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Concepts for Developing and Utilizing Crowdsourcing for Neurotechnology Advancement

by Kaleb McDowell, Keith W. Whitaker, W. David Hairston, and
Kelvin S. Oie

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14. ABSTRACT

There is a large general interest in the development of brain-computer interactive technologies (BCIT), which couple the power of machines with the complexity and flexibility of the human brain. However, currently there is a gap between a general understanding of brain function and related neuroimaging tools, which is mostly limited to highly trained neuroscientists and engineers who wish to capitalize on this knowledge base. This program proposal outlines a three-pronged approach aimed to help bridge this gap while simultaneously spurring public interest in the BCIT field. It entails: (1) development and distribution of low-cost, modular electroencephalography (EEG) headsets, which can be assembled and used by a novice, (2) development of a series of tutorial modules on EEG data collection intended for users to become armature developers of BCIT applications, and (3) a Grand Challenge series centered around the use of crowdsourcing as a means of widespread application development. Included are some programmatic suggestions, as well as exemplar applications to fit this end goal.

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1. Summary

Informal discussions among personnel at the U.S. Army Research Laboratory (ARL) and other Department of Defense (DOD) agencies have led to the idea of generating extremely low cost (less than $100) neuroimaging technologies to enable a new generation of entrepreneurs and inventors to enter the rapidly growing brain/computer interaction technologies (BCIT) market. As roughly outlined, a two-stage process has been suggested involving: (1) proof-of-principle sensor hardware developed under a program, such as a Small Business Innovative Research (SBIR) award and (2) crowdsourcing to develop operationally relevant neurotechnologies through a program, such as a Grand Challenge.

The idea of low-cost brain activity sensors coupled with a Grand Challenge is inspiring and has the potential to yield a broad variety of novel, innovative neurotechnologies. This idea can also introduce and develop unique skills within the future workforce. As the Defense Advance Research Projects Agency (DARPA) Grand Challenges have demonstrated success in sparking interest in neuroscience-related problems among professionals in other fields, such as engineering and computer science, utilizing this approach to inspire true crowdsourcing approaches to neurotechnology development seems likely to result in technologies with significant military relevance, directly enhancing ARL's translational neuroscience goals.

Making the leap between low-cost hardware development and the use of such hardware in successful crowdsourced neurotechnology development, however, presents a significant challenge. We propose that achieving the vision delineated in these discussions will require bridging the knowledge and experience gap between scientists and technology innovators. In particular, scientists have deep knowledge of brain function and the signals available through neuroimaging measurement technologies, whereas the technology developers can apply their skills to advance crowdsourced applications development. This gap is *not* insurmountable. Indeed, we believe this situation presents a unique opportunity for the DOD to shape the future of this emerging field. In the following, we outline a three-pronged program that will systematically build the hardware, software, and knowledge infrastructure needed to provide a new generation of technology developers with the resources to focus their efforts on brain/computer interface technology applications that will, thus, enable emergence of advanced capabilities for tomorrow's Warfighters.

2.   Overview

As a distributed problem-solving and production model, crowdsourcing is a proven approach to product and technology development. The program concept presented here aims to use crowdsourcing to spur rapid advances in BCITs. The concept comprises the following three-pronged approach:

1. **Prong I: Modular EEG Hardware**. Produce 1000 low-channel density modular electroencephalography (EEG) "kits" to remove the limitations that exist in current low-cost solutions that inhibit the potential ingenuity of application developers. Current state-of-the-art technology and manufacturing options suggest that creation of such kits is feasible on a very short time scale using existing technologies.

2. **Prong II: Crowdsourcing Software Modules**. Utilize crowdsourcing among experts in the neuroscience research and neurotechnology development community to create a set of tutorials for interested technology developers with minimal knowledge in BCIT development. The tutorials will guide the users to quickly reproduce exemplar BCITs using the modular EEG hardware from Prong I. The tutorials should utilize an open-source software platform and should systematically introduce critical knowledge to bridge the gap between neuroscience experts and technology innovators.

3. **Prong III: Crowdsourcing BCIT Development**. Conduct a Grand Challenge to incentivize crowdsourced application development for novel, innovative BCITs within an expanded science and technology (S&T) developer community.

The systematic development of hardware, software, and knowledge infrastructure within such a program will likely result in new technologies with significant military relevance, and it will encourage a new generation of technology developers to use these resources and this knowledge to focus their efforts on BCIT applications to provide advanced capabilities to tomorrow's Warfighters.

2.1   Rationale

It is widely believed that the emerging field of neuroscience-based technologies, or "neurotechnologies," presents tremendous potential to revolutionize Warfighter capabilities. Yet the development of neurotechnologies, including the development of BCITs, remains limited to a relatively small circle of scientists and technology developers and has not achieved a broader focus within the greater S&T development community. It is likely that the inability to tap into the broad-based workforce within the S&T community has limited innovation in BCIT development to date.

In part, the lack of a broad-based workforce focused on BCIT development is due to the incredible complexity of brain and nervous system function and the vast breadth and depth of the neuroscience knowledge base. On one hand, this has driven the vast majority of neuroscience researchers to focus on understanding *how the brain works*, rather than on the translational question of *how to use* information about the brain to develop practical applications. On the other hand, the neuroscience knowledge needed for neurotechnology development represents a significant barrier to entry by application developers who do not already have a sophisticated knowledge of human brain function and neuroimaging measurement approaches.

In the approach described here and summarized in figure 1, hardware, software, and crowdsourcing of application development are approached in three interrelated "prongs." The development of innovative Warfighter BCIT applications will be the most direct outcome of the program. However, bridging the gap between neuroscience experts with deep knowledge of brain function and the signals available through neuroimaging measurement technologies and technology innovators who can advance technology applications development may ultimately be the greater and more lasting contribution of such a program.

Figure 1. Overall project timeline.
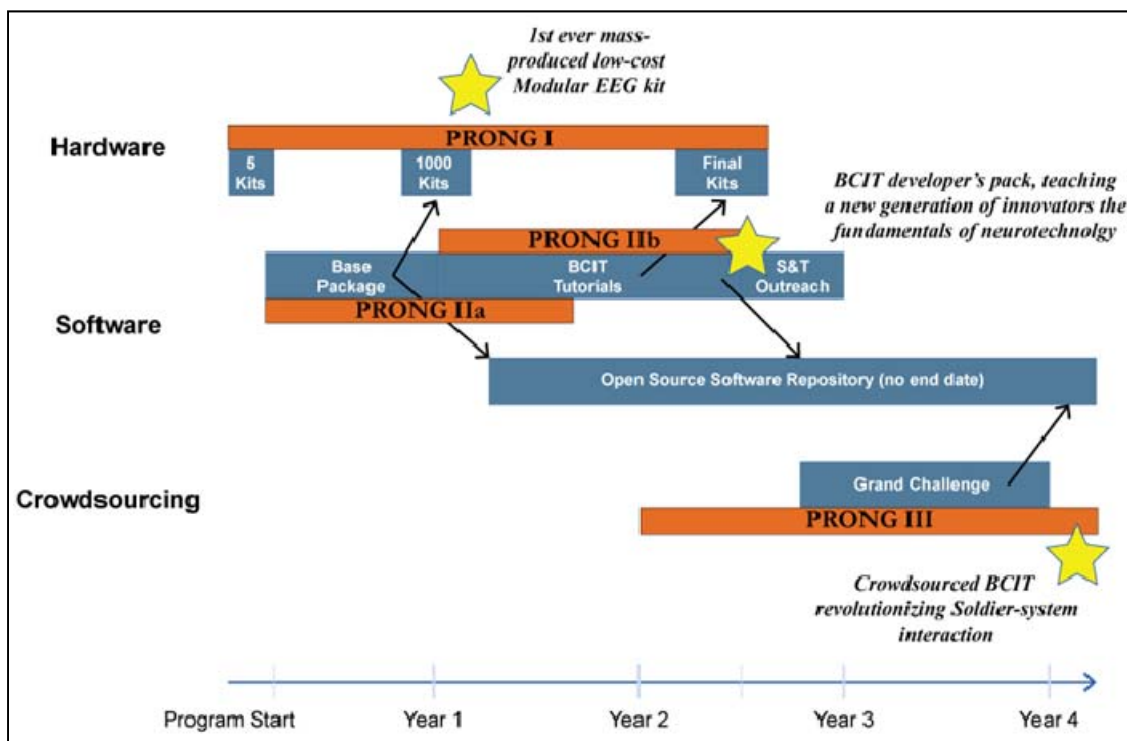
Briefly, Prong I entails the initial development of five kits for testing and use in the base package software development during Prong II. Following successful base package development, 1000 kits would be made available for a competition to develop BCIT tutorials. Tutorial materials and improved kits would be distributed to the S&T community to expand the BCIT developer base.

Prong II would consist of two phases: IIa for the development of base package software built on an initial open-source, modular development platform to provide core BCIT functionality; and IIb for the development of a set of BCIT tutorial packages built on the hardware and software from Prongs I and IIa. An open-source software repository could also be created and would be a valuable resource to support and enhance future crowdsourced BCIT development beyond program timelines. Prong III would be a final Grand Challenge program that engages a broadened BCIT developer base within the S&T community.

3. Program Phase Descriptions

3.1 Prong I: Modular EEG Hardware

3.1.1 General Concept

Produce and distribute 1000 copies of a first-of-its-kind, modular, low-cost EEG hardware "kit" that will serve as the basis for software and neurotechnology development. The modularity of the kits should be low cost to remove barriers to entry typically posed by expensive, laboratory-grade measurement solutions. In order to reduce financial barriers and to focus on application development, kits should include sensor technologies that do not require extensive setup or costly consumables, such as electrode gels. Finally, the kits should emphasize flexibility and universality. Flexibility in hardware configurations will enable individual developers to explore creative and nonstandard system configurations. Universality is an essential element to promote crowdsourcing of configurations and extensions to the kits' basic hardware to achieve robust performance in real-world applications.

3.1.2 Current Solutions and Limitations

Several companies are currently producing either high-cost, relatively flexible and modular EEG solutions or relatively low-cost, integrated EEG solutions that provide little flexibility to the developer in terms of system configuration and data access (see table 1). Currently available systems, therefore, present significant barriers to entry into the BCIT field and limit potential innovation.

Table 1. Sample of currently available EEG devices: Some of the features of the EEG systems that we have had direct experience with are listed below.

Vendor	Modular	No. Chans.	Reconfigurable	Change Sensor Type	Wireless	Raw Data Access	Cost	Cost Per EEG Sensor
Biosemi	Yes	Up to 256	No	No	No	Yes	$22,000 to $970,000	$1375 to $379
Quasar	No	21	No	No	Yes	Yes	$50,000[a]	$2381
Emotiv	No	14	No	No	Yes	Yes[b]	$750	$53
ABM	No	4, 10, or 24	No	Yes	Yes	Yes	$35,000	$1458
Neurosky	No	1	No	No	Yes	No	$130	$130
Mattel	No	1	No	No	Yes	No	$90	$90

[a] Cost is an estimate based on a 2011 quote.
[b] Restricted to research-only use and requires exclusive distribution of developed apps through the vendor.

3.1.3 Programmatic Mechanisms and Timelines

Although available systems present various limitations the component technologies necessary for producing a modular low-cost EEG kit already exist. One potential approach for integrating the existing components into a low-cost, modular solution would be to leverage ARL's Cognition and Neuroergonomics Collaborative Technology Alliance (CaN CTA). Consultation with CaN CTA research and development partners indicates that an initial set of five kits for testing and use in the development of the base package of software (see Prong IIa, below) could likely be produced under the CTA's existing technology transition agreement within 3 months of overall program onset. Assuming the base package development would take 9–12 months, the initial 1000 kits would be available in time for the tutorial development described in Prong IIb, below, and improved kits could be made available for distribution to the greater S&T community ahead of a Grand Challenge program (Prong III).

3.1.4 Example Solution

Figure 2 illustrates an example EEG kit that is expected to cost less than or equal to $30 per channel for the production of 1000 units. The components of the kits include (1) a set of dry electrode sensors, (2) a set of channel electronics with pre-amplification for each channel, (3) a main board for integration and wireless transmission, and (4) a flexible, coded head attachment system. Ideally, the kit would also include a power source for the main board and the wiring for component integration. Each component of the kit is designed for maximum flexibility in application as is described below.

Figure 2. Sample kit. Counterclockwise from
the upper left are sensors, channel
electronics, main board, and
attachment system. The pictured
components are intended to illustrate
the concept. They are not functional.

3.2   Modular EEG Kit Component Descriptions

3.2.1 Sensor Set

The sensors should be based on a dry sensor design that does not require conductive media (e.g., saline gel) and can use commonly available attachments, such as a simple snap connector. The dry sensor solution increases the usability of the sensors. The commonly available attachment mechanism permits development and integration of alternative sensors.

3.2.2 Channel Electronics Set

The channel electronics should include a pre-amplifier and wires to connect to the main board with commonly available attachments. The pre-amplifier should be included for increased signal quality. The commonly available attachment mechanism would enable alternative channel electronics to be easily integrated into the system.

3.2.3 Main Board

The main board should handle the A/D conversion, power, and the wireless transmission. This board should also be easily replaceable or swappable with other common microprocessors (e.g., Arduino, Raspberry Pi, etc.). Further, the kit should be designed to allow for multiple main boards or an alternative board to be used in parallel. This capability would enable higher density EEG and multi-aspect systems (i.e., systems with multiple sensors detecting different types of data; see Oie et al., 2012).[1]

3.2.4 Flexible, Coded Head Attachment System

The attachment system would consist of multiple Velcro straps and should be coded with a number/lettering systems to promote repeatability across applications. The Velcro strap system would enable sensors to be attached in a wide variety of configurations allowing for the maximal flexibly by the application developer (for examples, see figure 3). The coding system should enable clear reporting and reproducibility of sensor montages. Instructions for standardization of reporting montages would be included on a Wiki-type website.

Figure 3. Three potential attachment configurations. Left: general EEG set-up with sensors distributed across the head. Middle: central configuration for maximal sensor coverage over the motor cortex which could be used for motor control applications. Right: posterior configuration with maximal sensor coverage over the occipital cortex, which could be used for visual detection applications.

3.3 Prong II: Crowdsourcing Software Modules

3.3.1 General Concept

Utilize crowdsourcing, including experts in the neuroscience research and neurotechnology development community, to develop a set of tutorials for interested technology developers with minimal requisite knowledge in BCIT development (though scalable across levels of expertise).

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[1] Oie, K.; McDowell, K.; Gordon, S. The Multi-Aspect Measurement Approach: Rationale, Technologies, Tools, and Challenges for Systems Design. In *Designing Soldier Systems: Current Issues in Human Factors*; Ashgate Publishing; 2012, pp. 217−247.
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The tutorials should use the modular EEG hardware from Prong I and guide users to quickly reproduce six exemplar BCITs while instructing them on critical learning objectives for BCIT development. For example, such objectives would include the nature of scalp EEG and sensors, data quality, and data content; basic signal processing for EEG and event-related potentials (ERP); dealing with non-brain-related signal components or "artifacts," and/or approaches to the classification of EEG and ERP. Each tutorial should be built upon a base package of software to support core BCIT functionality developed within a common, open-source platform. The critical goal of the six tutorials, as a learning experience, is to provide a bridge between neuroscientists and current neurotechnology developers and the broader S&T community by providing tutorial users with a functional BCIT-focused knowledge base that can enable innovative development in a BCIT Grand Challenge, as described in Prong III below. With this goal in mind, developers should proceed with the aim that the entire set of tutorials could be successfully completed in a short time to minimize the costs in time and effort for technologically-sophisticated individuals with limited prior neuroscience and neurotechnology experience to enter into the BCIT development field.

3.3.2 Current Solutions and Limitations

Currently, BCIT software generally falls into two broad categories. (1) Academic, **laboratory-grade** software that provides huge flexibility to address different experimental paradigms and issues. Several examples of modular, open-source laboratory grade software packages exist (e.g., BCILAB, EEGLAB [Delorme et al., 2011];[2] and Fieldtrip [Oostenveld et al., 2011]).[3] However, the effective use of this type of software is associated with extensive training requirements including substantial neuroscience and a signal-processing background. Furthermore, these open-source software packages are built on (and require) very expensive proprietary software. (2) Alternatively, several companies (such as Emotiv or NeuroSky) have produced easy-to-use software that has proprietary components providing "**black-box**" processing based on encrypted data and proprietary analysis algorithms. This approach might enable the development of BCIT applications on short time scales (e.g., a naïve inventor could demonstrate some level of control of an object on screen on a time scale of hours) but also prohibits developers from understanding what features of the signal are critical for successful application performance. For example, because EEG recorded at any given sensor reflects some combination of all the sources of electrical activity in the head, a "brain sensor" will often be picking up substantial muscle activity or other sources of artifacts. However, those artifacts may actually be the most relevant component of the putative BCIT application. Thus, the lack of understanding of the fundamental basis of the signals being used dramatically limits the ability of

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[2] Delorme, A., Mullen, T., Kothe, C., Akalin Acar, Z., Bigdely-Shamlo, N., Vanko, A., Makeig, S., EEGLAB, SIFT, NFT, BCILAB, and ERICA: New Tools for Advanced EEG Processing. *Comp Intel & Neuro* **2011**, *10,* pp.1−12.

[3] Oostenveld, R., Fries, P., Maris, E., Schoffelen, J.-M. FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG and Invasive Electrophysiological Data. *Comp Intel & Neuro* **2011**, *1,* pp. 1−9.

developers to extend applications, develop novel applications, and troubleshoot when the applications fail.

3.3.3 Programmatic Mechanisms and Timelines

We believe that sufficient tools, knowledge, and applications currently exist for a research program to directly address the critical limitation to crowdsourced neurotechnology development and create base software capabilities on short time scales. An initial effort (Prong IIa) is needed for the development of a base package to provide core functionality for BCIT application development. Given sufficient resources, it seems reasonable for a contracted effort to develop such a base package that integrates with the hardware from Prong I in 12 months (see figure 1). In Prong IIb, a program could be set up to crowdsource advanced academics and developers to develop software modules capable of realizing six BCIT tutorials, which are described below. Using the example detailed below, a 12- to 18-month program would be sufficient.

3.3.4 Example Solution

Here, we describe an example approach to the crowdsourcing of software modules with two distinct phases: Prong IIa: as suggested above, a contracted effort could provide a base package of software to provide the core functionality for BCIT application development: data I/O, data and system interface, data synchronization, etc. The base package should be developed within a common open-source development platform that does not require expensive, proprietary software (e.g., MATLAB),[*] which will maximize user accessibility and enable future crowdsourcing BCIT efforts through, for example, an online open-source BCIT developer community and software repository. Prong IIb: in the second stage, an open competition for software development for each of the six BCIT tutorials could be conducted under a formal program. A Modular EEG kit and base package software implementations could be provided to the proposers from the neuroscience research and neurotechnology development communities who submit a short proposal for the development of each of the six BCIT tutorials, which meets specified minimal requirements. Initial solutions-including hardware configurations based on the Modular EEG kit, software based on base package capabilities, and instructions and knowledge content could be evaluated, with prizes awarded for numerous categories related to overall design and performance, module design, educational content, and hardware kit upgrades. Solutions to each of the six tutorials should be made available in an open-source, crowdsourced process to improve the hardware, software, and knowledge products and, ultimately, to produce a final set of kits and tutorials for widespread distribution within the greater S&T community.

3.4   BCIT Tutorial Examples

The general philosophy behind the BCIT tutorial development is to rely on the ingenuity of a crowdsourcing community to create novel educational tools and to focus that community by clearly defining the topic areas of the tutorials. Secondarily, as the focus is on educational

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[*] MATLAB is a registered trademark of MathWorks, Inc.

tutorials rather than developing novel BCITs, the proposers should be encouraged but not required to target existing BCITs approaches (e.g., those based on neural signals, such as the P300, steady-state visual evoked potential, or motor system). The structuring of the topic areas should focus on critical understandings of brain processing, as well as issues critical to applications development. The topics areas would need to adequately present a functional BCIT-related knowledge base for the Grand Challenge described below in Prong III to be successful. Although an optimal structure for the BCIT tutorials will likely depend on the specific Grand Challenge envisioned, for illustrative purposes we propose an example structure that highlights several of the critical topic areas and is structured to provide crowdsourcing opportunities at multiple stages in the development process:

3.4.1 Stage 1: Simple Tutorials

The first three tutorials are envisioned to be simpler BCITs that can be produced within the first 9 months and then provided as open-sourced resources to be leveraged in the development of the more complex tutorials in Stage 2.

- Tutorial 1: Understanding visual processing, frequency-based analysis approaches, and the importance of system timing for relating stimuli to neural data.

- Tutorial 2: Understanding higher-level processing, event-related potentials (ERPs), and EEG artifacts.

- Tutorial 3: Understanding motor processing and the relationship between electrode location and the location of neural activity.

Winning solutions for the simple tutorials are expected to include modules for identifying frequency content in data; addressing timing issues, such as jitter and drift; extracting ERPs; identifying and removing different types of artifact; detecting EEG motor-related features; classifying both discrete and continuous events; and leveraging unique configurations of sensor placement.

3.4.2 Stage 2: Complex Tutorials

The second set of tutorials is envisioned to cover more advanced and complex topic areas, and the proposers should be encouraged to leverage and enhance the open-source modules created for the simple tutorials in Stage 1.

- Tutorial 4: Understanding the concept of overlapping or parallel neural processes, the differences between the brain's sensory systems, and an advanced understanding of the processing of discrete sensory inputs.

- Tutorial 5: Understanding brain function associated with multitasking and the issues with isolating a particular neural signal from other neural signals when human behavior is not constrained as it is in typical laboratory settings

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- Tutorial 6: A deeper understanding of how environmental and state factors influence the generation and extraction of neural signal and sensor management.

Winning solutions for the complex tutorials are expected to include advanced modules for feature detection; classifying overlapping discrete sensory inputs; leveraging spatial, temporal, and frequency content to isolating specific neural processing within a continuous data stream without markers of human behavior; identifying artifact and separating artifact from neural features, and leveraging both brain and artifact; assessing signal quality in individual sensors; and integrating signal quality into classification approaches.

3.4.3 Stage 3: Crowdsourced Enhancements of Tutorial

In this final stage, all six BCIT tutorials would be released as open-source, and crowdsourcing would be utilized to enable further refinement and integration across the winning submissions. As structured, this example approach provides several opportunities for crowdsourced improvements to the modular EEG kits, base package software, and the set of tutorials to provide the best possible products and toolsets for widespread distribution within the greater S&T community. These tools should provide the critical infrastructure to enable a successful Grand Challenge program with the goal of sparking the development of innovative BCIT solutions, which will be described in Prong III.

3.5   Prong III: Crowdsourcing BCIT Development

3.5.1 General Concept

Crowdsource the development and demonstration of innovative BCIT solutions by building on the modular EEG kits and open-source BCIT software resources developed within Prong II, as well as the expanded base of developers within the greater S&T community that were engaged as a result of these efforts. A Grand Challenge could be used to incentivize and spark innovative, cross-disciplinary development to provide novel solutions for real-world and military-relevant capabilities needs.

3.5.2 Current Solutions and Limitations

Currently, there are no crowdsourced efforts to stimulate innovative BCIT application development in the greater S&T community. Online communities dedicated to developing EEG-based software do exist (OpenEEG.com, Emotiv's user forums), but lack wide-spread awareness and adoption. These communities highlight the lack of cross-disciplinary expertise among the workforce. The U.S. government funded efforts to develop software for neuroimaging are focused on full-time scientists with some knowledge of computer programming (EEGLAB, ERPLab, BCILAB, etc.). Although it is possible for independent researchers to develop and distribute software code that works with these tools, there is no forum to facilitate access and, therefore, sharing of software tools and resources is largely confined to individual labs.

Most progress in BCIT development to date has been in tools aimed at improving the quality of life for medical patients with specific problems, such as "locked-in" or paraplegic patients. Teams of researchers and scientists focus on a single patient with a debilitating medical issue and a device with customized software applications is created to serve that single patient or issue. Although this research greatly impacts the lives of some people, the tools that are developed are not generalizable across or accessible to the broader population of normally healthy individuals. This vastly limits the potential impact of current BCITs for the U.S. military.

3.5.3 Programmatic Mechanisms and Timelines

As indicated, the Grand Challenge model would seem an ideal programmatic mechanism to capitalize and increase exposure for real-world BCIT development. Combining a Grand Challenge program with the efforts described above in Prongs I and II will require sufficient time between initial distribution of the Modular EEG kits and tutorials to the development community.

3.5.4 Example Solution

A potential Grand Challenge for innovative BCIT application development could, for example, be designed around specific target capabilities, such as robotic or vehicle control, enhancing situational awareness or adaptive information displays. Alternatively, as described here, a Grand Challenge could be designed to examine how novel BCITs perform under various real-world conditions: In development for clinical populations, certain limitations of use can be prescribed to overcome technical obstacles, such as limiting user movement to minimize unwanted signal artifacts. However, BCIT applications developed for healthy users, including Warfighters, are not likely to be adopted unless robust and reliable performance can be achieved under the various operational conditions that human users experience. Even in many previous BCIT development efforts, generalizability of technology solutions developed in the laboratory have yet to demonstrate fieldable performance levels.

In the envisioned Grand Challenge, competing BCIT solutions in specified classes of target capabilities (e.g., direct control, supervisory control, state-based adaptive systems, affect-based human/computer communication) could be assessed in a "decathlon" of 10 different real-world conditions. For example, a BCIT competitor might be subjected to different motion profiles on a moving platform, loud music, or crowd noise, changes in ambient temperature or humidity, or multi-task conditions, with solutions within each class providing the best overall performance winning the competition.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
BCIT	brain/computer interaction technologies
CaN	Cognition and Neuroergonomics
CTA	Collaborative Technology Alliance
DARPA	Defense Advance Research Projects Agency
DOD	Department of Defense
EEG	electroencephalography
ERP	event-related potentials
S&T	science and technology

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