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Instantiating the progress of neurotechnology for applications in national defense intelligence

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Abstract

This article outlines a series of intersections that highlight the potential for strategic fruitful support of basic neuroscience research to enhance technological design and training for national defense intelligence efforts. These intersections include ideas related to acclimatizing the defense community for change and adaptation to new definitions of warfare, increasing scientific literacy about neuroimaging methods for improved partnerships between basic and applied research, balancing translation goals between advancing research and enhancing mission capabilities, and aligning social neuroscience paradigms with training needs. The discussion also provides an overview of research activity funded from within and outside Department of Defense agencies from the recent past and work in progress compared with efforts highlighted in the report, "Opportunities in Neuroscience for Future Army Applications" by the National Research Council (2009). Finally, as a means of discussing the migration of neurotechnologies to national security applications, the notions of fitness and enhancing physical health, well-being and quality of life are presented in the context of products and strategies that people currently adopt for these purposes.

Key words: neuroimaging, scientific literacy, neurotechnology, social neuroscience, individual differences

Introduction

The publication of "Opportunities in Neuroscience for Future Army Applications" by the National Research Council (NRC) (1) presented a status of neuroscience contributions to the defense community and recommendations for continued intersection with anticipated gain across the short (0-5 years) and long term (5+ years). It is a thorough treatment of efforts to date that attempt to capture the processes and products that show us the physical and affective dynamics of the warfighter. Ambitious undertakings early in the time when an interest in this marriage was first maturing demonstrated the possibilities of adaptive aiding (2,3) applied to problems such as air traffic control (4) and information workload management (5,6). Building on these efforts, the goal of this article is to present the reader with a series of intersections that highlight the potential for accurate and fruitful support of basic neuroscience research that will yield processes for technological design and training support for national defense intelligence efforts. These intersections include ideas related to acclimatizing the defense community for change, increasing scientific literacy for improved partnerships between basic and applied research and development efforts, balancing translation goals, and aligning social neuroscience paradigms with training needs. Following this is: 1) an overview of activity from the recent past compared with efforts highlighted in the report by the NRC (1), and 2) a more direct discussion of work in progress and fruitful avenues for future neuroscience research and technological application to support national defense intelligence.

Acclimatizing for change

The defense intelligence community is confronted with the reality of knowing the dynamics of human ability and performance and the ethics and contingencies that come with that information. In particular, there are two climate issues related to the social norms that underwrite a way forward. The first is getting comfortable with the idea of individual differences and understanding the limitations of neuroimaging techniques to assess at the individual level, but also understanding that instrumentation (psychometric and biometric) exists that could well inform how we choose individuals for military service, team them, train them and assign to maximize skill development and expertise. Keeping in mind that we test our nation's school children and disabled with some of these methods in order to provide for their adequate education and special needs adds some levity to this idea. It is important to emphasize that modern imaging techniques are sophisticated pattern recognition methods and not tools that mind read. The NRC report emphasizes that prioritizing the assessment of individual variability guarantees that treatment of differences related to other qualities such as gender and race are more neutral and comprehensive (1).

The second notion involves supporting added flexibility in leadership structures (7) with the idea that this nuance will lead to a more empowered soldier on the ground, better team cohesion, and, ultimately survivability and success. For example, a conversation with a Special Forces soldier who recently returned from his third mission in Afghanistan revealed his frustration with the conflicting norms and expectations placed on him to do his job undercover. This meant growing his hair and beard and changing his dress, his disposition, and his communication style in order to blend in and engender trust in the local citizens he relied on to do his work. He lamented that when his superiors saw him upon return that he was admonished for his appearance and affect. These expectations are also confounded by the awareness that some of the most potent, persistent, and difficult to heal war wounds are physically invisible yet psychologically life-changing. Even a well soldier takes time to assimilate his or her own experience and change in context upon return from the field.

Preceding translation and application with scientific literacy

Recent meetings of the joint chiefs observe that attempts to come up to speed on asymmetrical tactics are not yet a fit for the chameleonic stance of modern warfare. "Embracing uncertainty" and "managing complexity" are the memes designed to capture a new philosophy of forecasting and how to engage in modern warfare. Consequently, within this sentiment is the growing expectation that basic research in the neurosciences will change how we prepare soldiers and support them in warfare.

Adding to this is the rapid and constant refresh rate of the state of neuroscience research as findings about human function and technological advances emerge almost daily. The rate of the change is met with equal curiosity and enthusiasm. Even in the general public, neurobiological information goes viral. Colorful magnetic resonance imaging (MRI) scans adorn the news showing us brains aging, brains gambling, brains reading, etc. Yet, very little explicit literacy education has gone on to create a discerning public about what this data really means (8). A two-volume special issue of *Roeper Review* on the cognitive neuroscience of giftedess included a neuroprimer designed to increase scientific literacy in the layperson (9). The neuroprimer illustrates a number of principles that cognitive neuroscientists use to inform experimental design (block versus event-related design), data analysis decisions (fixed versus random and mixed effects analysis, the importance of single subject validation), and the limitations and utilities of various structural and functional neuroimaging methods. These are key methodological principles that ultimately determine the context, interpretability, and inferential power of the data. Those principles have yielded heightened interest in how neuroimaging findings are translated and speak to the need for a campaign in scientific literacy as the public becomes increasingly expectant about the capabilities of basic neuroscience to transform applications that will help heal, enrich, extend, and augment human ability and performance in settings ranging from classrooms to sports arenas to the battlefield whether physical (combat) or data-driven (intelligence).

Most functional MRI studies are to be understood in the context that statistically significant group findings come from the right-handed college undergraduate. While these studies give an estimate of generalizable human neurobiological function, they lack generalizability and the soldier's context. Basic research designed to mine ways to support the warfighter in the field must eventually be based on those individuals. This gap is discussed at length, compared, and contrasted with current training and assessment capabilities for the Army in several chapters of the NRC report (1) that discuss priorities for training, learning, decision-making, and sustaining performance. Instrument capabilities exist to execute these experiments non-invasively. One of the understandable obstacles is the plea for the comfort and un-encumbrance of the soldier during such exercises. Another is the security and safety of equipment that might be used to acquire data in the soldier's environment.

Setting translation priorities – What and how goes into testing and experimentation is as important as the sophistication of analysis capabilities

The NRC report (1) recommends high-priority opportunities for the Army's investment in neuroscience technologies. The list is characterized by current investment status and timeframe expectancy for realizing different funding priorities:

1. Does the technology enable missions or further research?
2. Is the investment low, medium, or high?
3. Is the nature of the investment commercial or academic?
4. Can deliverables be anticipated in 0-5/ 5-10/ 10+ years?

Of the dozen technology priorities listed, the *single effort* receiving "high" support is the academic development of signal processing and data fusion for neuroimaging techniques (1). One of the two priorities listed "low" in both the commercial and academic spheres includes the identification of biomarkers to predict individual response to environmental stress. The other is the development of near-infrared spectroscopy (NIRS) and diffuse optical tomography (DOT). Other priorities in the "low" category include developing functional magnetic resonance imaging (fMRI) paradigms for specific military interests and training and fatigue prediction models. The rankings of these priorities forecast that data mining, fusion, and analysis capabilities have near-term utility and thus are appropriately well-supported. Whereas efforts related to the application of biomarkers to soldier characterization and of more portable imaging technologies such as near-infrared spectroscopic imaging (NIRS) in the field, while equally important still requires much more dedication to bring to term. In this gap, lies the opportunity to continue to create more ecologically valid and sophisticated experimental design to align experimental goals with the needs and outcomes whether they are technology or training based.

Linking information yielded from behavior assessed by various neuroimaging technologies

Infrared imaging technologies cannot compete with the resolution capabilities of fMRI, electroencephalography (EEG), and magnetoencephalography (MEG). They do provide advantage, however, in the need for imaging systems that are portable to specific environments, non-invasive, and robust to motion and other artifact. An intermediate effort to co-register and/or validate behavioral performance across these imaging modalities is needed to bridge knowledge derived from basic research in the laboratory into real-time and flexible methods of assessment and support. These measures have to provide a certain resolution but maintain robust operation in training and battle contexts. Though the signal that demarcates fMRI, blood-oxygen level dependent (BOLD) signal, is not a direct measure of neuronal firing (it is a ratio change between oxygenated and de-oxygenated blood in an active area of the brain measured 3-16 seconds later than the actual "event"), it is still the gold standard for assessing the spatial resolution of functional neural systems. Despite its limited time resolution, fMRI shows us how neural systems change and respond at an unmatched level of specificity and completeness. Emerging capabilities to couple timecourse information derived from EEG with the spatial resolution of BOLD will provide an unprecedented measure of human cognition in real-time in the laboratory setting. It is important to note in the face of this potential that all imaging modalities such as fMRI, EEG, NIRS, and MEG rely on signal averaging techniques to realize data. Neurotechnology based measures of developing brain structure and emerging function in real time remains a future accomplishment.

Following this, the goal is to build algorithms to represent certain behavioral dynamics (that can be more readily correlated with measures such as galvanic skin response, heartbeat, eye movement, pupilometry) in the full context of emotional and/or environmental changes. Those measures, when validated with the fMRI and other neuroimaging techniques will become a markedly more sensitive and specific shorthand for nervous system function. Continued innovation in experimental design will advance models of decision-making and performance under stress from heuristic to prescriptive. Collaboration between neuroscientists and defense strategy and training experts can leverage fMRI in its current form for near-term benefit even though functional specificity and sensitivity at the individual level, for medical application in particular, is still sought.

Expectations for social neuroscience paradigms

The goal of applying social and neuroeconomic paradigms to assess risk aversion is to take into account on an individual level the myriad ways people are incentivized. Currently, many of these paradigms contribute valuable evidence of behavioral patterns under economically framed influences. However, the brain can be widely incentivized by other factors in the social environment that are just as general (hunger, attraction) and primitive (emotion, smell). Some experimental paradigms, in an effort to deduce these relationships, fit the brain to the game rather than the other way around. Experimental design at its best, designs a "game" that captures the brain in a natural response tied to a contextual variable in the experiment that can still be aligned and translated back into real-time. In the face of emerging data that the brain calculates its own moves under conditions of uncertainty (10) and much earlier than the moment of response (11), that we believe we can assess one's action intention (12), and still characterize volitional action (13,14), it is even more important to understand how neural systems supporting higher level function are executed differently in varying contexts.

The military expects a wide range of expertise in its leadership and soldiers. The most highly prized individuals, those whom training programs seek to help others emulate, are those with a flexible and agile command of appropriate responses under pressure and uncertainty, but who also have "out of the box" intuitive assessment and planning capabilities that lead to consistent success and safety. To that end, a continued effort to understand the ways in which stress undermines and optimizes human performance along with the environmental factors that define those moments (fatigue, sleep loss, nutritional imbalance, mismatch of skill requirement or role to natural expertise, perception of threat) seems paramount to sharpen pedagogy and training designed to ensure an individual can excel under physical and psychological asymmetrical conditions.

Moving forward with a neuroscience research agenda tailored to strengthen applications for defense intelligence includes building on existing innovations that have been mined from other sources of progress as well as those strategically pursued for military purposes. Table 1 summarizes relevant activity funded outside of the military by NASA and the Department of Transportation (1).

Table 1

Author/Team	Year	Innovation	Factor	Non-DOD Funding Source
Graydon & colleagues Young & colleagues	2004 2006	Based on MEG and fMRI paradigms, matched real-world complexity and experimental conditions for an ecologically valid assessment of driving behavior	ED	SAVE-IT (DOT)
Bruns & colleagues Harada & colleauges	2005 2007	Real-time tracking of an individual while driving using EEG and NIRS	Tech	SAVE-IT (DOT)
Shepard & Kosslyn	2005	Novel device for the early detection of stress-induced deficits in problem solving, attention, and working memory	Tech	NSBRI (NASA)
Spiers & Maguire	2007	Analysis technique based on fMRI and driving game to assess individual activity	Tech	SAVE-IT (DOT)
Dinges & colleagues	2005 2007	Optical computer recognition to track facial expressions in astronauts to monitor for stress	Tech	NSBRI (NASA)

Table 1. Examples of application of basic neuroscience research supported outside of the defense community (1). The "Factor" column delineates ED, experimental design, or Tech, technological advancement. This is to highlight the nature of the innovation to emphasize the equal importance of the sensitivity and specificity of experimental design and technological advancements. Current patterns of funding support delineated as High Priority in the NRC report (1) indicate the ratio of support for these two factors of innovation.

In contrast, Table 2 catalogs a sampling of registered successes from DARPA's Augmented Cognition program (15). These are not meant to be comprehensive, but to provide proof of concept for leveraging neuroscience innovation within and between translational communities. More broadly, metrics that resulted from subsequent phases of the program reported success for increasing working memory, attention, and simultaneous sensory input by 100% and executive function by 500%. Several neuroscience labs produced methodological innovations tailored for improving human cognitive performance.

Table 2

Program	**Year**	**Innovation**	**Factor**	**DOD Funding Source**
Biocybernetics	1973-1980's	Ability to track EEG signal related to thinking words, control computer cursor movements, assess cognitive workload of pilots in flight	Tech	ARPA
Augmented Cognition (Phase I)	2002-2003	a. Ability to detect a verbal to spatial cognitive state shift in < 60s using real-time EEG b. Ability to measure cognitive state with infra-red imaging technology c. Ability to improve memory processes by 131% d. Ability to productively disrupt stress response and improve task completion e. Ability to assess and reduce human error by 23% using real-time EEG f. Ability of machine to infer operator situational interpretation with 87% accuracy	Tech Tech Tech, ED Tech, ED Tech Tech	DARPA
Augmented Cognition (Phase II)	2003-2004	General Innovation: Gauging Cognitive State a. Utilizing ERP P300 to assess attention (Sajda, 2004, Veryers, 2004) b. ECG assessment of arousal (Hoover, 2004; Hoover and Muth, 2004) c. Eye-tracking index of cognitive task (Marshall, 2004) d. Correlating postural control with cognitive load (Balaban et al., 2004) e. Correlating intrusive (i.e. blood pressure, pupil dilation) and non-intrusive (gestures, facial expression, speech prosody) indicators to assess emotional state (Sharma, 2004) f. Classifying cognitive state (Gratton, 2004; Fabiani, 2004; Chang, 2004; Belyavin, 2004; Dickson, 2004; Pleydell-Pearce et al, 2003)	Tech Tech Tech Tech, ED Tech, ED Tech	DARPA

Table 2. Examples of application of basic neuroscience research supported by the defense community (15). The "Factor" column delineates ED, experimental design, or Tech, technological advancement. This is to highlight the nature of the innovation to emphasize the equal importance of the sensitivity and specificity of experimental design and technological advancements.

The Augmented Cognition program pioneered the engineering of closed-loop technologies that set forth unmanned smart capabilities to keep humans out of harm's way and to aid the soldier under specific contexts. It is important to note that these innovations applied only to the person in the moment and did not permanently nor generally enable these individuals to become super-performers in their everyday life. In addition, the primary goal of these technologies was to support the person while preserving their overall performance state. In other words, at no time was there loss of awareness, volition, or ability to successfully execute the task. In the current circumstances of war where the context is more highly ambiguous, rapid and dynamic, the capabilities to assess, adapt, and predict open qualities in an engineered system that has the finesse of human judgment have not matured. Although, the field of neuroprosthetics illustrates the potential of human-machine interface (16).

Migration of neurotechnologies to national security applications

There is an idealized process that would lead neurotechnologies toward adoption for national security applications: 1) academic research establishes the scientific foundations, 2) systems engineering assures technologies address/satisfy recognized needs without introducing undue trade-offs, and 3) the acquisition system provides for test and evaluation and an incremental transition and fielding. This sequence of events assumes a deliberative process that relies heavily on established suppliers from industry and academia. However, there are other credible scenarios that may be more probable, particularly for the initial applications of neurotechnology.

Despite the interest and investment of current government agencies responsible for technology research and development for national security applications, several factors lessen the likelihood that these endeavors will produce innovation leading to initial neurotechnology application. First, the most basic of these factors is cost. The institutions capable of effectively operating in this domain are expensive, favoring relatively rigorous and highly scrutinized trajectories of development as opposed to rapid turnaround trial-and error. Second, corporate and institutional intellectual property protection policies and practices generally restrict the sharing of information and broad-based collaborations. Consequently, there are few opportunities to benefit from scaling factors that occur with open source-like development efforts and crowd-sourcing paradigms, resulting in duplication of effort (e.g., multiple companies developing algorithms to accomplish the same signal processing function). Third, there is a heavy emphasis placed on operational relevance steering experimental applications to environments that impose practical constraints. Consequently, time and energy are often lost addressing these constraints, as well as the associated skepticism of potential end-users. In these domains, applications are often narrow and the benefits hard to establish, making it difficult to convincingly argue for a return on investment particularly when there are numerous other broad ranging needs. Finally, there are not many individuals who combine a sufficient understanding of neuroscience with a technical understanding of application environments, and associated technologies, which begs the need for increased scientific literacy in the translational community.

Arguably, the more probable scenario, observed increasingly more often with information technologies comes when the initial innovation occurs within an entrepreneurial context motivated by profits derived through the consumer marketplace. Such innovation most likely centers on a relatively simple idea that consumers can readily understand, and that on the surface, does not involve complex technology. Then, through a combination of promotion, chance, and particular discourse within social networks, a buzz develops initiating a demand for the technology and associated capabilities. The initial instantiation may not be particularly effective or reliable, but driven by demand-inspired profit potentials, rapid maturation occurs through several generations, progressing past the early adopters to capture the interest of customers swayed by "coolness" and "must-have" dynamics. Invariably, interest from national security domains will emerge as a result of bottom-up influences (e.g., operational forces/front-line analysts asking why they cannot have what their cohorts have back home). At this time, all the conditions will be in place for a re-purposing of the technology and accompanying modification and/or adaptation to meet the unique demands and constraints of operational environments.

One might ask, "what will be the breakthrough technology?" The initial application(s) will be particularly important as its success will open the door for other more complex, and perhaps less intuitive, applications. Predictions concerning the initial application(s) require some speculation. However, it is most probable that the first application(s) will address fundamental needs that are otherwise currently addressed, although somewhat ineffectively (17). It is less likely that the first application(s) of neurotechnology will enable activities unimaginable without neurotechnology. Instead, the emergence and dissemination of neurotechnology will follow a pattern similar to that observed with recent innovations in information technology (e.g., online services, email, Instant Messaging, etc.).

Acknowledging the speculative nature of predictions concerning the success of anticipated technologies, a few candidates come to mind. One example involves electrical or neuropharmaceutical stimulation to enhance arousal or attentiveness. A substantial portion of the population use various substances to do this today, and a booming new line of beverage products has arisen targeting this widely shared need. Neurotechnologies that accomplish this same objective more effectively, with fewer side effects and, most importantly, may be self-administered would likely have broad appeal.

A second candidate involves the assessment of education and training, and the determination of aptitudes. A substantial industry exists today to serve these needs and much attention is focused on more effective and efficient approaches. One may envision neurotechnology that supplements current approaches to indicate the confidence, immunity to forgetting, and resilience to the stress of material presented through education and training programs. Interventions are being applied and tested to remediate certain intellectual disabilities, although longitudinal studies to provide adequate characterization and fidelity of neural plasticity that significantly changes a person's function, intellectual achievement, and quality of life have yet to be reported.

A third example applies neurotechnology for biometric self-monitoring. These tools target and enjoy wide-use with health enthusiasts and some focus on cognitive capacities. Today, this occurs in most homes using the familiar bathroom scale, new portable puzzles and mental challenges to keep the aging mind sharp, and platform-based computer games that can assess an individual's "performance age" connected to weight, fitness, and age. Recent advances such as these that allow one to track and anticipate performance have much broader appeal and relevance to almost anyone, not merely those interested in optimizing their physical performance.

While many other similar examples may be proposed, the key point is that initial application(s) will likely be simple and straightforward on the surface, addressing a need shared broadly by those outside, as well as within the national security domain. This is very much in opposition to current portrayals of neurotechnology that lean toward the fantastic and involve enabling somewhat super-human capabilities. Keeping in mind that our gymnasiums are filled with monitoring equipment for physical status and performance, and our bathrooms with scales, dentures, contact lenses, vitamins, supplements, and medicines, reminds us that monitoring and augmentation occurs every day without fantastic consequence, though we wish it might be different. On a more serious note, work in the field of neuroprosthetics to replace and interlace lost motor and cognitive function by a direct neural impulse, has shown us successful demonstrations of this in both primates and humans. In that spirit, initial, simple applications of neurotechnology will lay the groundwork for more sophisticated technologies that may have some of the flare of popular Science Fiction. But, the metrics for getting there are in full view.

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Competing interests

The author(s) declare that they have no competing interests.

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