempts.

New Areas of Exposure to Harm or Influence

Red team participants noted that because BCI technologies may directly connect to an operator's brain, they may present new areas of potential exploitation. Physical vulnerabilities would likely be most acute with the invasive variant of the technology. Already, unconventional attacks are suspected of causing traumatic brain injuries to U.S. government employees in China and Cuba.[121] If adversaries are currently experimenting with disrupting the human brain at a distance using ultrasonic frequencies, microwaves, or other methods, implants could provide direct entry into the brain for damage. Just as it is possible to hack a pacemaker or insulin pump, it is quite conceivable—albeit far in the future—that someone could hack a BCI and send cognitive commands or even thoughts to the brain.[122]

Reports of Russian *pinpoint propaganda*, text messages that seek to demoralize individual Ukrainian soldiers through threats and false reports of leadership desertion, offer one insight into how technology can enhance emotional manipulation tactics.[123] Hacking BCI capabilities could theoretically provide adversaries with direct pathways into the emotional and cognitive centers of operators' brains to sow confusion or emotional distress. In the extreme, adversary hacking into BCI devices that influence the motor cortex of human operators could theoretically send false directions or elicit unintended actions, such as friendly fire, although such influence may be technically difficult to achieve in the near term. Even an attack that broadly degraded gross motor skills could prove debilitating during combat.

Institutional Vulnerabilities

Trust

BCI research related to tactical applications has largely been driven by the "push" of technological advances, rather than the "pull" of requests for BCI capabilities from the military field. Some participants in the game suggested that service members were likely to be skeptical about the practical utility of BCI technologies. Although this issue of trust is not unique to BCI technology, it should be a focus point for future policy. Those with direct infantry and close combat experience may be most wary of the potential risks and downsides of the technology because of the need to balance technology with lethality.[124]

Acceptance of BCI may also be complicated by a general phenomenon referred to in the bioethics community as the "yuck factor," in which a negative emotional response is provoked by new advances in biotechnology.[125] Lack of trust would likely be more acute for invasive BCI, which requires alterations to the human body and poses health risks, such as infection. Trust could also be influenced by the scope of the information accessed by BCI technologies. Service members may not want to provide the U.S. government, or its machines, with access to the inner workings of their minds.

Additionally, the potential pace of decisionmaking permitted by BCI—as well as the delegation of tasks to AI—may raise particular concerns among warfighters.[126] Such concerns could exist in an environment driven by technological advances even in the absence of BCI. Some of these concerns also could be offset by the advent of civilian technologies that employ BCI, or generational shifts that yield a force for whom BCI technologies and biotechnological interventions are more acceptable.[127] In other areas of human enhancement, including study drugs, modafinil, or tDCS, civilian technologies and applications have outpaced those of DoD. If this trend were to continue with BCI, military adoption could plausibly lag civilian adoption, potentially enhancing popular trust in the technology.

Conversely, too much trust in BCI technology could compound potential operational vulnerabilities: As they became reliant on BCI technologies, warfighters might someday be unable to operate in its absence. Participants highlighted the need for redundancy. Examples might include maintaining secure radios to supplement computer-mediated telepathy, ensuring that members of military units continue to be well-versed in traditional navigational techniques, and ensuring alternative means of communicating with machines on the battlefield.

Erosion of Unit Cohesion

As humans become more closely intertwined with machines through BCI, technology could have profound implications for the interpersonal relationships that have traditionally played a preeminent role in warfighting. The implications may be difficult to predict. On the one hand, an ability to directly sense the thoughts and emotions of other members of a combat team could increase unit cohesion. On the other, there is evidence that advances in virtual communication technologies that permit "chat-room coordinated strikes" may already reduce emotional and psychological bonds among soldiers.[128] To the extent that they would replace traditional interactions among members of a military unit, future BCI capabilities could fundamentally alter the nature of these human relationships. An increasing use of robotics and AI in combat could compound this challenge. In fact, preliminary research on robots on the battlefield has indicated the development of strong human-robot attachment, or even a feeling of "self-extension into the robot," that might influence operational decisionmaking.[129]

More broadly, the introduction of new BCI technologies raises questions about the future structure

Service members may not want to provide the U.S. government, or its machines, with access to the inner workings of their minds.

of the human force. What does a company or platoon look like when some or all of the force is neurally plugged into various weapon systems, drones, or robots? Will these capabilities be integrated, or will they be assigned to specialized detachments? How might it affect unit cohesion when senior officers can monitor service members' emotions or even thoughts, and when some unit members have access to BCI capabilities while others do not?

Erosion of Unit Leadership

Technologies that permit senior officers to monitor and communicate directly with the brains of combat personnel could potentially undermine effective squad-level leadership, extending micromanagement to new frontiers. In one hypothetical dynamic, BCI technologies could exacerbate an existing trend toward what has been dubbed the *tactical general*: Senior officers, empowered through such new technologies as drone feeds, may tend to use these technologies to exert greater control over operators in the field.[130] Future BCI technologies that permit direct brain-to-brain communication could potentially exacerbate this dynamic, contributing to a more robotic, less adaptive and resilient approach to unit-level leadership.

Unit-level leadership could also be jeopardized by BCI technologies that provide senior leadership with access to individuals' physiological, emotional, and cognitive states. Traditionally, it has been the role of a squad leader to understand the physical and emotional states of his or her team through months of relationships, evaluation, training, and combat experience. Technologies that allowed senior officers to bypass unit-level leaders and second-guess their judgments might be undermining unit leadership rather than supporting it.

Ethical and Legal Risks

Two decades ago, biotechnology ethicists wrote that "the most frightening implication of [BCI] technology is the grave possibility that it would facilitate totalitarian control of human. . . . a paramount worry involves who will control the technology and what will be programmed."[131] More recently, the National Institutes of Health established a neuroethics working group that meets periodically to consider ethical challenges in the development or application of neurotechnologies at large, including BCI.[132] As BCI technologies advance, government bodies that support and use the technologies will need to develop systems to supervise and manage BCI use to mitigate abuse. A National Academy of Sciences study, in particular, emphasizes the need for organizational safety nets in the development and application of future BCI technologies.[133] This section explores two issues deserving of ethical and legal consideration: responsibilities *to a BCI operator* both during and after military tenure, and responsibilities *of the BCI operator* for actions taken in combat with BCI technologies.

Responsibility to the BCI Operator

BCI breakthroughs will require consideration of the risks to operators, some of which would be amplified within a military context. Potential risks to operators may occur during R&D, during operations, and even long after exposure. As with any biotechnical advance, the U.S. government will need to prepare for new responsibilities at each stage of use. A 2014 report by the National Academy of Sciences, commissioned by DARPA, begins to address potential risks associated with the use of neurotechnologies within a military setting, but additional questions are likely to arise as the technologies progress.[134]

The safety of neuroscience-based interventions represents a primary concern for the U.S. government.[135] Currently, the health risks associated with BCI are not fully known. Invasive techniques may prompt the most vigorous public discussion of health impacts, given the fact that they require the implantation of a foreign object into a major organ and may carry immediate risks of infection from surgery. However, the long-term implications of noninvasive techniques are also unknown.[136]

The extent to which neurotechnologies represent changes to the human brain and body has legal as well as ethical implications. By statute, DoD is responsible for any changes to a veteran's body during their time of service. To the extent that BCI may change a service member's baseline health over the long term, the U.S. government would be responsible for any service-related disability.[137] Beyond the physical implications of the technology itself, the withdrawal of "superhuman" capabilities afforded by BCI—such as control over machines or cognitive enhancement—might elicit psychological harm for which the U.S. government would be responsible.

Given the potential safety risks associated with BCI, any U.S. government agency developing and operationalizing the technologies would need to consider how to protect the principle of informed and voluntary consent of operators. Consent to any new and potentially risky technology may be complicated by the unique "competitive and coercive pressures" of the military context.[138] Limited personal autonomy among military personnel, as well as a lack of information about long-term health risks, have led some ethicists outside of government to argue that BCI interventions, such as noninvasive brain stimulation techniques, are currently inappropriate for a military or security sector setting.[139]

Because BCI technologies could provide direct access to the human brain, the U.S. government will need to consider implications for the privacy and liberty of the operators.[140] Cognitive liberty is a related concern for neuroenhancements, because, as one bioethicist has articulated, it "concerns an organ that mediates human identity."[141] Given these challenges, ethicists have proposed four emergent rights: "the right to cognitive liberty, the right to mental privacy, the right to mental integrity, and the right to psychological continuity."[142] As few are likely to volunteer for a mission that permanently eliminates personal privacy, it would benefit DoD to develop meaningful privacy policies surrounding BCI use *before* adopting the technology. In particular, how might mental and cognitive privacy rights be applied in a combat environment? Over the longer term, would data extracted from service members' brains through BCI be anonymized? Should it expire? Alternatively, might this technology be used to identify "super warriors" to form future elite forces?

Ethicists also emphasize the need for independent institutional review, appropriate training, and adherence to international guidelines.[143] DARPA program manager Al Emondi has highlighted some ethical questions surrounding BCI, anticipating

Ethicists also emphasize the need for independent institutional review, appropriate training, and adherence to international guidelines.

that "if N3 is successful . . . we could face questions related to agency, autonomy, and the experience of information being communicated to a user."[144] Within the military context, services might consider arbitration mechanisms so that service members and their commanding officers may discuss or object to unethical or harmful uses of BCI technology. Such a mechanism might lie outside the chain of command—similar to the State Department "dissent channel"—in an effort to counter some of the institutional pressures of a highly hierarchical organization.

Responsibility of the BCI Operator

As with many ethical and legal issues, responsibilities rest not only on the institution but also on the individual. The prospect of lethal autonomous systems on the future battlefield, for example, has prompted extensive discussion about the potential legal and ethical challenges associated with human accountability for the laws of war, as well as the need to retain human agency and intent in decisions to use force.[145] As one writer has noted, when an autonomous system kills noncombatants, who is responsible? Is it the software programmers who coded for target identification, the system's commanding officer, the combatant commander who authorized the operation and use of the system, or someone else?[146] One guiding concept in this debate has been *meaningful* human control, meaning a human should make the final determination over whether or not to kill another human. It was this logic that prompted DoD

BCI may also contribute to a diffusion of operator responsibility.

to develop a directive requiring that autonomous weapon systems permit operators to exercise "appropriate levels of human judgment over the use of force."[147] As the International Committee of the Red Cross recently proposed, human engagement should be of the "type and degree of control that preserves human agency and upholds moral responsibility in decisions to use force"[148] However, *meaningful* in this context can often be ambiguous and debatable and, thus, should be revisited as new technologies emerge and advance.[149]

The incorporation of AI on the battlefield and the accelerating pace of future warfare may make it increasingly difficult to ensure that DoD preserves "appropriate levels of human judgment" over use-of-force decisions. As noted earlier, BCI may permit humans to accelerate decisionmaking in an effort to maintain operational relevance on a battlefield that incorporates AI.[150] Should this be technically feasible, it is not clear that a decision made within the necessary time frame would allow for reasonable moral and ethical judgment.

BCI may also contribute to a diffusion of operator responsibility. Once humans and machines work more closely (via BCI) to make use-of-force decisions during the heat of combat, it may be more difficult to determine the meaning of *meaningful human control* or "appropriate levels of human judgment." In the traditional military "kill chain," decisions can be rolled back at each stage to determine legal culpability and the existing "kill web," in which several people contribute to a decision error and no one is ultimately found culpable.[151] Could this dynamic be exacerbated by BCI-facilitated decisionmaking in which individuals share thoughts and decisionmaking instantaneously with machines and with one another?

Potential cognitive and emotional changes associated with BCI technologies that modify the human brain raise further questions about operator responsibility. Ethicists have concluded that altering the levels of fear and aggression in service members could "expose soldiers, their missions, and society in general to increased risk of injury or death."[152] A National Academy of Sciences report notes that electrical disruption of one region of the brain may reduce the inhibitions of soldiers about morally problematic behaviors.[153] If these regions are stimulated by BCI during the course of combat and result in atrocities, the report asks, "How and under what circumstances might neurally-manipulated soldiers be accountable for activities that violate the laws of war?"[154] Currently, a soldier is required to refuse an illegal order. Would the soldier's ability to refuse be more complicated if the instructions came directly from a brain implant? If so, how might the erosion of personal agency—and culpability—further influence combat decisionmaking? While such a scenario appears unlikely to emerge in the near or even medium-term future, it is a potential element of the technology's future trajectory that may need to be considered.

Conclusions and Recommendations

Summary and Primary Findings

Former Secretary of Defense Ashton Carter has observed that while "the accelerating pace of innovation is already bringing great progress . . . it would be foolish to let inertia set the agenda."[155] As an example, BCI technologies, developed in part by DoD funding, have advanced significantly in recent years and are likely to continue to progress, whether under government, academic, or private-sector auspices. The U.S. government thus has an opportunity to play a constructive role in the coming decades in supporting elements of BCI technology that benefit U.S. national security and seeking to mitigate risks.

This report has provided an initial evaluation of the potential applications of BCI in a military setting and has highlighted potential policy issues that should be addressed. Our analysis and game prototype contributed to nascent discussions on the extent to which BCI technologies might open up new areas of operational risk during combat. Our work also considered how an evolving relationship between humans and machines, facilitated by BCI, might profoundly alter existing military organizational structures and relationships and pose new ethical and legal challenges for DoD.

In addition to considering policy issues and the potential tactical value of BCI, this research yielded a systematic approach to exploring the implications of emerging technology. This approach, which incorporated technology review, operational considerations, and technology deconstruction (into a set of practical capabilities) into a TTX for testing in-theater implications, is scalable and can be applied to a variety of emerging technologies.

Our game and associated research indicated that despite valid concerns, BCI can likely be useful for future military operations, even in the most difficult test case: infantry ground force combat. This utility may become particularly pronounced once technology for military applications of AI and robotics develops further, and once adversaries have access to these capabilities. Nonetheless, the application of BCI would support ongoing DoD technological initiatives, including human-machine collaboration for improved decisionmaking, assisted-human operations, and advanced manned and unmanned combat teaming.

Of course, as with most significant technological advances, there are potential risks. BCI falls subject to the capability-vulnerability paradox, with counterweighted benefits and risks, and, as development efforts and eventual acquisition efforts progress, requirements will need to account for such risks. Cybersecurity will be a significant risk going forward, amplified by the use of BCI. Because cybernetworks touch nearly all dimensions of BCI, further development of BCI capabilities will have to integrate with associated cybersecurity measures. Our game insights suggested that, while human-to-human communication had the highest reward and greatest number of opportunities for use, it also presented the greatest operational and organizational risks. Risks will depend on whether this capability can be turned on and off and used selectively. The game highlighted a few ideas to mitigate operational risks, including potential use of EW shielding integrated into armor, secure networks, and steps to ensure that traditional backup methods are preserved.

Recommendations

Moving forward, we recommend that the U.S. government conduct additional national security gaming to further assess the operational risks and benefits of BCI technology in combat, including provisions for additional domains and contingencies. Beyond operational risks, the government will need to address a potential lack of trust in BCI technologies, which is an issue that emerged during the game as a potential impediment to adoption by the armed services. This, in turn, requires special attention to how BCI is deployed as it matures. Our review of current technological progress highlighted work done in academic and private-sector laboratories, and the U.S. government should seek to leverage work in both, especially as the commercial sector increasingly dominates technology R&D. Developing and deploying BCI technologies in the national security sector will require institutional adaptation to operators at each stage of the process. Next, we offer some concluding suggestions on each of these points.

Expand Analyses to Illuminate Operational Relevance and Vulnerabilities

Over the coming decades, it will be critical that operational needs and risks, rather than just technical opportunities, drive BCI development. To help support this need, we developed a systematic approach to evaluating the potential operational applications of BCI and other over-the-horizon military technologies. During the TTX testing, pairing of operational experience with technological expertise yielded rigorous and fruitful discussions, and this process should be replicated on a larger scale. These approaches could supplement existing internal exercises, such as the Marine Corps Advanced Naval Technology Exercise, to explore the practical utility of BCI and other prospective technologies to future warfighters.

By incorporating a disruptive and creative Red team of RAND experts, the game also highlighted

It is important to consider ethical and policy issues before emerging technologies mature and are disseminated.

potential new areas of operational vulnerability, as well as initial ideas to mitigate them. As the U.S. government seeks to build resilience from early phases of BCI development, similar methods could help to unearth the full range of adversary threats. Beyond BCI, the approaches developed in this pilot project are scalable and could be applied to a variety of emerging technologies.

Address the Trust Deficit

One major theme to emerge from the study was that cultural barriers to BCI, particularly among infantry service members, are likely to be high, and this is a common theme with many new and emerging technologies. These barriers can be mitigated with the following steps.

As BCI capabilities are integrated into the force, they may initially be more readily accepted among service members who already rely heavily on machine technologies, and who experience greater requirements for direct interaction with computers or machines.

During the R&D process in the coming decades, noninvasive measures are less likely to encounter cultural resistance. They may also be easier to reverse and control. Similarly, work on medical or therapeutic applications may offer near-term benefit for today's wounded warriors and is likely to encounter the least cultural resistance.

Unsurprisingly, service members are more likely to trust capabilities that have been appropriately vetted and tested before use. Thus, once BCI capabilities are further developed, robust testing for failure in noncombat scenarios, including training and data processing and analysis, before introducing them into combat will help to strengthen trust and reduce the potential for unanticipated risk.

Collaborate and Anticipate

Research for this project highlighted multiple examples in which DoD seed funding for BCI laboratory research yielded successes. Significant future advances may take place in the private sector, and the U.S. government should seek to leverage private-sector R&D when possible. If carefully pursued, private-sector advances may also improve trust gaps within the military: As the U.S. public begins to use BCI, there may be less skepticism about its use in a national security setting. As private-sector technology advances and begins to be applied to the military sphere, International Traffic in Arms Regulations, Export Administration Regulations, and other restrictions should be considered with respect to BCI. BCI intellectual property should be carefully monitored by DoD and the Department of Commerce during these early periods of development.

As emerging technology accelerates, it becomes increasingly important to consider integrated systems and how different technologies depend on one other. BCI could prove an important tool for integrating human-machine systems, whether by enhancing big data analysis, accelerating accurate decisionmaking, or improving the control of exoskeleton, drone swarms, or semiautonomous systems. However, there is a risk that the research could occur in isolation without consideration of additional and related emerging technologies. Thus, current development efforts should make provisions for the eventual availability of BCI, even if its applications are currently still in the basic-research phase.

Plan Ahead for BCI Institutional Implications

As the U.S. government prepares to incorporate BCI technologies into future military capabilities, appropriate institutional planning will help to ensure a smooth rollout and execution. It is important to consider ethical and policy issues before emerging technologies mature and are disseminated.

During the research phase, it will be important to continue to integrate ethical, legal, and societal considerations into research funding. DARPA currently requires that research teams conduct ethical analysis for many grants surrounding BCI. Rigorous internal analysis should continue beyond basic research throughout the development, design, and application of new BCI technologies for defense and national security use. The U.S. government should continue to implement National Academy of Sciences ethical recommendations in development and implementation, particularly regarding (1) questions of consent that are specific to service members, (2) potential health implications for invasive BCI, (3) considerations surrounding enhanced human performance, and (4) potential risks to privacy.

As BCI technologies are disseminated across national security institutions, services will want to identify clear oversight mechanisms for BCI development and application. Given the broad range of potential applications for BCI, there is significant risk of stovepiping with related R&D. A department-wide oversight mechanism, potentially residing in the Office of the Secretary of Defense or the Joint Staff, should track and review BCI developments for senior DoD approval. Once BCI is integrated into services, individual services might consider coordinated arbitration mechanisms outside the chain of command to allow service members and their commanding officers to discuss or object to unethical or harmful uses of BCI technology.

Finally, DoD may need to plan for a range of additional warfighter and veteran care needs after the incorporation of BCI technologies. BCI carries the potential for new dimensions of care requirements, potentially including BCI withdrawal, brain injuries, posttraumatic stress disorder, and ongoing care for invasive devices through Veterans Affairs.

Appendix. Game Design and Execution

The table-top game was designed to answer the question, "Can brain-computer interfaces support national security and future warfare and, if so, how?" This question is well-suited to a game for several reasons. It is fundamentally speculative in nature, because there is no way to capture observations of future technological capabilities today. Thus, many empirical approaches, such as prototyping and field experiments, are premature. In the absence of data from early fielding, games represent one of the few ways to gather data about a new technology in a specific setting. We were also interested in questions of human decisionmaking—when given the option of using this technology, would players take it, or would they prefer to depend on more traditional approaches? Perhaps more important, why were they making these decisions? Unlike modeling and simulation, which can provide a detailed sense of what the technology could be capable of, games focus on human decisionmaking and how it will ultimately impact the usefulness of a new tool. Finally, games provide a forum for various experts to pool their collective understanding of a technology like BCI that has not been used in an operational setting. Our game allowed us to synthesize the experience of different players to gain a fuller picture than one-on-one interviews alone could provide.

Vignette Selection

Drawing from our literature review, we selected tactical scenarios related to urban operations to provide a challenging setting for the game. Several criteria drove this selection. First, urban operations are an area of focus for the future force based on global trends. U.S. Army analysis has highlighted the urbanization of global populations and the rise of megacities as key trends that may yield potential requirements for urban combat.[156] Both the Army and the Marine Corps are updating their urban operations doctrine, and their leaderships have publicly advocated for more urban-focused efforts.[157]

Second, urban operations are an area where the value of technological superiority is often called into question. As Joint Publication 3-06, *Joint Urban Operations*, notes, "Cities may reduce the advantages of the technologically superior force."[158]

Finally, the selection of the urban environment played into previously identified cultural barriers. Infantry from the Army and Marine Corps were likely to be the most skeptical of the value of BCI during combat. Infantry has traditionally been the primary fighting force in the urban environment, so setting the game there would provide a strong test of some of the cultural barriers that might prevent effective deployment of BCI.

In the limited scope of our pilot research, we could examine only a handful of vignettes related to one type of operation. Given this restriction, we opted to adopt a logic similar to that of the "critical case."[159] If the game showed that BCI was useful—even under what were projected to be difficult settings—that would offer evidence for the potential utility of BCI on the battlefield.[160] Selecting a stressful scenario increased the likelihood of a robust debate about how and why BCI was or was not useful, giving us richer data to explore.

Game Process

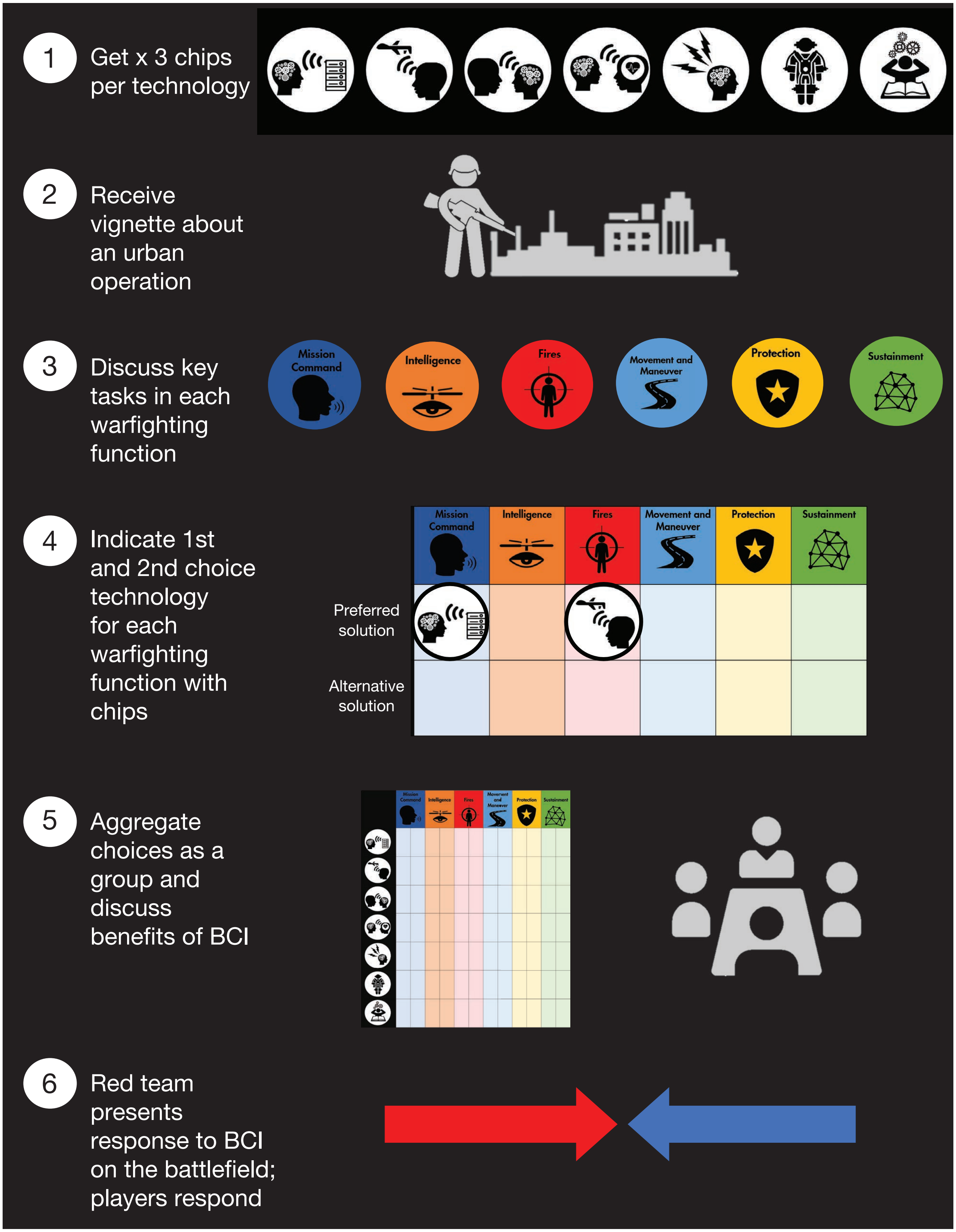
Our game was focused around players deciding what aspect or component of BCI technology they would use in a particular operational context. For each of two vignettes, the game moved through six phases: (1) get chips representing the BCI capabilities itemized in the toolbox, (2) receive a tactical vignette, (3) discuss the tasks that must be completed in the vignette, organized by warfighting functions, (4) as individuals, select which, if any, BCI capabilities players would opt to employ, (5) as a group, discuss selections to note areas of alignment or clarify areas of disagreement, and (6) receive feedback from experts about how adversaries could exploit the BCI capabilities and discuss the risks of the approach developed in steps 4 and 5. Figure A.1 provides a visualization of the game process as a whole.

The first three stages of the game were designed to allow players to develop a common understanding of the BCI toolbox and the challenges associated with the tactical vignette. First, players were introduced to seven capabilities or *tools* in the BCI toolbox (described in detail in the "Testing BCI Capabilities Through National Security Gaming" section). This provided participants with the opportunity to gain a common understanding of the scope of the technology to ensure shared terms of reference. Each tool from the toolbox was represented by a poker chip with an icon illustrating the tool. Players were then confronted with a tactical vignette and given the opportunity to discuss the core tasks associated with each of the joint warfighting functions: command and control, intelligence, fires, movement and maneuver, protection, and sustainment.[161] Use of the joint warfighting functions ensured that participants considered a wide variety of problems, while group discussion allowed for a consensus on the types of tasks involved in each area.

The fourth and fifth steps focused on how players thought BCI could be used. For each warfighting function, players had selected one or two BCI tools they would employ. Players indicated this choice by moving a poker chip with the tool's symbol onto an individual "placemat," which showed each warfighting function (an example is shown in step 4 of Figure A.1). Players had the option to not use any BCI tool and instead depend on traditional solutions, which was indicated by placing no chip on the mat. Players had only three chips for each BCI tool, so while each tool could be used more than once, players could not use the same tool to address all warfighting functions. After individuals had had a chance to make their selections, in the next stage, they presented to the group and discussed key similarities and differences between their selections. This provided an opportunity to clarify differences in understanding and identify trends in player preferences.

FIGURE A.1

BCI TTX Process



Notes

[1] Nick Stockton, "Woman Controls a Fighter Jet Sim Using Only Her Mind," *Wired*, March 5, 2015.

[2] Michael Joseph Gross, "The Pentagon's Push to Program Soldiers' Brains," *The Atlantic*, November 2018.

[3] M. O. Krucoff, S. Rahimpour, M. W. Slutzky, V. R. Edgerton, and D. A. Turner, "Enhancing Nervous System Recovery Through Neurobiologics, Neural Interface Training, and Neurorehabilitation," *Frontiers in Neuroscience***,** Vol. 10, December 2016, p. 584.

[4] William Eliason, "An Interview with Robert Work," *Joint Force Quarterly 84*, January 26, 2017.

[5] Mark Pomerleau, "DoD's Third Offset Strategy: What Man and Machine Can Do Together," *Defense Systems*, May 4, 2016; Aaron Mehta, "Work Outlines Key Steps in Third Offset Tech Development," *Defense News*, December 14, 2015; Jason Sherman, "DoD Unveils Technology Areas That Will Drive 'Third Offset' in Investments, Experimentation," *Inside Defense,* December 9, 2015.

[6] Sydney Freedberg, "Centaur Army: Bob Work, Robotics, and the Third Offset Strategy," *Breaking Defense* blog, 2015. See also Arwen H. DeCostanza, Amar R. Marathe, Addison Bohannon, A. William Evans, Edward T. Palazzolo, Jason S. Metcalfe, and Kaleb McDowell, "Enhancing Human–Agent Teaming with Individualized, Adaptive Technologies: A Discussion of Critical Scientific Questions," Human Research and Engineering Directorate, Army Research Laboratory, May 2018.

[7] Tim Marler, "The American Intellectual Property," *Real Clear Defense*, December 19, 2017.

[8] Pomerleau, 2016; Mehta, 2015; Sherman, 2015.

[9] Daniel Cebul, "DARPA Wants to Connect Human Brains and Machines," *TechWatch*, March 19, 2018.

[10] Sydney Freedberg, "Iron Man, Not Terminator: The Pentagon's Sci Fi Inspirations," *Breaking Defense* blog, May 3, 2016.

[11] Freedberg, 2016.

[12] Defense Advanced Research Projects Agency, "Neural Engineering System Design (NESD) Program," press release, January 19, 2015.

[13] A. F. Salazar-Gomez, J. Del Preto, S. Gil, F. H. Guenther, and D. Rus, "Correcting Robot Mistakes in Real Time Using EEG Signals," *2017 IEEE International Conference on Robotics and Automation (ICRA)*, Singapore, July 2017.

[14] C. S. Nam, A. Nijholt, and F. Lotte, *Brain-Computer Interfaces Handbook*, Boca Raton, Fla.: CRC Press, 2018.

[15] The International BCI Society was founded in 2015.

[16] The first issue of the *Journal of Brain-Computer Interfaces* was published in 2014.

[17] Douglas Fox, "Brain Cells Communicate with Mechanical Pulses, Not Electric Signals," *Scientific American*, April 1, 2018.

[18] H. Berger, "Ueber das Elektroenkephalogramm des Menschen," *Archiv fur Psychiatrie und Nervenkrankheiten*, Vol. 87, 1929, pp. 527–570.

[19] J. J. Vidal, "Towards Direct Brain-Computer Communication," *Annual Review of Biophysics and Bioengineering*, Vol. 2, 1973, pp. 157–180.

[20] There are some nonelectrical signals that also are muffled. For example, functional near-infrared spectroscopy systems use light to measure bold activity in the brain.

[21] "The BRAIN Initiative," homepage, undated-a.

[22] "What Is the BRAIN Initiative?" blog post, Chicago Council on Science and Technology, September 24, 2015.

[23] Defense Advanced Research Projects Agency, "Towards a High-Resolution, Implantable Neural Interface," press release, July 10, 2017.

[24] Patrick Tucker, "The Military Is Altering the Limits of Human Performance," *The Atlantic*, July 14, 2017.

[25] Roger Mola, "Super Helmet: F-35 Pilots Get X-Ray Vision and Other Magic Powers," *Air & Space Magazine,* September 2017.

[26] M. Hajinoroozi, Z. Mao, and Y. Huang, "Prediction of Driver's Drowsy and Alert States from EEG Signals with Deep Learning," *2015 IEEE Sixth International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)*, Cancun, December 13–16, 2015, pp. 493–496; Sara Reardon, "Brain Implants for Mood Disorders Tested in People," *Nature*, Vol. 551, November 30, 2017, p. 549.

[27] S. Chen, "'Forget the Facebook Leak': China Is Mining Data Directly from Workers' Brains on an Industrial Scale," *South China Morning Post*, April 29, 2018.

[28] Stockton, 2015; M. Kryger, B. Wester, E. A. Pohlmeyer, M. Rich, B. John, J. Beaty, M. McLoughlin, M. Boninger, and E. C. Tyler-Kabara, "Flight Simulation Using a Brain-Computer Interface: A Pilot, Pilot Study," *Experimental Neurology*, Vol. 287, 2017, pp. 473–478.

[29] A. F. Salazar-Gomez, J. Del Preto, S. Gil, F. H. Guenther, and D. Rus, "Correcting Robot Mistakes in Real Time Using EEG Signals," *2017 IEEE International Conference on Robotics and Automation (ICRA)*, Singapore, July 2017, pp. 6570–6577.

[30] Human-Oriented Robotics and Control Lab, "Research Project 1: Brain-Swarm Interaction and Control Interfaces," webpage, University of Delaware, undated; Karavas, George, Daniel T. Larsson, and Panagiotis Artemiadis, "A Hybrid Brain-Machine Interface for Control of Robotic Swarms: Preliminary Results," *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Vancouver, Canada, September 24–28, 2017, pp. 5065–5075; A. Beall, "The Drones That Fly Using Mind Control: Swarms of UAVS Developed for the US Military Could Be Guided by Brain Waves, *Daily Mail*, July 19, 2016.

[31] J. Dearen, "Mind-Controlled Drones Race to the Future," Associated Press, 2016.

[32] Chethan Pandarinath, Paul Nuyujukian, Christine H. Blabe, Brittany L. Sorice, Jad Saab, Francis R. Willett, Leigh R. Hochberg, Krishna V. Shenoy, and Jaimie M. Henderson, "High Performance Communication by People with Paralysis Using an Intracortical Brain-Computer Interface," *eLife*, Vol. 6, February 21, 2017.

[33] Stanford Medicine News Center, "Brain-Computer Interface Advance Allows Fast, Accurate Typing by People with Paralysis," press release, February 21, 2017.

[34] A. Regalado, "Reversing Paralysis," *MIT Tech Review*, February 22, 2017; Marco Bonizzato, Galyna Pidpruzhnykova, Jack Digiovanna, Polina Shkorbatova, Natalia Pavlova, Silvestro Micera, and Grégoire Courtine, "Brain-Controlled Modulation of Spinal Circuits Improves Recovery from Spinal Cord Injury," *Nature Communications*, Vol. 9, No. 1, 2018, p. 3015.

[35] Regalado, 2017.

[36] M. Parman, "Robotic Arm Reaches Toward Success," *Johns Hopkins News-Letter*, January 31, 2013; S. N. Flesher, J. L. Collinger, S. T. Foldes, J. M. Weiss, J. E. Downey, E. C. Tyler-Kabara, S. J. Bensmaia, A. B. Schwartz, M. L. Boninger, and R. A. Gaunt, "Intracortical Microstimulation of Human Somatosensory Cortex," *Science Translational Medicine*, Vol. 8, October 19, 2016.

[37] E. A. Pohlmeyer, M. Fifer, M. Rich, J. Pino, B. Wester, M. Johannes, C. Dohopolski, J. Helder, D. D'Angelo, J. Beaty, S. Bensmaia, M. McLoughlin, and F. Tenore, "Beyond Intuitive Anthropomorphic Control: Recent Achievements Using Brain Computer Interface Technologies," in T. George, A. K. Dutta, and S. Islam, eds., *Micro- and Nanotechnology Sensors, Systems, and Applications IX*, Proceedings of SPIE (Society of Photo-optical Instrumentation Engineers), 2017.

[38] S. Saproo, J. Faller, V. Shih, and P. Sajda, "Cortically Coupled Computing: A New Paradigm for Synergistic Human-Machine Interaction," *Computer*, Vol. 45, September 2016.

[39] Darrell Etherington, "Elon Musk Could Soon Share More on His Plan to Help Humans Keep up with AI," *TechCrunch*, January 25, 2017.

[40] A. Kharpal, "Elon Musk: Humans Must Merge with Machines or Become Irrelevant in AI Age," CNBC *Tech Transformers,* February 13, 2017; N. Statt, "Elon Musk Launches Neuralink, a Venture to Merge the Human Brain with AI," *The Verge*, March 27, 2017b.

[41] DARPA, "Progress in Quest to Develop a Human Memory Prosthesis," press release, March 28, 2018; Tristan McClure-Begley, "Restoring Active Memory," Defense Advanced Research Projects Agency, webpage, undated a.

[42] "Prosthetic Memory System Successful in Humans," *Neuroscience News*, Vol. 15, March 28, 2018; R. E. Hampson, D. Song, B. S. Robinson, D. Fetterhoff, A. S. Dakos, B. M. Roeder, X. She, R. T. Wicks, M. R. Witcher, D. E. Couture, A. W. Laxton, H. Munger-Clary, G. Popli, M. J. Soliman, C. T. Whitlow, V. Z. Marmarelis, T. W. Berger, and S. A. Deadwyler, "Developing a Hippocampal Neural Prosthetic to Facilitate Human Memory Encoding and Recall," *Journal of Neural Engineering*, Vol. 15, No. 3, June 2018.

[43] H. Zhao, L. Qiao, D. Fan, S. Zhang, O. Turel, Y. Li, J. Li, G. Xue, A. Chen, and Q. He, "Modulation of Brain Activity with Noninvasive Transcranial Direct Current Stimulation (tDCS): Clinical Applications and Safety Concerns," *Frontiers in Psychology*, Vol. 8, 2017, p. 685.

[44] P. Dockril, "The US Military Is Working on Tech That Could Turn Soldiers into Cyborgs," *Science Alert*, January 22, 2016; T. Hatmaker, "DARPA Awards $65 Million to Develop the Perfect, Tiny Two-Way Brain-Computer Interface," *TechCrunch*, July 10, 2017.

[45] Al Emondi, "Neural Engineering System Design (NESD)," Defense Advanced Research Projects Agency, webpage, undated.

[46] Cebul, 2018.

[47] R. P. N. Rao, A. Stocco, M. Bryan, D. Sarma, T. M. Youngquist, J. Wu, and C. S. Prat, "A Direct Brain-to-Brain Interface in Humans," *PLOS ONE*, Vol. 9, No. 11, November 5, 2014.

[48] L. Jiang, A. Stocco, D. M. Losey, J. A. Abernethy, C. S. Prat, and R. P. N. Rao, "BrainNet: A Multi-Person Brain-to-Brain Interface for Direct Collaboration Between Brains," *Scientific Reports*, Vol. 9, 2019, p. 6115.

[49] M. Pais-Vieira, M. Lebedev, C. Kunicki, J. Wang, and M. A. L. Nicolelis, "A Brain-to-Brain Interface for Real-Time Sharing of Sensorimotor Information," *Scientific Reports*, Vol. 3, 2013, p. 1319.

[50] S. S. Yoo, H. Kim, E. Filandrianos, S. J. Taghados, and S. Park, "Non-Invasive Brain-to-Brain Interface (BBI): Establishing Functional Links Between Two Brains," *PLOS ONE*, Vol. 8, No. 4, 2013.

[51] I. H. Stevenson and K. P. Kording, "How Advances in Neural Recording Affect Data Analysis," *Nature Neuroscience*, Vol. 14, 2011, pp. 139–142.

[52] Defense Advanced Research Projects Agency, 2017.

[53] Samuel Moore, "Wireless Network Brings Dust-Sized Brain Implants a Step Closer," *IEEE Spectrum*, Institute of Electrical and Electronics Engineers, May 14, 2019.

[54] Paradromics, "A New Paradigm in Neural Recording," press release, January 7, 2020.

[55] Chief Information Officer, "DoD Policy Recommendations for the Internet of Things (IoT)," U.S. Department of Defense, Washington, D.C., 2016; M. Weisgerber, "A Short-Staffed Air Force Wants Robots to Do More Human Jobs," *Defense One*, 2017.

[56] V. Machi, "Internet of Things to Provide Intelligence for Urban Warfare," *National Defense*, January 22, 2018a.

[57] Gross, 2018.

[58] N. Statt, "Kernel Is Trying to Hack the Human Brain—but Neuroscience Has a Long Way to Go," *The Verge*, February 22, 2017a.

[59] Statt, 2017b.

[60] Paradromics, homepage, undated.

[61] S. Samuel, "Facebook Is Building Tech to Read Your Mind. The Ethical Implications Are Staggering," *Vox*, August 5, 2019.

[62] Stephan Waldert, "Invasive vs. Non-Invasive Neuronal Signals for Brain-Machine Interfaces: Will One Prevail?" *Frontiers in Neuroscience*, Vol. 10, June 27, 2016, p. 295.

[63] Cebul, 2018.

[64] Lawrence Freedman, *The Future of War: A History*, New York: Hachette Book Group, 2017, p. xxi.

[65] Freedman, 2017.

[66] John D. Winkler, Timothy Marler, Marek N. Posard, Raphael S. Cohen, and Meagan L. Smith, *Reflections on the Future of Warfare and Implications for Personnel Policies of the U.S. Department of Defense*, Santa Monica, Calif.: RAND Corporation, PE-324-OSD, 2019.

[67] Peter Roberts, “The Future Conflict Operating Environment out to 2030,” Royal United Services Institute, *Occasional Papers*, June 3, 2019.

[68] “Future of Warfare,” Center for New American Security, website, undated.

[69] Cognition and Neuroergonomics Collaborative Technology Alliance, "Vision,” webpage, undated.

[70] Jim Nash, “In the Fog of Battle Acoustic Sensors Pinpoint Gunfire by Measuring Air Movement” *Scientific American*, April 30, 2013; Kelsey Atherton “Dedicated Drone Tracker Can Now Detect Swarming Robots,” C4ISR.net, September 20, 2018; Lori Aratani, “Officials Unveil New Facial Recognition System at Dulles International Airport,” *Washington Post*, September 7, 2018; Jamie Condliffe, “Big Investors Are Placing Bets on China’s Facial Recognition Start-ups” *New York Times*, July 24, 2018.

[71] Adam Stone, “The Internet of Battlefield Things Will Depend on Modernized Networks,” C4ISR.net, August 3, 2018.

[72] Winkler et al., 2019.

[73] Jim Lester and Russell Vieira, “U.S. Air Force Combat Cloud Operating Concept,” March 2016, as cited in Aaron Kiser et al., *The Combat Cloud: Multidomain Command and Control Across the Range of Military Operations*, Air Command and Staff College, Air University, Maxwell Air Force Base, Ala., March 2017. See also V. Machi, “Air Force Wants Platforms Built with Connectivity in Mind,” *National Defense*, February 23, 2018b.

[74] Committee on Military and Intelligence Methodology for Emergent Neuropsychologic and Cognitive Neural Science Research in the Next Two Decades, *Emerging Cognitive Neuroscience and Related Technologies*, Washington, D.C.: The National Academies Press, 2008.

[75] Mark Pomerleau, “How Artificial Intelligence Went from an Advantage to a Worldwide Threat,” C4isr.net, April 4, 2018.

[76] “Robotic and Autonomous Systems Strategy,” Headquarters, Department of the Army, Washington, D.C., March 2017.

[77] Eliason, 2017.

[78] Elsa Kania, “Battlefield Singularity: Artificial Intelligence, Military Revolution, and China’s Future Military Power,” Center for New American Security, November 2017, p. 29.

[79] Paul Scharre, *Army of None: Autonomous Weapons and the Future of War*, New York: W. W. Norton & Company, 2018, p. 326.

[80] Todd South, “Drone Swarm Tactics Get Tryout for Infantry to Use in Urban Battlespace,” *Army Times*, January 8, 2018.

[81] Shawn Snow, “No Man’s Land: How New Tactics and Robots Will Push Marines Deeper into the Fight,” *Marine Corps Times*, August 8, 2018.

[82] Peng Yuan, Yijun Wang, Lian Gao, Tzyy-Ping Jung, and Xiaorong Gao, “A Collaborative Brain-Computer Interface for Accelerating Human Decision Making,” in C. Stephanidis and M. Antona, eds., *Universal Access in Human-Computer Interaction: Design Methods, Tools, and Interaction Techniques for eInclusion*, Lecture Notes in Computer Science, Berlin: Springer, Vol. 8009, 2013, pp. 672–681.

[83] Jack Corrigan, “The Pentagon Wants to Bring Mind-Controlled Tech to Troops,” Nextgov.com, July 17, 2018.

[84] Carl Governale, “Brain-Computer Interfaces Are Game Changers,” *Real Clear Defense*, August 31, 2017.

[85] Defense Advanced Research Projects Agency, “N3 Proposers Day,” press release, April 3, 2018.

[86] Kania, 2017.

[87] Amir Husain, *Hyperwar: Conflict and Competition in the AI Century*, Austin, Tex.: SparkCognition, 2018.

[88] Scharre, 2018, p. 321.

[89] Corrigan, 2018.

[90] P. W. Singer, *Wired for War: The Robotics Revolution and Conflict in the Twenty-First Century*, New York: Penguin Press, 2009, p. 126.

[91] “Brain Swarm Interface (BSI)” fact sheet, Multi-robot Systems Lab, Boston University, undated.

[92] Patrick Tucker, “Actual Telepathy Is One Step Closer to the Battlefield,” *Defense One*, September 2, 2014.

[93] Katie Drummond, “Pentagon Preps Soldier Telepathy Push,” *Wired*, May 14, 2009.

[94] Patrick Cutter, “The Shape of Things to Come: The Military Benefits of the Brain-Computer Interface in 2040,” research report for Master of Operational Arts and Sciences, Maxwell Air Force Base, Ala., April 2015.

[95] Noah Shachman, Pentagon’s Mind Reading Computers Replicate,” *Wired*, March 18, 2008.

[96] Cognition and Neuroergonomics Collaborative Technology Alliance, undated.

[97] “Cognition and Neuroergonomics Collaborative Technology Alliance August 2010,” briefing slides for U.S. Army Research Labs and Research, Development and Engineering Command, August 2010.

[98] D. D. Langleben, J. Loughead, W. B. Bilker, K. Ruparel, A. Childress, S. I. Busch, and R. Gur, “Telling the Truth from Lie in Individual Subjects with Fast Event-Related fMRI,” *Human Brain Mapping*, Vol. 26, No. 4, December 2005.

[99] This potential application was identified in Committee on Military and Intelligence Methodology for Emergent Neuropsychologic and Cognitive Neural Science Research in the Next Two Decades, 2008.

[100] Jonathan Moreno, *Mind Wars: Brain Science and the Military in the 21st Century*, New York: Bellevue Literary Press, 2012, p. 144. Moreno address the 2012 state of the art of a “brain prosthesis” chip, genetic alterations that could theoretically

enhance cognition, and electrical stimulation via transcranial direct current stimulation (tDCS) (pp. 143–149).

[101] Murray Carpenter, "Inside the Crazy Lab Where the Army Spikes Its Rations with Caffeine," *Wired*, March 14, 2014.

[102] J. Nelson, R. A. McKinley, C. Phillips, L. McIntire, C. Goodyear, A. Kreiner, and L. Monforton, "The Effects of Transcranial Direct Current Stimulation (tDCS) on Multitasking Throughput Capacity," *Frontiers in Human Neuroscience*, November 29, 2016.

[103] Defense Advanced Research Projects Agency, "Boosting Synaptic Plasticity to Accelerate Learning," press release, March 16, 2016.

[104] "Broad Agency Announcement: Targeted Neuroplasticity Training (TNT)," Solicitation number DARPA-SN-16-20, DARPA Biological Technologies Office, April 1, 2016.

[105] Eric Van Gieson, "Electrical Prescriptions (ElectRx)," Defense Advanced Research Projects Agency, website, undated. Patrick Cutter also makes this point on p. 24 of Cutter, 2015.

[106] Ben Connable, Michael J. McNerney, William Marcellino, Aaron Frank, Henry Hargrove, Marek N. Posard, S. Rebecca Zimmerman, Natasha Lander, Jasen J. Castillo, James Sladden, Anika Binnendijk, Elizabeth M. Bartels, Abby Doll, Rachel Tecott, Benjamin J. Fernandes, Niklas Helwig, Giacomo Persi Paoli, Krystyna Marcinek, and Paul Cornish, *Will to Fight: Returning to the Human Fundamentals of War*, Santa Monica, Calif.: RAND Corporation, RB-10040-A, 2019.

[107] Potential elimination of fear through neuroscience is addressed in Moreno, 2012, pp. 149–151.

[108] Gross, 2018.

[109] The TNT program seeks to "boost the neurochemical signaling in the brain that mediates neural plasticity and facilitates long-term retention of new cognitive skills." Tristan McClure-Begley, "Targeted Neuroplasticity Training (TNT)," Defense Advanced Research Projects Agency, webpage, undated b.

[110] J. J. Vidal, "Tomorrow Soldier: The Military Is Altering the Limits of Human Performance," *Defense One,* July 12, 2017; Y. Tadjdeh, "SOCOM's Top 10 Tech Needs—Biotechnology," *National Defense*, May 2018.

[111] Brian Wang, "TALOS Special Ops Exoskeleton Today and Plans for Exoskeleton Divisions in 2030s," *nextBIG Future*, November 5, 2018.

[112] Bing West, "Urban Warfare, Then and Now," *The Atlantic*, June 30, 2018, as cited in Todd South, "The Future Battlefield: Army, Marines Prepare for 'Massive' Fight in Megacities," *Military Times*, March 6, 2018b.

[113] As described in more detail in the appendix, players always had the option to play an unspecified, non-BCI technology. Players were told to assume that this chip represented an extension of current approaches—for example, the C2 function might be provided by an upgraded radio with greater range and clarity. However, because the technological alternative was not fully fleshed out for players, there is some risk that this approach may have biased players toward using BCI technologies.

[114] Marine Corps Warfighting Publication 12-1-B.1, *Military Operations in Urban Terrain (MOUT)*, Washington, D.C.: Headquarters U.S. Marine Corps, May 2, 2016, pp. C6–C8.

[115] Elliot Ackerman, "Relearning Storm Troop Tactics: The Battle of Fallujah," *Marine Corps Gazette*, September 2006.

[116] Scott Cuomo, "Secretary Mattis' 'Guardian Angel' and How Marine Corps Aviation Can Get Back on Target," *War on the Rocks* blog, July 20, 2017.

[117] Ackerman, 2006.

[118] L. Andrews and J. MacDonald, "Five Costs of Military Innovation," *War on the Rocks* blog, February 18, 2016.

[119] Tucker, 2014.

[120] Thomas Grove, Julian Barnes, and Drew Hinshaw, "Russia Targets NATO Soldier Smartphones, Western Officials Say," *Wall Street Journal*, October 4, 2017; Ellen Nakashima and Paul Sonne, "China Hacked a Navy Contractor and Secured a Trove of Highly Sensitive Data on Submarine Warfare," *Washington Post*, June 8, 2018.

[121] William J Broad, "Microwave Weapons Are Prime Suspect in Ills of U.S. Embassy Workers," *New York Times*, September 1, 2018; Emily Rauhala and Carol Morello, "State Department Warns U.S. Citizens in China After Employee Suffers Possible Sonic Attack," *Washington Post*, May 23, 2018.

[122] "How Medical Devices Like Pacemakers and Insulin Pumps Can Be Hacked," CBS News, November 8, 2018.

[123] "Sinister Text Messages Reveal High-tech Front in Ukraine War," Voice of America News, May 11, 2017.

[124] Shawn Snow, "Enhancing the Grunt: Sophisticated New Tech Means Greater Responsibility, Heavier Load," *Marine Corps Times*, March 2018.

[125] L. Niemela, "What Puts the 'Yuck' in the 'Yuck Factor,'" *Bioethics*, Vol. 25, No. 5, June 2011, pp. 267–279.

[126] Matthew Cox, "The Army Wants Autonomous Aviation Tech. But Do Pilots Trust It?" Military.com, September 6, 2018.

[127] "Thousands of Swedes Are Inserting Microchips Under Their Skin," National Public Radio, *All Things Considered*, October 22, 2018.

[128] Singer, 2009, p. 335.

[129] Julie Carpenter, *Culture and Human-Robot Interaction in Militarized Spaces: A War Story*, Abingdon, UK: Routledge, 2016.

[130] Singer, 2009, p. 335.

[131] Ellen M. McGee and G. Q. Maguire, Jr., "Ethical Assessment of Implantable Brain Chips," paper presented to the Twentieth World Congress of Philosophy, Boston, Mass., August 10–15, 1998.

[132] BRAIN Initiative, "Neuroethics Working Group," webpage, undated-b.

[133] National Research Council and National Academy of Engineering, *Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal,*

and Societal Issues, Washington, D.C.: The National Academies Press, 2014.

[134] National Research Council and National Academy of Engineering, 2014.

[135] National Research Council and National Academy of Engineering, 2014, p. 75.

[136] Bernhard Sehm and Patrick Ragert, "Why Non-Invasive Brain Stimulation Should Not Be Used in Military and Security Services," *Frontiers in Human Neuroscience*, Vol. 7, September 2013.

[137] This point is highlighted in Moreno, 2012, p. 199.

[138] National Research Council and National Academy of Engineering, 2014, p. 74; Moreno, 2012, p. 156.

[139] Sehm and Ragert, 2013; M. N. Tennison and J. D. Moreno, "Neuroscience, Ethics, and National Security: The State of the Art," *PLoS Biology*, Vol. 10, 2012.

[140] National Research Council and National Academy of Engineering, 2014, p. 53.

[141] K. Brukamp and D. Gross, "Neuroenhancement—A Controversial Topic in Contemporary Medical Ethics," in *Contemporary Issues in Bioethics*, D. P. A. Clark, ed., Rijeka, Croatia: InTech, 2012, p. 48. Broader philosophical considerations surrounding human identity and future concepts of "mind-machine merger" are addressed in Susan Schneider, *Artificial You: AI and the Future of Your Mind*, Princeton, N.J.: Princeton University Press, 2019.

[142] Marcello Ienca and Roberto Andorno, "Towards New Human Rights in the Age of Neuroscience and Neurotechnology," *Life Sciences, Society and Policy*, Vol. 13, No. 5, 2017.

[143] J. Brunelin, J. Levasseur-Moreau, and S. Fecteau, "Is It Ethical and Safe to Use Non-Invasive Brain Stimulation as a Cognitive and Motor Enhancer Device for Military Services? A Reply to Sehm and Ragert," *Frontiers in Human Neuroscience*, Vol. 7, 2013.

[144] Corrigan, 2018.

[145] "Ethics and Autonomous Weapon Systems: An Ethical Basis for Human Control?" International Committee of the Red Cross, April 2018.

[146] Singer, 2009, p. 408.

[147] Department of Defense Directive 3000.09, *Autonomy in Weapon Systems*, November 21, 2012; "A Human Touch: Autonomous Weapons, DoD Directive 3000.09 and the Interpretation of 'Appropriate Levels of Human Judgment over the Use of Force,'" in N. Bhuta, S. Beck, R. Geiβ, H. Liu, and C. Kreβ, eds., *Autonomous Weapons Systems: Law, Ethics, Policy*, Cambridge, UK: Cambridge University Press, 2016, pp. 185–208.

[148] "Ethics and Autonomous Weapon Systems: An Ethical Basis for Human Control?" 2018.

[149] Heather M. Roff and Richard Moyes, "Meaningful Human Control, Artificial Intelligence and Autonomous Weapons," briefing paper prepared for the Informal Meeting of Experts on Lethal Autonomous Weapons Systems, UN Convention on Certain Conventional Weapons, April 2016.

[150] Carl Governale, "Brain-Computer Interfaces Are Game Changers," *Real Clear Defense*, August 31, 2017.

[151] Peter W. Singer, appearance on *National Security and the Future of Warfare*, CSPAN, March 18, 2018, 5:02 am–7:00 am EDT; Megan Eckstein, "Interview: Rear Adm. Mike Manazir on Weaving the Navy's New Kill Webs," USNI News, October 3, 2016.

[152] Stockdale Center on Ethical Leadership, U.S. Naval Academy, "New Warriors and New Weapons: The Ethical Ramifications of Emerging Military Technologies," report of the 2010 McCain conference, Annapolis, Md., April 23, 2010, cited in Moreno, 2012, pp. 150–151.

[153] The right temporo-parietal junction; National Research Council and National Academy of Engineering, 2014, p. 77.

[154] National Research Council and National Academy of Engineering, 2014, p. 77.

[155] Ash Carter, "America Needs to Align Technology with a Public Purpose," *Belfer Center for Science and International Affairs Magazine*, November 25, 2018.

[156] Army Capabilities Integration Center, *The Megacity: Operational Challenges for Force 2025 and Beyond, Army Chief of Staff's Future Study Plan*, Washington, D.C.: Headquarters Department of the Army, 2014, cited in Gian Gentile, David E. Johnson, Lisa Saum-Manning, Raphael S. Cohen, Chara Williams, Carrie Lee, Michael Shurkin, Brenna Allen, Sarah Soliman, and James L. Doty III, *Reimagining the Character of Urban Operations for the U.S. Army: How the Past Can Inform the Present and Future*, Santa Monica, Calif.: RAND Corporation, RR-1602-A, 2017.

[157] South, 2018b; Gidget Fuentes, "Marines Experiment with New Technology Concepts for the Urban Battlefield," *USNI News*, March 26, 2018.

[158] U.S. Joint Chiefs of Staff, *Joint Urban Operations*, Joint Publication 3-06, Washington, D.C., November 20, 2013, pp. vii–viii, cited in Gentile et al., 2017, p. 14.

[159] Robert K. Yin, *Case Study Research: Design and Methods*, 2nd ed., Thousand Oaks, Calif.: Sage Publishing, 1994, pp 38–39.

[160] Conversely, had the game not supported the hypothesis, it was only the maximalist version of the hypothesis that would have been rejected—that is, that BCI might not be useful in all settings but may offer enough utility in select areas to be worth investment. However, we felt at this stage of exploration that evidence about where a technology might not be appropriate was likely to be quite valuable in setting reasonable expectations.

[161] U.S. Joint Chiefs of Staff, *Joint Operations*, Joint Publication 3-0, Washington, D.C., January 17, 2017, pp. xiii–xix.

References

Ackerman, Elliot, “Relearning Storm Troop Tactics: The Battle of Fallujah,” *Marine Corps Gazette*, September 2006.

Andrews, L., and J. MacDonald, “Five Costs of Military Innovation,” *War on the Rocks*, February 18, 2016.

Aratani, Lori, “Officials Unveil New Facial Recognition System at Dulles International Airport,” *Washington Post*, September 7, 2018.

Army Capabilities Integration Center, *The Megacity: Operational Challenges for Force 2025 and Beyond, Army Chief of Staff’s Future Study Plan*, Washington, D.C.: Headquarters Department of the Army, 2014.

Atherton, Kelsey, “Dedicated Drone Tracker Can Now Detect Swarming Robots,” C4ISR.net, September 20, 2018.

Beall, A., “The Drones That Fly Using Mind Control: Swarms of UAVS Developed for the US Military Could Be Guided by Brain Waves, *Daily Mail*, July 19, 2016.

Berger, H. “Ueber das Elektroenkephalogramm des Menschen,” *Archiv fur Psychiatrie und Nervenkrankheiten*, Vol. 87, 1929, pp. 527–570.

Bonizzato, Marco, Galyna Pidpruzhnykova, Jack Digiovanna, Polina Shkorbatova, Natalia Pavlova, Silvestro Micera, and Grégoire Courtine, “Brain-Controlled Modulation of Spinal Circuits Improves Recovery from Spinal Cord Injury,” *Nature Communications*, Vol. 9, No. 1, 2018, p. 3015.

BRAIN Initiative, homepage, undated-a. As of May 4, 2020: http://www.braininitiative.org/

———, “Neuroethics Working Group,” webpage, undated-b. As of February 23, 2020: https://braininitiative.nih.gov/about/neuroethics-working-group

Broad, William J., “Microwave Weapons Are Prime Suspect in Ills of U.S. Embassy Workers,” *New York Times*, September 1, 2018.

Brukamp, K., and D. Gross, “Neuroenhancement—A Controversial Topic in Contemporary Medical Ethics,” in *Contemporary Issues in Bioethics*, D. P. A. Clark, ed., Rijeka, Croatia: InTech, 2012.

Brunelin, J., J. Levasseur-Moreau, and S. Fecteau, “Is It Ethical and Safe to Use Non-Invasive Brain Stimulation as a Cognitive and Motor Enhancer Device for Military Services? A Reply to Sehm and Ragert,” *Frontiers in Human Neuroscience*, Vol. 7, 2013, p. 874.

Carpenter, Julie, *Culture and Human-Robot Interaction in Militarized Spaces: A War Story*, Abingdon, UK: Routledge, 2016.

Carpenter, Murray, “Inside the Crazy Lab Where the Army Spikes Its Rations with Caffeine,” *Wired*, March 14, 2014.

Carter, Ash, “America Needs to Align Technology with a Public Purpose,” *Belfer Center for Science and International Affairs Magazine*, November 25, 2018.

Cebul, Daniel, “DARPA Wants to Connect Human Brains and Machines,” *TechWatch*, March 19, 2018.

Center for New American Security, “Future of Warfare,” website, undated. As of January 8, 2019: https://www.cnas.org/research/future-of-warfare

Chen, S., “‘Forget the Facebook Leak’: China Is Mining Data Directly from Workers’ Brains on an Industrial Scale,” *South China Morning Post*, April 29, 2018.

Chief Information Officer, “DoD Policy Recommendations for the Internet of Things (IoT),” U.S. Department of Defense, Washington, D.C., 2016.

Chicago Council on Science and Technology, “What Is the BRAIN Initiative?” blog post, September 24, 2015. As of May 5, 2020: https://www.c2st.org/what-is-the-brain-initiative/

Cognition and Neuroergonomics Collaborative Technology Alliance, "Vision," webpage, undated. As of May 4, 2020: https://www.cancta.net//vision.shtml

———, “Cognition and Neuroergonomics Collaborative Technology Alliance August 2010,” briefing slides for U.S. Army Research Labs and Research, Development and Engineering Command, August 2010.

Committee on Military and Intelligence Methodology for Emergent Neuropsychologic and Cognitive Neural Science Research in the Next Two Decades, *Emerging Cognitive Neuroscience and Related Technologies*, Washington, D.C.: The National Academies Press, 2008.

Condliffe, Jamie, “Big Investors Are Placing Bets on China’s Facial Recognition Start-ups” *New York Times*, July 24, 2018.

Connable, Ben, Michael J. McNerney, William Marcellino, Aaron Frank, Henry Hargrove, Marek N. Posard, S. Rebecca Zimmerman, Natasha Lander, Jasen J. Castillo, James Sladden, Anika Binnendijk, Elizabeth M. Bartels, Abby Doll, Rachel Tecott, Benjamin J. Fernandes, Niklas Helwig, Giacomo Persi Paoli, Krystyna Marcinek, and Paul Cornish, *Will to Fight: Returning to the Human Fundamentals of War*, Santa Monica, Calif.: RAND Corporation, RB-10040-A, 2019. As of May 8, 2020: https://www.rand.org/pubs/research_briefs/RB10040.html

Corrigan, Jack, “The Pentagon Wants to Bring Mind-Controlled Tech to Troops,” Nextgov.com, July 17, 2018. As of May 8, 2020: https://www.nextgov.com/emerging-tech/2018/07/pentagon-wants-bring-mind-controlled-tech-troops/149776/

Cox, Matthew, “The Army Wants Autonomous Aviation Tech. But Do Pilots Trust It?” Military.com, September 6, 2018.

Cuomo, Scott, “Secretary Mattis’ ‘Guardian Angel’ and How Marine Corps Aviation Can Get Back on Target,” *War on the Rocks*, July 20, 2017.

Cutter, Patrick, “The Shape of Things to Come: The Military Benefits of the Brain-Computer Interface in 2040,” research report for Master of Operational Arts and Sciences, Maxwell Air Force Base, Ala., April 2015.

DARPA—*See* Defense Advanced Research Projects Agency.

Dearen, J., “Mind-Controlled Drones Race to the Future,” Associated Press, 2016.

DeCostanza, Arwen H., Amar R. Marathe, Addison Bohannon, A. William Evans, Edward T. Palazzolo, Jason S. Metcalfe, and Kaleb McDowell, “Enhancing Human-Agent Teaming with Individualized, Adaptive Technologies: A Discussion of Critical Scientific Questions,” Human Research and Engineering Directorate, Army Research Laboratory, May 2018.

Defense Advanced Research Projects Agency, “Neural Engineering System Design (NESD) Program,” press release, January 19, 2015. As of May 5, 2020: https://www.darpa.mil/news-events/2015-01-19

———, “Boosting Synaptic Plasticity to Accelerate Learning,” press release, March 16, 2016. As of May 4, 2020: https://www.darpa.mil/news-events/2016-03-16

———, “Towards a High-Resolution, Implantable Neural Interface,” press release, July 10, 2017.

———, “Progress in Quest to Develop a Human Memory Prosthesis,” press release, March 28, 2018.

———, “N3 Proposers Day,” press release, April 3, 2018.

Department of Defense Directive 3000.09, *Autonomy in Weapon Systems*, November 21, 2012.

Dockril, P., “The US Military Is Working on Tech That Could Turn Soldiers into Cyborgs,” *Science Alert*, January 22, 2016.

Drummond, Katie, “Pentagon Preps Soldier Telepathy Push,” *Wired*, May 14, 2009.

Eckstein, Megan, “Interview: Rear Adm. Mike Manazir on Weaving the Navy’s New Kill Webs,” *USNI News*, October 3, 2016.

Eliason, William, “An Interview with Robert Work,” *Joint Force Quarterly 84*, January 26, 2017. As of May 6, 2020: https://ndupress.ndu.edu/Media/News/Article/1038783/an-interview-with-robert-o-work/

Emondi, Al, “Neural Engineering System Design (NESD),” Defense Advanced Research Projects Agency, webpage, undated. As of May 7, 2020: https://www.darpa.mil/program/neural-engineering-system-design

Etherington, Darrell, “Elon Musk Could Soon Share More on His Plan to Help Humans Keep up with AI,” *TechCrunch*, January 25, 2017.

Flesher, S. N., J. L. Collinger, S. T. Foldes, J. M. Weiss, J. E. Downey, E. C. Tyler-Kabara, S. J. Bensmaia, A. B. Schwartz, M. L. Boninger, and R. A. Gaunt, “Intracortical Microstimulation of Human Somatosensory Cortex,” *Science Translational Medicine*, Vol. 8, October 19, 2016.

Fox, Douglas, “Brain Cells Communicate with Mechanical Pulses, Not Electric Signals,” *Scientific American*, April 1, 2018.

Freedberg, Sydney, “Centaur Army: Bob Work, Robotics, and the Third Offset Strategy,” *Breaking Defense* blog, 2015.

———, “Iron Man, Not Terminator: The Pentagon’s Sci Fi Inspirations,” *Breaking Defense* blog, May 3, 2016.

Freedman, Lawrence, *The Future of War: A History*, New York: Hachette Book Group, 2017.

Fuentes, Gidget, “Marines Experiment with New Technology Concepts for the Urban Battlefield,” *USNI News*, March 26, 2018. As of May 14, 2020: https://news.usni.org/2018/03/26/marines-experiment-new-technology-concepts-urban-battlefield

Gentile, Gian, David E. Johnson, Lisa Saum-Manning, Raphael S. Cohen, Chara Williams, Carrie Lee, Michael Shurkin, Brenna Allen, Sarah Soliman, and James L. Doty III, *Reimagining the Character of Urban Operations for the U.S. Army: How the Past Can Inform the Present and Future*, Santa Monica, Calif.: RAND Corporation, RR-1602-A, 2017. As of May 5, 2020: https://www.rand.org/pubs/research_reports/RR1602.html

Governale, Carl, “Brain-Computer Interfaces Are Game Changers,” *Real Clear Defense*, August 31, 2017.

Gross, Michael Joseph, “The Pentagon’s Push to Program Soldiers’ Brains,” *The Atlantic*, November 2018.

Grove, Thomas, Julian Barnes, and Drew Hinshaw, “Russia Targets NATO Soldier Smartphones, Western Officials Say,” *Wall Street Journa*l, October 4, 2017.

Hajinoroozi, M., Z. Mao, and Y. Huang, “Prediction of Driver’s Drowsy and Alert States from EEG Signals with Deep Learning,” *2015 IEEE Sixth International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)*, Cancun, December 13–16, 2015, pp. 493–496.

Hampson, R. E., D. Song, B. S. Robinson, D. Fetterhoff, A. S. Dakos, B. M. Roeder, X. She, R. T. Wicks, M. R. Witcher, D. E. Couture, A. W. Laxton, H. Munger-Clary, G. Popli, M. J. Soliman, C. T. Whitlow, V. Z. Marmarelis, T. W. Berger, and S. A. Deadwyler, “Developing a Hippocampal Neural Prosthetic to Facilitate Human Memory Encoding and Recall,” *Journal of Neural Engineering*, Vol. 15, No. 3, June 2018.

Hatmaker, T., “DARPA Awards $65 Million to Develop the Perfect, Tiny Two-Way Brain-Computer Interface,” *TechCrunch*, July 10, 2017.

“How Medical Devices Like Pacemakers and Insulin Pumps Can Be Hacked,” CBS News, November 8, 2018.

Human-Oriented Robotics and Control Lab, “Research Project 1: Brain-Swarm Interaction and Control Interfaces,” University of Delaware, webpage, undated. As of May 6, 2020: https://sites.udel.edu/horclab/research-bsi/

Husain, Amir, *Hyperwar: Conflict and Competition in the AI Century*, Austin, Tex.: SparkCognition, 2018.

Ienca, Marcello, and Roberto Andorno, “Towards New Human Rights in the Age of Neuroscience and Neurotechnology,” *Life Sciences, Society and Policy*, Vol. 13, No. 5, 2017.

International Committee of the Red Cross, “Ethics and Autonomous Weapon Systems: An Ethical Basis for Human Control?” April 2018.

Jiang, L., A. Stocco, D. M. Losey, J. A. Abernethy, C. S. Prat, and R. P. N. Rao, “BrainNet: A Multi-Person Brain-to-Brain Interface for Direct Collaboration Between Brains,” *Scientific Reports*, Vol. 9, 2019, p. 6115.

Kania, Elsa, “Battlefield Singularity: Artificial Intelligence, Military Revolution, and China’s Future Military Power,” Center for New American Security, November 2017.

Karavas, George, Daniel T. Larsson, and Panagiotis Artemiadis, “A Hybrid Brain-Machine Interface for Control of Robotic Swarms: Preliminary Results,” *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Vancouver, Canada, September 24–28, 2017, pp. 5065–5075.

Kharpal, A., “Elon Musk: Humans Must Merge with Machines or Become Irrelevant in AI Age,” CNBC *Tech Transformers,* February 13, 2017.

Kiser, Aaron, Jacob Hess, Mostafa El Bouhafa, and Shawn Williams, "The Combat Cloud: Enabling Multi-Domain Command and Control Across the Range of Military Operations," Air Command and Staff College, Air University, Maxwell Air Force Base, Ala., March 2017.

Krucoff, M. O., S. Rahimpour, M. W. Slutzky, V. R. Edgerton, and D. A. Turner, "Enhancing Nervous System Recovery Through Neurobiologics, Neural Interface Training, and Neurorehabilitation," *Frontiers in Neuroscience*, Vol. 10, December 2016, p. 584. As of May 5, 2020: https://doi.org/10.3389/fnins.2016.00584

Kryger, M., B. Wester, E. A. Pohlmeyer, M. Rich, B. John, J. Beaty, M. McLoughlin, M. Boninger, and E. C. Tyler-Kabara, "Flight Simulation Using a Brain-Computer Interface: A Pilot, Pilot Study," *Experimental Neurology*, Vol. 287, 2017, pp. 473–478.

Langleben, D. D., J. Loughead, W. B. Bilker, K. Ruparel, A. Childress, S. I. Busch, and R. Gur, "Telling the Truth from Lie in Individual Subjects with Fast Event-Related fMRI," *Human Brain Mapping*, Vol. 26, No. 4, December 2005, pp. 262–272.

Lester, Jim, and Russell Vieira, "U.S. Air Force Combat Cloud Operating Concept," March 2016, as cited in Aaron Kiser, Jacob Hess, Mostafa El Bouhafa, and Shawn Williams, *The Combat Cloud: Multidomain Command and Control Across the Range of Military Operations*, Air Command and Staff College, Air University, Maxwell Air Force Base, Ala., March 2017.

Machi, V., "Internet of Things to Provide Intelligence for Urban Warfare," *National Defense*, January 22, 2018a.

———, "Air Force Wants Platforms Built with Connectivity in Mind," *National Defense*, February 23, 2018b.

Marine Corps Warfighting Publication 12-1-B.1, *Military Operations in Urban Terrain (MOUT)*, Washington, D.C.: Headquarters U.S. Marine Corps, May 2, 2016 .

Marler, Tim, "The American Intellectual Property," *Real Clear Defense*, December 19, 2017.

McClure-Begley, Tristan, "Restoring Active Memory," Defense Advanced Research Projects Agency, webpage, undated a. As of May 5, 2020: https://www.darpa.mil/program/restoring-active-memory

———, "Targeted Neuroplasticity Training (TNT)," Defense Advanced Research Projects Agency, webpage, undated b. As of May 14, 2020: https://www.darpa.mil/program/targeted-neuroplasticity-training

McGee, Ellen M., and G. Q. Maguire, Jr., "Ethical Assessment of Implantable Brain Chips," paper presented to the Twentieth World Congress of Philosophy, Boston, Mass., August 10–15, 1998.

Mehta, Aaron, "Work Outlines Key Steps in Third Offset Tech Development," *Defense News*, December 14, 2015.

Mola, Roger, "Super Helmet: F-35 Pilots Get X-Ray Vision and Other Magic Powers," *Air & Space Magazine*, September 2017.

Moore, Samuel, "Wireless Network Brings Dust-Sized Brain Implants a Step Closer," *IEEE Spectrum*, Institute of Electrical and Electronics Engineers, May 14, 2019.

Moreno, Jonathan, *Mind Wars: Brain Science and the Military in the 21st Century*, New York: Bellevue Literary Press, 2012.

Multi-robot Systems Lab, Boston University, "Brain Swarm Interface (BSI)" fact sheet, undated. As of May 8, 2020: http://sites.bu.edu/msl/research/brain-swarm-interface-bsi/

Nakashima, Ellen, and Paul Sonne, "China Hacked a Navy Contractor and Secured a Trove of Highly Sensitive Data on Submarine Warfare," *Washington Post*, June 8, 2018.

Nam, C. S., A. Nijholt, and F. Lotte, *Brain-Computer Interfaces Handbook*, Boca Raton, Fla.: CRC Press, 2018.

Nash, Jim, "In the Fog of Battle Acoustic Sensors Pinpoint Gunfire by Measuring Air Movement" *Scientific American*, April 30, 2013.

National Research Council and National Academy of Engineering, *Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal, and Societal Issues*, Washington, D.C.: The National Academies Press, 2014.

Nelson, J., R. A. McKinley, C. Phillips, L. McIntire, C. Goodyear, A. Kreiner, and L. Monforton, "The Effects of Transcranial Direct Current Stimulation (tDCS) on Multitasking Throughput Capacity," *Frontiers in Human Neuroscience*, November 29, 2016.

Niemela, L., "What Puts the 'Yuck' in the 'Yuck Factor,'" *Bioethics*, Vol. 25, No. 5, June 2011, pp. 267–279.

Pais-Vieira, M., M. Lebedev, C. Kunicki, J. Wang, and M. A. L. Nicolelis, "A Brain-to-Brain Interface for Real-Time Sharing of Sensorimotor Information," *Scientific Reports*, Vol. 3, 2013.

Pandarinath, Chethan, Paul Nuyujukian, Christine H. Blabe, Brittany L. Sorice, Jad Saab, Francis R. Willett, Leigh R. Hochberg, Krishna V. Shenoy, and Jaimie M. Henderson, "High Performance Communication by People with Paralysis Using an Intracortical Brain-Computer Interface," *eLife*, Vol. 6, February 21, 2017.

Paradromics, homepage, undated. As of May 7, 2020: https://paradromics.com/

———, "A New Paradigm in Neural Recording," press release, January 7, 2020.

Parman, M., "Robotic Arm Reaches Toward Success," *Johns Hopkins News-Letter*, January 31, 2013.

Pohlmeyer, Eric A., M. Fifer, M. Rich, J. Pino, B. Wester, M. Johannes, C. Dohopolski, J. Helder, D. D'Angelo, J. Beaty, S. Bensmaia, M. McLoughlin, and F. Tenore, "Beyond Intuitive Anthropomorphic Control: Recent Achievements Using Brain Computer Interface Technologies," in T. George, A. K. Dutta, and S. Islam, eds., *Micro- and Nanotechnology Sensors, Systems, and Applications IX*, Proceedings of SPIE (Society of Photo-optical Instrumentation Engineers), 2017.

Pomerleau, Mark, "DoD's Third Offset Strategy: What Man and Machine Can Do Together," *Defense Systems*, May 4, 2016.

———, "How Artificial Intelligence Went from an Advantage to a Worldwide Threat," C4isr.net, April 4, 2018.

"Prosthetic Memory System Successful in Humans," *Neuroscience News*, Vol. 15, March 28, 2018.

Rao, R. P. N., A. Stocco, M. Bryan, D. Sarma, T. M. Youngquist, J. Wu, and C. S. Prat, "A Direct Brain-to-Brain Interface in Humans," *PLOS ONE*, Vol. 9, No. 11, November 5, 2014.

Rauhala, Emily, and Carol Morello, "State Department Warns U.S. Citizens in China After Employee Suffers Possible Sonic Attack," *Washington Post*, May 23, 2018.

Reardon, Sara, “Brain Implants for Mood Disorders Tested in People,” *Nature*, Vol. 551, November 30, 2017, p. 549.

Regalado, A., “Reversing Paralysis,” *MIT Tech Review*, February 22, 2017.

Roberts, Peter, “The Future Conflict Operating Environment out to 2030,” Royal United Services Institute, *Occasional Papers*, June 3, 2019.

“Robotic and Autonomous Systems Strategy,” Headquarters, Department of the Army, Washington, D.C., March 2017.

Roff, Heather M., and Richard Moyes, “Meaningful Human Control, Artificial Intelligence and Autonomous Weapons,” briefing paper prepared for the Informal Meeting of Experts on Lethal Autonomous Weapons Systems, UN Convention on Certain Conventional Weapons, April 2016.

Salazar-Gomez, A. F., J. Del Preto, S. Gil, F. H. Guenther, and D. Rus, “Correcting Robot Mistakes in Real Time Using EEG Signals,” *2017 IEEE International Conference on Robotics and Automation (ICRA)*, Singapore, July 2017, pp. 6570–6577.

Samuel, S., “Facebook Is Building Tech to Read Your Mind. The Ethical Implications Are Staggering,” *Vox*, August 5, 2019.

Saproo, S., J. Faller, V. Shih, and P. Sajda, “Cortically Coupled Computing: A New Paradigm for Synergistic Human-Machine Interaction,” *Computer*, Vol. 45, September 2016.

Saxon, D., “A Human Touch: Autonomous Weapons, DoD Directive 3000.09 and the Interpretation of ‘Appropriate Levels of Human Judgment over the Use of Force,’” in N. Bhuta, S. Beck, R. Geiβ, H. Liu, and C. Kreβ, eds., *Autonomous Weapons Systems: Law, Ethics, Policy*, Cambridge, UK: Cambridge University Press, 2016, pp. 185–208.

Scharre, Paul, *Army of None: Autonomous Weapons and the Future of War*, New York: W. W. Norton & Company, 2018.

Schneider, Susan, *Artificial You: AI and the Future of Your Mind*, Princeton, N.J.: Princeton University Press, 2019.

Sehm, Bernhard, and Patrick Ragert, “Why Non-Invasive Brain Stimulation Should Not Be Used in Military and Security Services,” *Frontiers in Human Neuroscience*, Vol. 7, September 2013, p. 553.

Shachman, Noah, “Pentagon’s Mind Reading Computers Replicate,” *Wired*, March 18, 2008.

Sherman, Jason, “DoD Unveils Technology Areas That Will Drive ‘Third Offset’ in Investments, Experimentation,” *Inside Defense*, December 9, 2015.

Singer, Peter W., appearance on *National Security and the Future of Warfare*, CSPAN, March 18, 2018.

———, *Wired for War: The Robotics Revolution and Conflict in the Twenty-First Century*, New York: Penguin Press, 2009.

“Sinister Text Messages Reveal High-tech Front in Ukraine War,” Voice of America News, May 11, 2017.

Snow, Shawn, “Enhancing the Grunt: Sophisticated New Tech Means Greater Responsibility, Heavier Load,” *Marine Corps Times*, March 2018a.

———, “No Man’s Land: How New Tactics and Robots Will Push Marines Deeper into the Fight,” *Marine Corps Times*, August 8, 2018b.

South, Todd, “Drone Swarm Tactics Get Tryout for Infantry to Use in Urban Battlespace,” *Army Times*, January 8, 2018a.

———, “The Future Battlefield: Army, Marines Prepare for ‘Massive’ Fight in Megacities,” *Military Times*, March 6, 2018b. As of May 14, 2020: https://www.militarytimes.com/news/your-army/2018/03/06/the-future-battlefield-army-marines-prepare-for-massive-fight-in-megacities/

Stanford Medicine News Center, “Brain-Computer Interface Advance Allows Fast, Accurate Typing by People with Paralysis,” press release, February 21, 2017. As of May 4, 2020: https://med.stanford.edu/news/all-news/2017/02/brain-computer-interface-allows-fast-accurate-typing-by-people-with-paralysis.html

Statt, N., “Kernel Is Trying to Hack the Human Brain—but Neuroscience Has a Long Way to Go,” *The Verge*, February 22, 2017a.

———, “Elon Musk Launches Neuralink, a Venture to Merge the Human Brain with AI,” *The Verge*, March 27, 2017b.

Stevenson, I. H., and K. P. Kording, “How Advances in Neural Recording Affect Data Analysis,” *Nature Neuroscience*, Vol. 14, 2011, pp. 139–142.

Stockdale Center on Ethical Leadership, U.S. Naval Academy, “New Warriors and New Weapons: The Ethical Ramifications of Emerging Military Technologies,” report of the 2010 McCain conference, Annapolis, Md., April 23, 2010.

Stockton, Nick, “Woman Controls a Fighter Jet Sim Using Only Her Mind,” *Wired*, March 5, 2015.

Stone, Adam, “The Internet of Battlefield Things Will Depend on Modernized Networks,” C4ISR.net, August 3, 2018.

Tadjdeh, Y., “SOCOM’s Top 10 Tech Needs—Biotechnology,” *National Defense*, May 2018.

Tennison, M. N., and J. D. Moreno, “Neuroscience, Ethics, and National Security: The State of the Art,” *PLoS Biology*, Vol. 10, 2012.

“Thousands of Swedes Are Inserting Microchips Under Their Skin,” National Public Radio, *All Things Considered*, October 22, 2018.

Tucker, Patrick, “Actual Telepathy Is One Step Closer to the Battlefield,” *Defense One*, September 2, 2014.

———, “The Military Is Altering the Limits of Human Performance,” *The Atlantic*, July 14, 2017.

U.S. Joint Chiefs of Staff, J*oint Urban Operations*, Joint Publication 3-06, Washington, D.C., November 20, 2013.

———, *Joint Operations*, Joint Publication 3-0, Washington, D.C., January 17, 2017.

Van Gieson, Eric, “Electrical Prescriptions (ElectRx),” Defense Advanced Research Projects Agency, website, undated. As of August 26, 2019: https://www.darpa.mil/program/electrical-prescriptions

Vidal, J. J., “Towards Direct Brain-Computer Communication,” *Annual Review of Biophysics and Bioengineering*, Vol. 2, 1973, pp. 157–180.

———, “Tomorrow Soldier: The Military Is Altering the Limits of Human Performance,” *Defense One*, July 12, 2017.

Waldert, Stephan, “Invasive vs. Non-Invasive Neuronal Signals for Brain-Machine Interfaces: Will One Prevail?” *Frontiers in Neuroscience*, Vol. 10, June 27, 2016, p. 295.

Wang, Brian, "TALOS Special Ops Exoskeleton Today and Plans for Exoskeleton Divisions in 2030s," *nextBIG Future*, November 5, 2018.

Weisgerber, M., "A Short-Staffed Air Force Wants Robots to Do More Human Jobs," *Defense One*, 2017.

West, Bing, "Urban Warfare, Then and Now," *The Atlantic*, June 30, 2018. As of May 14, 2020: https://www.theatlantic.com/international/archive/2017/06/urban-warfare-hue-mosul/532173/

Winkler, John D., Timothy Marler, Marek N. Posard, Raphael S. Cohen, and Meagan L. Smith, *Reflections on the Future of Warfare and Implications for Personnel Policies of the U.S. Department of Defense*, Santa Monica, Calif.: RAND Corporation, PE-324-OSD, 2019. As of May 7, 2020: https://www.rand.org/pubs/perspectives/PE324.html

Yuan, Peng, Yijun Wang, Lian Gao, Tzyy-Ping Jung, and Xiaorong Gao, "A Collaborative Brain-Computer Interface for Accelerating Human Decision Making," in C. Stephanidis and M. Antona, eds., *Universal Access in Human-Computer Interaction: Design Methods, Tools, and Interaction Techniques for eInclusion*, Lecture Notes in Computer Science, Berlin: Springer, Vol. 8009, 2013, pp. 672–681.

Yin, Robert K., *Case Study Research: Design and Methods*, 2nd ed., Thousand Oaks, Calif.: Sage Publishing, 1994.

Yoo, S. S., H. Kim, E. Filandrianos, S. J. Taghados, and S. Park, "Non-Invasive Brain-to-Brain Interface (BBI): Establishing Functional Links Between Two Brains," *PLOS ONE*, Vol. 8, No. 4, 2013.

Zhao, H., L. Qiao, D. Fan, S. Zhang, O. Turel, Y. Li, J. Li, G. Xue, A. Chen, and Q. He, "Modulation of Brain Activity with Noninvasive Transcranial Direct Current Stimulation (tDCS): Clinical Applications and Safety Concerns," *Frontiers in Psychology*, Vol. 8, 2017, p. 685.

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About This Report

This report reviews the operational utility and policy considerations of the potential future application of brain-computer interface technologies in military combat. This report is part of a broader effort, an initiative of RAND Ventures, to envision critical security challenges in the world of 2040, considering the effects of political, technological, social, and demographic trends that will shape those security challenges in the coming decades. The research was conducted within the RAND Center for Global Risk and Security.

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The Department of Defense has invested in the development of technologies that allow the human brain to communicate directly with machines, including the development of implantable neural interfaces able to transfer data between the human brain and the digital world. This technology, known as brain-computer interface (BCI) may be used to monitor a soldier's cognitive workload, control a drone swarm, or link with a prosthetic, among other examples. Further technological advances could support human-machine decision making, human-to-human communication, system control, performance enhancement and monitoring, and training. However, numerous policy, safety, legal, and ethical issues should be evaluated before the technology is widely deployed. This project developed a national security game to explore the use of BCI in future combat scenarios, convened experts in military operations, human performance, and neurology to explore how the technology might affect military tactics, which aspects may be most beneficial, and which aspects might present risks, and offered recommendations to policymakers. The project sought to assess current and potential BCI applications for the military to ensure that the technology responds to actual needs, practical realities, and legal and ethical considerations, in addition to the intentions of developers.

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