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Transitioning brain research – From the laboratory to the field

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Abstract

While brain research (involving both neuroscience and cognitive science) shows great potential for advancing critical national security interests, the products of the laboratory cannot be realized in operational practice without the polishing and maturing demanded by federal science and technology (S&T) acquisition processes, particularly those of the Department of Defense. Although many acquisition planning functions are relatively conventional, new or evolving capabilities resulting from brain research applications may impact national security doctrine in unexpected ways. Integrating brain research into operating doctrine and practice may therefore demand a fresh look at the steps of the acquisition process itself, and earlier collaborations between researchers, operational communities, and acquisition managers to ensure the significant benefits of this S&T domain without inducing unwanted surprise.

Key words: neuroscience, acquisition, transition, Technology Readiness Level, autonomous systems, human-machine interaction

Background

Contributions of brain research to human knowledge have flourished in recent years, owing in large measure to the increasing sophistication of direct brain monitoring, imaging, and interventional technologies and cognitive modeling tools. (1) Focused research collaborations, such as the Decade of the Mind (2) will ensure the rapid emergence of further insights into human cognition, emotion, and behavior. While neuroscience research is yielding important benefits to mental health, education, and computational science (the motivating aspects for the Decade of the Mind), the rapid pace of such work can also offer other capabilities to enhance national security, with knowledge and capability to improve:

- Human cognitive performance – through better understanding of basic processes involved with memory, emotion, and reasoning, including the formation of biases and heuristics. (3) Such knowledge can provide improved task design, information structuring and presentation, and decision support to enhance human analysis, planning, and forecasting capabilities.
- Training efficiency – enabling rapid mastery of knowledge and skills, with longer retention times, (4) through individualized, real-time tailoring of instructional material. Such capability could provide more flexible job assignment and more effective employment of available manpower.
- Medical treatment and rehabilitation – providing more rapid and complete recovery from injury, and enhanced resilience to the stresses and hazards of military operations, (5) so as to prevent or ameliorate the human costs of military service and enhance post-military health.
- Team processes performance – by sensing, modeling, and supporting the dynamic social cognition processes needed to bridge organizational, cultural, and expertise gaps across team members (6), neuroscience research can enhance the productivity of heterogeneous groups.
- System engineering – including technologies to support shared-initiative problem solving between humans and machines, (7) thereby enhancing the information processing capabilities of both individuals and organizations.

The knowledge and tools generated by and from cognitive neuroscience activities have the potential to fundamentally alter many national security processes. Optimi-

zation of human-system performance capabilities, better employment (and protection of) available manpower, and reduced operational costs can dramatically expand the options available to government and military leaders in implementing national security policy. The value of brain/mind research to national security needs has been recognized among government, military, and science agencies, and investment in human cultural, cognitive, behavioral, and neural sciences has steadily emerged as a national budgetary priority (8).

Some of the potential benefits of cognition research (CR) and neuroscience research (NR) activities are detailed throughout this issue. Realization of scientific potential in the practical world, however, is the result of labor required to fashion new knowledge and technologies into forms suitable for operational use, with accompanying acceptance and policy change. Therefore, the goal of this essay is to explore the requirements necessary to evaluate and implement brain/mind-related research products in some of the settings important to national security, particularly the Department of Defense (DOD). Furthermore, because the insights generated by neuroscience promise to change many current assumptions about both human and machine capabilities, transition will likely face unique, additional challenges. This essay introduces some of these challenges in order to highlight the discussion and planning needed to anticipate and avoid them.

The S&T transition process

All DOD transition programs are designed to shepherd new products into acquisition programs, where they are purchased for operational use. Although the S&T community sponsors research projects through funding support, it is the acquisition community that handles the major tasks of transition. This expands the range of people and issues that researchers must accommodate to guide their work into operational practice. Among other responsibilities, acquisition agencies ensure that products contain sufficient clarity of purpose (i.e., fits a need and will be used), reliability (i.e., will perform "as advertised"), and sustainability (i.e., can be maintained and supported, and operators can be trained, throughout its operational life).

The current DOD S&T acquisition strategy – the Joint Capabilities Integration and Development System (JCIDS) – emphasizes incremental development and evaluation, to allow projects to mature and improve as a result of new discoveries and lessons learned (9). Two forms of transition are used: Incremental Development, in which the technology is essentially known from the beginning and maturation, occurs during a linear process, and Spiral Development, in which the technology is less defined, but is resolved through iterative user experience and feedback.

Transition is a process involving continual performance measurement, with product performance reflected as a Technology Readiness Level (TRL). As shown in Figure 1, the TRL model provides an operational description of both the S&T performance goals, and the evaluation environments in which they are demonstrated (10); success in a more challenging environment results in a higher TRL.

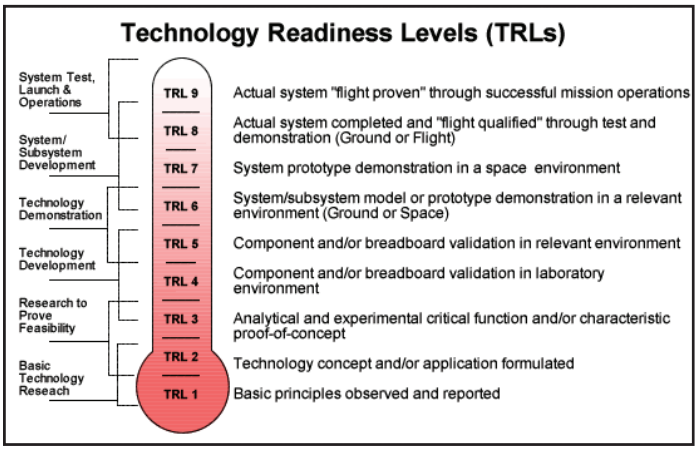

Figure 1
Technology Readiness Levels (10)
(Image credit: NASA)

TRLs are based on a variety of factors (11), including:

- Effectiveness – does the technology work?
- Suitability – does the technology work for the intended user, in the intended environment?
- Cost – is the technology affordable?
- Schedule – can the technology be delivered when needed?
- Quality – does the technology represent the best available S&T?
- Reliability – will the technology work consistently?
- Productibility – can the technology be produced in quantity?
- Supportability – can the technology be maintained in operational use?

DOD manages a variety of processes to accelerate the transition process by channeling attention and resources upon the S&T product by all of the government communities required for evaluation (9). Primary among these processes are the Advanced Technology Demonstration (ATD), focused on technology development, and the Advanced Concept Technology Demonstration (ACTD), focused on technology integration. Although each military service has its own transition programs that address unique user community needs, all of their methods are aligned with the objectives of these DOD-wide processes. Thus, while each service also supports rapid transition opportunities for high potential products (12), selected products must still negotiate critical maturity and performance benchmarks before transition is concluded.

These processes can structure, but not ensure, viable transition. While much of the brain/mind-based technologies developed over the last decade have demonstrated enormous potential, few of these have transitioned into operational use, due in large part to the considerable challenges of demonstrating the higher maturity levels of the TRL model, or of addressing each of the acquisition factors (reliability, producibility, etc.). The results of new CR and NR efforts will be similarly at risk unless these requirements are addressed early and explicitly in the S&T planning process. Two classes of issues require consideration: 1) general challenges of the transition process, and 2) potentially unique challenges resulting from the unknown impact of the science itself.

Brain/mind research transition – General challenges

Regardless of the cognizant agency, or the specifics of the S&T product, certain themes appear across all transition processes. The first of these is that transition is fundamentally a needs-driven process. While S&T sponsors always welcome and encourage disruptive "breakthroughs," in a climate of conflicting budget priorities and transition schedules, needs-based S&T products will almost always have priority. A needs-driven product directly addresses an existing or anticipated capability shortfall, and S&T is harnessed to solve a recognized problem; its value is apparent. An opportunity-driven product, however, emerges from new discoveries and applications must be identified; its ultimate value may be understood only as the product evolves. Although S&T programs typically include a mix of needs-driven ("tech pull") and opportunity-driven efforts ("tech push") efforts, because CR/NR generates a high level of fundamental new knowledge, its applications are almost certain to be opportunity-driven. The most critical outcomes may not be those that were anticipated when research began, and fitting to a needs-driven process can therefore be extremely challenging (13).

All of the tasks required to validate a product for acquisition – e.g., producibility, cost, supportability, etc. – imply that transition is also an engineering process. That is, DOD acquisition processes conform to a system engineering model, which involves predictable steps of evaluation and gradual improvement toward a robust, understood, and supportable outcome (10). Because the typical artifacts of such outcomes are tangible hardware and software products with perceivable, measurable performance effects, it can be difficult to cast the artifacts of cognition and neuroscience research into such engineering forms (with the exception of certain medical applications, where this research may simply inform operational practices and technologies).

To realize the practical benefits of brain research for national security, the products of that research must relate to perceivable user needs and must be defined with engineering constructs. These requirements can be illustrated with a representative example – a human-machine interface system that uses direct physiological sensing to determine a human operator's cognitive state in real time and adaptively modifies system operation to enhance mission performance. A simplified illustration of such an interface is depicted in Figure 2.

Figure 2
Brain-based human machine interface
(image © Patrick Worcester, Potomac Institute for Policy Studies, used with permission)

Measures of brain activity and psychological signals can reveal human states of workload, comprehension, and fatigue that could be used by system processing routines to adjust information presentation rates, or dynamically move manual tasks to automated execution (14). DOD interest in this form of neuroscience has been both intense and long (15). The brain-based interface application represents a candidate for near-term S&T transition in that it:

- Addresses known operational performance problems. Many military systems can tax the information processing capabilities of human operators. These capabilities, furthermore, fluctuate with changes in operator fatigue, motivation, ability and attention. These factors can have major impact on decision quality and mission performance.
- Involves current hardware and software systems used for surveillance and weapons control. While sensing algorithms and control logic are still the focus of active research, even first generation interface applications could be treated as front end modules to existing military technologies.
- Is grounded in a wealth of foundational psychophysiological research and principles. The science needed to construct a physiological sensing system is sufficiently understood to establish at least basic working software models with useful operational impact (although other technological hurdles still exist)
- Has been discussed and socialized within DOD communities via S&T demonstration efforts (16).

To initiate transition, the originator of such an advanced human machine interface, and affiliated S&T sponsors, would need to:

1. *Define, or map to, an operational need.* This requires engagement with one or more prospective user communities to establish identifiable capability gaps. Although military user communities are comfortable with technology and typically have a good familiarity with emerging science, they necessarily think in terms of mission needs. It is the responsibility of the S&T community to engage with users to reach a consensus on operational needs. Because many S&T products represent new discoveries and often reveal new capabilities, such gaps may not be perceived. If the need isn't apparent, however, then further development is necessary and the product isn't yet a transition candidate. For the interface example, there must be a destination platform, such as a command center surveillance system, a shipboard radar console, or an aircraft navigation suite. Next, a case must be made that the current interface is inadequate. Finally, because NR can yield deep understanding of cognitive processes, systems that depend on this research will likely be more sophisticated; a case must be made that any anticipated performance improvement is worth the price in complexity.
2. *Establish performance metrics in engineering-relevant terms*. The S&T sponsor and acquisition team must develop specific answers to relevant questions that are often deferred until very late in the research process. For example, will the advanced interface reduce operator workload? If so, by how much and at what times in the mission profile? Will the interface elicit better decision making from the operator? Under what circumstances? In fact, how will workload and decision quality be defined so that user communities can understand and accept such metrics? What current metrics like this can be used as baselines, to evaluate improvements from the technology? Will the advanced interface relax the need for strict operator selection or lengthy training (e.g., due to enhanced automation support)? And, what data on current performance is being used as a baseline, given that brain and other physiological signals are not currently measured in operations? Even dramatic laboratory success may not translate to operational environments, so metrics must be carefully chosen and agreed upon early in the transition effort. This task is made easier if capability gaps (step 1) are first clearly defined, which can facilitate the early definition of performance metrics as the research effort proceeds.
3. *Address each of the topics required for acquisition planning*. As previously addressed (and detailed further in [17]), each of the topics in acquisition planning is essential to successful S&T transition. Systems must have plans in place for production, operator training, maintenance, and logistics before they are fielded. Although these topics are not commonly considered during the research and development process (which has more fundamental technical issues to contend with), such delay has ended countless business ventures; the "launching" of a new S&T product into military use is no less vulnerable to such failure. If the example human-machine interface system is to be transitioned into operational use, the acquisition community must identify and resolve a multitude of practical issues associated with operational intro-

duction. How many systems will be installed, and where? Will the new interface be implemented as a front end to existing systems or completely integrated with existing technology? Who will fund installations, repair, and technical support? What existing systems, possibly unrelated to the new S&T, might be impacted? Who will be trained to work with the new interface, and will they be available prior to system installations? Will different installations (i.e., units that have the new interface and units that don't) affect personnel assignability? Are failure models and maintenance procedures sufficiently developed to maintain operational readiness, at least through initial evaluation periods? S&T research sponsors can be of immense help in such situations, as the bridge between fundamental research, potential user applications, and transition requirements is their working domain.

These are essential but tractable tasks that are necessary to negotiate the transition process. The advanced interface was chosen because it fit current transition requirements better than some alternate technologies. Nevertheless, while it appears that most general research domains can directly navigate government acquisition processes to realize new capabilities, certain characteristics of CR/NR will still likely stretch the current transition model, as next discussed.

Brain research transition – Unique challenges

While aggressive government funding of CR/NR has enabled rapid scientific progress (18), significant and profound gaps still exist in our understanding of brain/mind function at many levels (19). Further consideration of current research in this area will highlight additional transition issues that emerge from the nature of the science itself. Among these issues are the disruptive impact of brain-based technologies, and the additional analyses required to account for agency, responsibility, and transparency (described below) connected with their use. This gives pause to any effort to insert such products into national security applications, where reliability is essential, and those involved in revolutionary S&T must respect the operational tension between innovation and conservatism.

Although system design based on human reasoning (e.g., expert systems, artificial intelligence) is not a new field, and the science of human machine interaction based on real time physiological states has sown great promise, the ontological implications of human-machine relations have not been resolved to any degree, and will likely have an initially disruptive impact on planning and practice of military operations. Advances in CR/NR could, for example, enable dramatic improvements in mission performance of both human operators and autonomous machines (20). Such capabilities will require a re-thinking of military operating doctrine at several levels. How much information will operators need to reveal about their cognitive functioning (i.e., by allowing their physiological status to be monitored) in order to obtain improved mission performance? How can the decision processes of brain-based human machine systems or autonomous systems be evaluated when the underlying algorithms are dynamic and may differ from mission to mission, from person to person, and at different times within a mission? How will brain-based systems interact with non brain-based systems in distributed networks? Initial answers to such questions, and assessments of their impact on military doctrine, must accompany any effort to introduce these technologies into operational use. While government transition processes provide for graduated testing of technologies (see Figure 1), the impact of the issues described here may not be manifested until operational experience and exposure with such systems is accumulated.

Brain-based systems used in national security applications will almost certainly reflect a combination of autonomous initiative and original problem solving by both human and machine. This means shared agency (who or what acts) and responsibility (who or what is accountable for the result) in military decisions. Although shared agency between humans and computers lies at the core of many combat tasks, such sharing is largely based on predetermined decision models that persist across operational conditions, and the machine role is one of instantiation of one or more rule sets. The issue of agency and responsibility is expanded, when machine intelligence is more powerful and based on real time exercise of human-like faculties, even if those faculties are used to support human decisions. Recognizing the new status of such advanced machine capabilities will require a large adjustment in military and societal thinking about what constitutes a legitimate "mind" in military operations. The effective proliferation of these technologies into any arena of human activity will depend on how much attention and

debate is offered to resolving such issues sooner, rather than later, in the transition process.

System operation based on either autonomous or shared information processing must be visible. Much of the difficulty encountered during early attempts to introduce intelligent (e.g., expert) systems into organizational settings was the lack of explanatory capabilities (21), or *transparency*; systems could not make their reasoning explicit and understandable to operators and, therefore, system output was often not trusted. Because systems based on cognition and neuroscience principles contain many of the defining features of artificial intelligence (e.g., shared-initiative decision making based on real time conditions), they necessarily contain many of the same potential problems, including the need to understand operating state and to recognize degraded conditions. Although system engineering models address these issues, their manifestation in brain-based technologies may not be easy to characterize.

New capabilities typically lead to new consequences that ripple through organizations, so the issues discussed here will necessarily influence the reactions of complex organizations to the introduction of CR/NR products. Certainly, the existing traditions and values of national security organizations, including military communities, act to stabilize their activities and limit the pace of change (22). While government agencies strive to make S&T transition expeditious, the process exercises an important restraining influence by imposing a structure and sequence to its component steps. Transition involves factors independent of the value of a new technology, and researchers must respect the *sociotechnical context* of the agencies with which they work. The advanced human-machine interface, used earlier, can again serve to illustrate some of the strategies that may be required to transition such fundamentally new S&T capabilities in the context of existing operational and technical traditions:

1. *Minimize disruption*. A step-wise introduction of disruptive capabilities, involving deployment of modest but well-understood applications, may become the desirable model for introduction to the effects of brain-based technologies. The human interface might, for example, be tested using only operator workload or fatigue as a performance parameter, and might only provide information feedback (instead of dynamic task support), delaying more advanced capabilities until initial performance has been operationally documented and user communities are satisfied with the results.
2. *Begin the dialogue to define agency and responsibility*. Who — human or machine — is ultimately responsible for decisions made or actions taken during mission execution with a brain-based interface? If a decision is wrong, which entity is responsible (i.e., legally or politically liable)? If these advanced interfaces are truly interactive, is the human operator sufficiently knowledgeable about their role in the task process to accept responsibility? And, understanding these issues, is the government or the larger society willing to accept the consequences involved in shared cognition? These questions require engagement with communities beyond those typically involved in S&T transition. Because these issues are likely consequences of the use of such systems (23), however, the brain research community (and their sponsors) should lead the way in establishing early discussion and debate with all of the operational communities that will deal with their impact.
3. *Design for transparency*. The advanced interface example is grounded in the real time measurement of the operator's cognitive state, which fluctuates according to mission conditions and individual factors. Because these measurements and the algorithms that operate on them are imperfect, some means of making these operations visible to the operator is essential. Although this is similar to the design of many artificial intelligence and expert systems, operations based on neural and physiological sensing may be accessing very personal information about the individual. What methods will be used to gather and reflect individual cognitive state, and who will have access to those data? There are currently no standards for collecting, displaying and using such information in daily practice, highlighting a new requirement for S&T and user community engagement to develop such methods in advance of successful transition.
4. *Respect sociotechnical contexts*. The transition effectiveness of the advanced interface considered here — or any other brain-based technology — could be enhanced through understanding and accommodating the conditions, values, and limitations of prospective user communities, e.g.:

    - Developing operational employment concepts in parallel with fundamental research. The ideas that generate scientific hypotheses should also serve to motivate thinking about applications, even if

new discoveries during the research process result in revisions to initial application concepts. How might the interface system be used? Under what conditions? For what missions? By which operators? The objective is to prepare solutions early to questions that are sure to be asked by military planners and users.

- Soliciting discussion and debate from all user communities. The generation fundamental precedent and foundation ethics regarding brain-based systems should necessarily find a place across agencies and applications. Key individuals and groups should be sought and engaged to develop early policy for interface employment and its consequences.
- Establishing, elaborating, or leveraging government transition tools to reduce risk early in the science process. Military or other agency facilities — having consistent involvement with prospective users — could provide a persistent (standing) exploration and development arena that could provide both the socialization of users to new interface science concepts and the long-term validation testing required to develop confidence in the system. Such technology "nurseries" might also serve to allow time and experience for operating doctrine to catch up with the potential of the science.
- Exploring applications across a wide front. The cultural traditions and operating conditions that govern the acceptance of new concepts may differ within and across user communities. A wide engagement can avoid the seduction of success based on only limited or specialized S&T introduction. Conversely, the choice of which technology, or which parts of a technology, to introduce first can impact transition success; early introduction and shrewd selection in one arena could counter resistance elsewhere. S&T transition is a tactical, as well as a strategic, effort.

The most relevant analog for transition of CR/NR into operational systems may be human factors engineering (HFE) and human-system integration (HSI) products (24), which directly address human-centric sciences and technologies. These engineering activities possess methodologies to ensure the effective functioning of human-machine systems at all levels, and address many of the issues described here, e.g., identifying the need, engaging user communities, defining performance metrics, and addressing the full panoply of operational employment issues (e.g., maintenance, training, etc.). Two relevant lessons from HFE experience are that:

- The user community can often identify novel applications for technologies before the developers themselves; early engagement pays dividends
- Effective transition requires persistent involvement with the operational environment; success depends on iteration.

The technological implications of CR/NR represent advances not just of degree but of kind, and will therefore reshape how we think about both humans and machines. Such understanding, involving individual and group cognition, is far more personal, and opens many more unexplored issues than most other topics of technology transition. Additional steps are needed, therefore, to tune transition processes to better address the consequences of such new science in operational practice.

Summary

Brain research offers extraordinary potential for expanding human performance in a wide range of national security endeavors and new, as-yet unforeseen capabilities will emerge as new knowledge of neural function is gained. It is because knowledge about the human mind is growing so rapidly, however, that additional efforts at mutual education – among the research, S&T, acquisition, and user communities – are so essential; converting brain research results into operational capabilities requires the contributions of many agents. The need for a broad, collaborative approach to transitioning such science from the laboratory to national security capabilities is apparent when matching the potentially disruptive products of the research enterprise to hard engineering and acquisition requirements, and to current operational demands.

Brain research holds significant potential to advance national security in original, fundamental ways. The applications discussed here were selected to bring a subset of issues into focus; certainly, other applications such as training, cognitive enhancement, improved social interaction and health care present additional issues that must also be debated and resolved before useful products are realized. The common points of all these applications are that cognition and neuroscience researchers must navigate a practical and structured transition process if the products of the laboratory are to be realized as tangible human ca-

pabilities, and that brain research discoveries may require elaboration of the transition process itself, to anticipate potentially disruptive consequences to operations. Early engagement around these topics among researchers, government transition communities, and users will, however, develop the conceptual foundation needed for significant advances in national security capabilities.

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Competing interests

The authors declare that they have no competing interests.

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