Commentary on Embodied Minds and Dancing Brains: New Opportunities for Research in Mathematics Education

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Stephen Campbell's chapter reads as a clarion call for education researchers to appreciate and make use of the concept that the process of learning mathematics, whether in kindergarten or graduate school, essentially involves grounding its the abstract concepts and symbol manipulations in the learner's imaginative experience, and that the experience of learners and researchers alike is dominated by and rooted in their experience as embodied agents moving in our 3-D world and interacting with objects and other agents including other people.

A revolution in psychological thinking has been spurred by the graphic confirmation of brain functional magnetic resonance imaging (fMRI) methods, that every turn of thought and focus of attention involves subtle shifts in the distribution of energy use throughout the brain (and hence, of new for newly oxygenated blood, leading to the measured BOLD signals). Work in the first decade of fRMI research focused on observing which brain areas participate in performance of which cognitive tasks, from counting dots to resolving ethical dilemmas. This has generated thousands of papers with pictures showing isolated 'blobs' of relative activation (and inactivation) in activity difference maps between this and that task. One unsettling finding has been that the same areas may become more active in many seemingly diverse tasks.

A second finding, highly relevant to education research, is that no human brain areas appear specialized for abstract thinking—including mathematical thinking. Instead, areas developed during mammalian evolution to manage behavior in the 3-D world also become more active in humans when they are given tasks requiring more abstract thinking. This is not to say that there are no differences between human brains and brains of other mammals. What is striking is that there are no brain areas that become active exclusively in abstract tasks that only humans can do. This fits the concept of 'embodied cognition' in which human ability to perform abstract thinking including mathematics is fundamentally rooted in our embodied experience and in the evolved capabilities of our brains to organize and optimize the *outcome* of our corporeal behavior.

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This conclusion from functional brain imaging also means that observing brain function during learning may give real clues as to what types of embodied thinking lead to successful learning and teaching. These may differ across students, meaning the study of individual differences in learning style, now widely acknowledged but not well understood, may be better understood through functional brain imaging research in education. Just as fMRI results have pushed the mainstream of psychology towards concepts related to embodied cognition, ongoing advances in genetic readout and interpretation are rapidly reinforcing the concept that we all have complex differences in our cognitive capacities—and in our preferred and more successful routes to learning of new abstract concepts.

However, for all their success fMRI and other metabolic brain imaging methods have three major shortcomings. Their equipment is *heavy* and *expensive*, and the metabolic activities they monitor are *slow*. fMRI BOLD signals actually measure the eventual (seconds later) overabundance of oxygenated blood in a brain area partially depleted through use, evidence of a marvelously efficient but slowly acting active and region-specific brain blood delivery system. The *sluggishness* of BOLD signal changes means that fMR imaging cannot keep up with either the speed of thought or the speed of motor behavior—the comparability of their speeds not coincidental, from the embodied cognition viewpoint.

The *quite high expense* of fMRI and other metabolic imaging is becoming more and more a factor as health care costs increasing dominate and bind the economies of the developed world.

The *heavy weight* of fMRI, PET, SPECT, and MEG brain scanners mean that the head of the subject being imaged must be brought in contact with the system and held by the subject rigidly in place, both to avoid signal dropouts and intrusion of catastrophic signal artifacts. This means that metabolic imaging cannot occur in normal teaching environments and body positions, and cannot involve normal subject movements and interactions—both important in the normal learning process.

The only form of functional brain imaging that (a) uses very lightweight sensors, (b) is relatively less expensive than metabolic imaging, and (c) is faster than thought itself is the scalp electroencephalogram (EEG). First developed in usable form in the late 1920's, EEG was the first brain imaging modality, but has lagged behind newer modalities in technical development, mainly in the development of mathematical methods to transform the scalp-derived signals into true 3-D functional images of changes in brain activity patterns during states and behavior of interest. Given its flexibility, potential, and relatively low cost, Campbell is right to emphasize EEG as an excellent method to combine with other measures of brain and behavior (audiovisual recordings, eye-tracking, heart rate, etc.). Acquiring, integrating, and synchronizing these various data streams in the study of mind, brain, and behavior, as he is now doing in his educational neuroscience laboratory, is a non-trivial and significant accomplishment, and one that could indeed open new frontiers for educational research and cognitive neuroscience in general.

My own work and that of my colleagues at UCSD and elsewhere has focused on research and development of methods for extracting and modeling the rich and temporally precise information about brain function available in modern high-density

EEG signals (Makeig et al. 1996, 2002, 2004). Success in our investigations, and relative perplexity of other EEG researchers about our new methods, lead us to put a rich toolbox of functions for the widely used Matlab (The Mathworks, Inc.) platform on the World Wide Web beginning in 1997, eventually leading to an integrated environment for electrophysiological signal processing, EEGLAB (Delorme and Makeig 2004) whose development is now supported by the National Institutes of Health USA, and whose many research users work in laboratories throughout the scientific world.

Our advancing research continues to reinforce my presumption that in coming years EEG will once again become an important and highly informative functional imaging research modality. In particular, the speed of changes in the brain's collective electrophysiological activity, measured by EEG, is sufficient to observe transient interlocking between the activities of otherwise distinct brain areas, and thus to observe distributed brain events that must support global cognition as well as behavior planning.

Quite recently, I have been studying how best to exploit another key advantage of EEG brain imaging—its light weight and thus, portability. In the last decade, high-density EEG systems have become available with up to 256 channels recording at 2,000 Hz or above—i.e. easily capable of collecting over a million bits per second of information about brain dynamics. The overall goal of cognitive neuroscience is to observe and model the links between brain dynamics and behavior. Yet following the classical tradition of psychophysics, the only measure of actual behavior collected in the vast majority of such experiments has been occasional minimal subject finger presses on one or more 'microswitches'—an information bandwidth of the order of one bit per second! It is no wonder, then, that progress in functional imaging of the relationship between behavior and brain activity has been relatively slow, its apparent momentum deriving more from the parallel research efforts of thousands of laboratories, too often generating isolated or weakly connected results.

To deal with the fundamental information bandwidth mismatch between recorded brain activity and behavior, most researchers have been content to collapse the richness of the brain data down by response averaging and 'peak picking' to a level equivalent to that of their derived measures of behavior (left or right finger presses, mean reaction time, etc.). However, a different conceptual approach is required to understand the richness of the functional connections between behavior and brain EEG dynamics. Rather than collapsing the complexity of the brain activity data collected in such experiments, it should be better to increase the complexity of the behavioral recording of subject behavior by incorporating additional psychophysiological measures, eye tracking, and body motion capture. Then, given relatively equally rich brain and behavioral data sets, use modern mathematical machine learning and data mining methods to find the functional connections between brain and behavior during learning and other cognitive tasks and activities.

Through his background in signal processing, Campbell also understands the need for more adequate signal methods to model new types of data. Although developing, first testing, and optimizing new methods of data analysis is a complex process, the resulting methods can be made more widely available to the research community through open software environments like EEGLAB, a project to which many electrophysiological researchers are now contributing.

My own thinking about the need for more adequate merging of brain and behavioral observations largely parallels that of Campbell. Recently, I and colleagues at UCSD have performed early research to combine high-density EEG and full body motion capture—forming in effect a new brain imaging modality I call Mobile Brain/Body Imaging or MoBI (Makeig et al. 2009). First experiments have been fairly rudimentary—reaching out to touch LED lights mounted on sticks, turning to look at, point at, or walk up to various objects placed on pedestals around the experiment room, performing simple visual attention tasks while walking on a treadmill. Our first results, for the most part not yet published, confirm that particular patterns of EEG activity in many parts of the brain's outer shell or cortex are involved in organizing even simple motivated behaviors.

The MoBI concept and current portable EEG technology also should allow the study of brain activity supporting social activities including tutoring and small group collaborative or competitive learning—a first experiment at the Swartz Center involves two subjects sitting side by side and playing a spatial learning game using a touch-screen, either competing against each other, playing solitaire, or collaborating against 'the computer,' which is programmed to play equally as well as (but also make mistakes like) a human player. Adding eye tracking data and analysis, as Campbell has already accomplished, is an important next step.

First funding for this new science in my laboratory has come from the Temporal Dynamics of Learning Center, a large group effort funded by the education division of the National Science Foundation USA and centered at UCSD, dedicated to studying both the brain biological and behavioral roots of successful learning and teaching. Currently, under other funding we are expanding our MoBI research to learning to perform cognitive monitoring and active reinforcement of subjects who must integrate information from multiple visual, audio and even tactile streams to make sound decisions.

This research direction looks to another ever more important trend in EEG brain research—the concept that modern microelectronics makes its possible for high-density EEG, body motion capture, and many other types of non-invasive human biosensors to be made nearly weightless and wireless, embedded in light undergarments hidden under outer clothing or in some cases recorded using video and other cameras not attached to the subject.

Next Christmas holiday season (2009), it has been reported that a leading toy manufacturer will offer a wireless EEG-based game in which children or adults will 'will' a ball floating in a variable-sped air stream up and down around a 3-D obstacle course using volitional control of their EEG patterns. The price for this game is expected to be only US $79.99! While this one-channel EEG game is far from the quality needed for brain imaging research, I expect it will strongly contribute to an ongoing sea change in attitude about EEG as generating data for researchers to study as one for user-subjects to use in a range of ways from games to alertness monitoring to biofeedback for changing or (hopefully) optimizing their attention patterns (e.g. during learning).

The new interest in brain-computer interface (BCI) design is bringing increasing numbers of students and young researchers with quantitative experience into the field, thereby accelerating the increase in mathematical sophistication needed to transform traditional EEG recording and interpretation into both a true functional brain imaging modality, and into a common learning, monitoring, and gaming appliance. Researchers in mathematics education research may feel satisfaction from knowing that the most important and challenging part of these developments will be in development and application of new mathematical machine learning methods—methods that current mathematics education is preparing a next generation of researchers to learn, further develop, and apply successfully.

The clarion call of Campbell, here, to incorporate multimodal brain and behavioral measures into educational research, represents only the leading edge of new methods and capacities that should eventually transform and energize research on learning and teaching, allowing it to advance through better understanding of the brain dynamics that intimately support these processes—perhaps even leading within a few years to new system aids to learning and teaching making active use of brain and behavioral monitoring. While such methods would be far from guaranteed to work, and even if so could (like other new ideas) have less than desirable side-effects, the knowledge about brain processes supporting learning and teaching gained in their development will likely prove intellectually liberating and will very likely, in my opinion, play an increasingly important role in future educational research.

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