EDUCATIONAL NEUROSCIENCE: NEW HORIZONS FOR RESEARCH IN MATHEMATICS EDUCATION

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This paper outlines an initiative in mathematics education research that aims to augment qualitative methods of research into mathematical cognition and learning with quantitative methods of psychometrics and psychophysiology. Background and motivation are provided for this initiative, which is coming to be referred to as educational neuroscience. Relations and differences between cognitive and educational neuroscience are discussed. This is followed by descriptions of methods, along with some of the kinds of expertise required for educational researchers to use such methods more effectively. Overall, this paper points to new horizons and opportunities for research in mathematics education, with some associated pitfalls in areas that appear to be particularly ripe for opening up with these new methods.

BACKGROUND AND MOTIVATION

The 26th annual PME conference in Norwich was a watershed moment in my thinking about research in mathematics education, where our field currently seemed to be, where it was heading, and how I would most like to and might best contribute. A colleague recently captured well the impressions and frustrations I had at that time: "Theories are like toothbrushes," he said, "everyone has their own, and no one wants to use anyone else's." I didn't feel that our various theories necessarily lacked in insight, or were wanting in intrinsic value, or practical applications. My frustrations were grounded in my lack of ability to discern which amongst a plethora of theories would best survive the test of time. I value theoretical speculation, but I seek empirical grounding. I had recently conducted studies in mathematical cognition and learning in which I had sought greater observational grounding through video capture of preservice teachers' overt behaviour as they engaged in problem solving activities working with computer-based learning environments, simultaneously with video capture of their on-screen activities (Campbell, 2003a). This method of "dynamic tracking" led me to believe I was capturing bona fide "aha! moments" of learners in the very act of conceptual understanding. As I attempted to analyse my observations from a perspective of schema theory (Campbell & Zazkis, 2002), I was deeply frustrated by the speculative nature of my interpretations about what was happening in the minds of these learners. My methods were much more tangible to me than my speculations. From a theoretical perspective of embodied cognition (Campbell, 2003b; Campbell & Dawson, 1995), I was left wishing I had some means to also simultaneously observe and record brain behaviour and various other embodied responses of my participants, such as eye-movement, pupil dilation, heart rate, and galvanic skin response. I wanted better grounding for my speculations.

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So it was, that I was enveloped with an excitement serving to dissolve my despair when I attended talks in Norwich by Wolfgang Schlöglmann (Schlöglmann, 2002), and Judith Sowder (Philipp & Sowder, 2002). Schlöglmann addressed some interesting psychometric results in connection with results from neuroscience regarding affect and cognition, while Sowder discussed the use of eye-tracking methods in tandem with qualitative interview methods. I knew there and then, that if I were to continue with empirical research in mathematics education, this direction, toward more embodied observational methods, was the clear way (for me) to go.

One might wonder why such approaches would have much import or relevance to the study of the minds of learners. More specifically, with regard to brain research, Byrnes (2001) presents three main arguments *against* the relevance of brain research to the psychology of cognition and learning. Roughly, the first argument pertains to a computer analogy, whereby brain is identified with hardware, and mind is identified with software. Accordingly, as educational researchers interested in matters of mind, we can restrict our consideration to the software/mind, independently of the hardware/brain. Byrnes counter-argues that this computational view is "anti-biological," as embodied views of cognition and learning naturally entail. Further, he suggests, the computer analogy notwithstanding, that interdependencies between software and hardware are much greater than commonly supposed. A second argument against the relevance of neuroscience to psychology is that they address different levels of analysis, and as such, they provide very different answers to the same questions. Byrnes illustrates this argument through the different kinds of answers that a physicist, physiologist, and psychologist attending a baseball game would provide to the question "Why did (the pitcher) throw a curve ball?" Educational researchers are typically loath to reduce psychological questions to matters of physiology, let alone physics. Byrnes suggests there are important insights to be gained from studies seeking understandings of interfaces between different levels of analysis, and between psychology and physiology in particular. One need not be a reductionist to maintain that such interfaces must interact in coherent ways. The third argument Byrnes poses for ignoring relationships between psychology and physiology, and neurophysiology in particular, is that too little is known about the brain at this point, and as brain science is in such flux, psychologists should just "forge ahead alone." Byrnes rightly emphasises that psychology and the neurosciences have much to offer each other. This is a key point: psychologists have cognitive and psychometric models that can help guide physiological investigations, and the results of those investigations can help substantiate and refine those models.

Indeed, to paraphrase Byrne, collaborations between cognitive psychologists and neuroscientists have been "forging ahead together," resulting in the vibrant and rapidly expanding new field of cognitive neuroscience. Driven by new imaging methods, coupled with decades of lesion studies, cognitive neuroscience is making great strides in correlating cognitive function with brain and brain behaviour. Research in mathematics education can benefit greatly from these developments.

FROM COGNITIVE TO EDUCATIONAL NEUROSCIENCE

Cognitive psychologists, computer and neuroscientists, psychophysiologists, geneticists, and others, have made substantive advances in understanding mental function, brain structure, and physiological behaviour. Furthermore, substantive progress is also being made in our understanding of the relations between these traditionally diverse and separate realms of disciplined inquiry (Gazzaniga, 2004). These interdisciplinary efforts have been fuelled by at least two major developments — an increasing knowledge base from lesion studies, and advances in brain imaging.

Brain lesions, i.e., neural damage, can result in various ways from developmental abnormalities, impact injuries, surgery, strokes, or disease. Lesions, be they local or widespread within the brain, typically result in altered or compromised mental functioning of those who suffer them. Lesions can have rather bizarre implications for cognitive function, some of which have been widely popularised by authors such as Oliver Sacks (e.g., 1990, 1995). Yet, in many cases, the mental life of those with brain lesions can be remarkably robust and quite adaptable as well (e.g., Sacks, 1989). The bottom line here is that there is a broad and multidimensional range of correlations between local and widespread damage to neural assemblies with specific and general aspects of mental functioning. Although innovations in brain imaging are providing new insights, neuroscientists are still working hard to understand various mechanisms behind such correlations, and psychologists can still find themselves at odds with neuroscientists regarding various fundamental assumptions about the nature of those correlations (e.g., Uttal, 2001).

Brain imaging techniques have opened new windows on brain structure and brain behaviour. From hemodynamic (blood mediated) techniques such as functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET), to electromagnetic techniques such as magnetoencephalography (MEG) and electroencephalography (EEG), great strides are being made in our understandings of correlates between brain anatomy, brain behaviour, and mental function (Gazzaniga, 2004). Of particular interest here, as will become more evident below, are brain oscillations in human cortex and cerebellum which are closely, if not causally, associated with mental phenomena characteristic of mathematical thinking ranging from profound insight to deep aversion. Such oscillations are readily detectable by EEG, within certain experimental conditions and thresholds of signal and noise.

Concerned as it is with understanding psychological, computational, neuroscientific, and genetic bases of cognition, cognitive neuroscience is now recognised as a well-established interdisciplinary field of study with its own society and annual meetings. The Cognitive Neuroscience Society (CNS) presents itself as a "a network of scientists and scholars working at the interface of mind, brain, and behavior research" (CNS, 2005). As such, it would seem, then, that cognitive neuroscience shares many areas of common interest with educational researchers, especially with regard to educational psychology and psychometrics.

Yet, at the same time, the CNS sees its members as "engaged in research focused on elucidating the biological underpinnings of mental processes" (ibid.), thereby suggesting that their approach is more fundamentally reductionist than interactionist in nature. Educational researchers such as myself want to be informed by biological mechanisms and processes underlying learning, and we also want to have access to the methods of cognitive neuroscience. As an educational researcher, however, my primary focus is not strictly on biological mechanisms and processes underlying cognition and learning. Rather, it is on the lived experiences of teaching and learning, along with the situational contexts and outcomes of those experiences.

Neuroscience, approached from a "hard" scientific orientation, has the luxury of focusing on various aspects of brain behavior solely in terms of neural structure, mechanisms, processes, and functions. On the other hand, neuroscience approached from a more humanistic orientation has the luxury of not having to be concerned with trying to explain, or explain away, the lived experience of learners solely in terms of biological mechanisms and processes underlying brain behavior.

The above considerations suggest the possibility of an *educational* neuroscience, as a new area of educational research that is both informed by the results of cognitive neuroscience, and has access to the methods of cognitive neuroscience, especially conscripted for the purposes of educational research into the lived experience of embodied cognition and learning. As such, educational neuroscience can be accurately described as a bona fide and full-fledged neurophenomenology (cf., Varela, 1996; Varela & Shear, 1999; Lutz & Thompson, 2003).

Indeed, educational neuroscience is a fast emerging and potentially foundational new area of educational research. A general consensus is emerging on two basic points. First, educational neuroscience should be characterized by soundly reasoned and evidence-based research into ways in which the neurosciences can inform educational practice, and, importantly, also vice versa. Secondly, educational research in cognitive psychology informed by, and informing, cognitive neuroscience should constitute the core of educational neuroscience (e.g, Berninger & Corina, 1998; Bruer, 1997; Geake & Cooper, 2003). New centres and labs to this end have recently opened in England, Germany, the United States, Canada, and elsewhere. This appears to be a very timely development, as there has been increasing emphasis on informing educational practice through advances in the neurosciences (NRC, 2000), along with increasing concern that much educational research, especially of the qualitative ilk, is lacking in a scientific "evidence-based" foundation (NRC, 2002). There is much to be said and much has been gained from qualitative research, and I would not wish to appear neglectful of these facts. Having said that, however, when protocols and data obtained from such research consists of "talk-aloud" reports, often of questionable reliability and validity, and cognitive models of learners' thinking remain essentially analytical or speculative in nature, one must ask: how robust and generalisable will our qualitative research into subjective mentalities ultimately prove to be? There are methods available for research in mathematics education to address these concerns.

METHODS AND EXPERTISE

What is gained from using methods such as EEG, are means for operationalising the psychological and sociological models educational researchers have traditionally developed for interpreting the mental states and interactions of learners in the course of learning mathematics. This statement holds for qualitative educational researchers and quantitative educational psychometricians alike. It bears emphasis that educational neuroscience can augment traditional qualitative and quantitative studies in cognitive modelling in general, and particularly, in research in mathematics education. McVee, Dunsmore, & Gavelek (2005) argue compellingly that schema theory, the mainstay of cognitive modelling, remains of fundamental relevance to contemporary orientations towards social and cultural theories of learning. Holding fast to a humanistic orientation, educational neuroscience concerns both psychological and sociological dimensions of learning, only now, using methods of cognitive neuroscience, all the while guided by, and yet also serving to test and refine, more traditional educational studies. No comprehensive treatment of these matters can be provided here, just brief indications of some possibilities and pitfalls.

Consider, for example, what kinds of detectable, measurable, and recordable psychophysiological changes are occurring in learners' brains and bodies during mathematical concept formation — that is, when various mental happenings coalesce into pseudo or bona fide conceptual understandings of some aspect of mathematics. For instance, what changes occurred in a student working with Geometer's Sketchpad™ as she came into a realisation that all right triangles inscribed in a circle must pass through the centre of that circle? And what of the student at ease with graphs, who cringed at the sight of mathematical symbols on the screen? (see Campbell, 2003a) Capturing moments such as these in some psychophysiological manner would provide a rich venue for analysis. But how best to go about it?

Of particular interest for educational researchers are EEG and Eye-tracking (ET) systems, and for a variety of reasons. First, relative to most other methods, EEG and ET instrumentation fall within the realm of affordability. Secondly, they are relatively easy and safe to use, involving minimal risk to participants. Thirdly, with sampling rates in the millisecond range, both EEG and ET are well suited for capturing the psychophysiological dynamics of attention and thought in real time. Both methods basically offer temporal resolution at the speed of thought and place fewer spatial constraints on participants than other methods. Furthermore, as evidence of increasing confidence in both the reliability and robustness of these methods, many "turnkey" acquisition and analysis systems are now readily available, placing fewer technical burdens on researchers venturing to use such systems.

Eye-tracking studies have commonly used methods severely limiting head movement (e.g., Hutchinson, 1989). More recently, less constraining, non-intrusive, methods have been developed for remotely measuring eye movements in human-computer interactions (e.g., Sugioka, Ebisawa, & Ohtani, 1996). These remote-based methods have become very reliable, quite robust, and easy to set up (e.g., Ebisawa, 1998).

Most instructional software today can be offered through computer-based environments. Remote-based eye-tracking, therefore, is bound to become an important and well established means for evaluating the design and usage of computer-based mathematics learning environments.

With EEG, cognitive neuroscientists have developed a viable approach to studying complex cognitive phenomena through electromagnetic oscillation of neural assemblies (e.g., Niebur, 2002; Klimesch, 1999). The key to this approach is the notion of event related desynchronization/synchronization (ERD/S) (Pfurtscheller & Aranibar, 1977). In the course of thinking, the working brain produces a fluctuating electromagnetic field that is not random, but rather appears to correlate well within distinct frequency ranges with cognitive function in repeatable and predictable ways.

As previously noted, brain oscillations in human cortex and cerebellum can be reliably correlated with mental phenomena characteristic of mathematical thinking ranging from insight (Jung-Beeman, et al, 2004) to aversion (Hinrichs & Machleidt, 1992). There have been increasing efforts to tease out a "neural code" for such correlates of affect and mentation (such as emotional response, working memory, attention, anxiety, intelligence, cognitive load, problem solving etc.) of synchronic brain behaviour in distinct frequency bands, variously identified as Delta (< 1-4 Hz), Theta (~ 4-8 Hz), Alpha (~ 8-13 Hz), Beta (~ 13-30 Hz), and Gamma (~ 30-60 > Hz).

A prerequisite to understanding and using this method is a basic mathematical understanding of signal processing, such as sampling, aliasing, Nyquist frequencies, and spectral analysis. There are two fundamental pitfalls in signal processing. The first is mistaking noise for signal, and the second is mistakenly eliminating meaningful signals. The first pitfall is typically a matter of faulty interpretation, whereas the second is typically a matter of faulty data acquisition and/or analysis (Campbell, 2004). Gaining an elementary level of expertise in such matters should be relatively straightforward for researchers in mathematics education with a mathematics, physics, or engineering degree. For those researchers in mathematics education with insufficient prerequisite expertise, or who would simply rather not delve into such matters, there is always the option of seeking out cognitive neuroscientists with expertise in EEG, and especially in other, more sophisticated methods as well. While there are many benefits to interdisciplinary collaboration, there are some drawbacks — in that, allocations of lab time and equipment usage would typically not be under the direction or control of the educational researcher.

As powerful as the tools and methods of cognitive neuroscience are, however, and as promising as the prospects for bridging gaps in our understanding regarding the relation between brain and mind may be, some philosophical problems appear as intransigent and recalcitrant as ever. What are we to make of a "mindbrain"? What does such a thing look like? Well, it looks like a brain. And how does it think? Well, it thinks like a mind. Like quicksand, questions like these can quite readily draw the unwary back into classical dualist conundrums (Campbell, 2002).

References

Berninger, V. W., & Corina, D. (1998). Making cognitive neuroscience educationally relevant: Creating bi-directional collaborations between educational psychology and cognitive neuroscience. *Educational Psychology Review*, *10*(3), 343-354.

Bruer, J. T. (1997). Education and the brain: A bridge too far. *Educational Researcher*, *26*(8), 4-16.

Byrnes, J. P. (2001). *Minds, brains, and learning: Understanding the psychological and educational relevance of neuroscientific research*. New York: The Guilford Press.

Campbell, S. R. (2004). Forward and inverse modelling: Mathematics at the nexus between mind and world. In H.-W. Henn & W. Blum (Eds.) *ICMI Study 14: Applications and modelling in mathematics education – pre-conference volume* (pp. 59-64). Dortmund, Germany: University of Dortmund.

Campbell, S. R. (2003a). Dynamic tracking of preservice teachers' experiences with computer-based mathematics learning environments. *Mathematics Education Research Journal*, *15*(1), 70-82.

Campbell, S. R. (2003b). Reconnecting mind and world: Enacting a (new) way of life. In S. J. Lamon, W. A. Parker, & S. K. Houston (Eds.), *Mathematical modelling: A way of life* (pp. 245-253). Chichester, UK: Horwood Publishing.

Campbell, S. R. (2002). Constructivism and the limits of reason: Revisiting the Kantian problematic. *Studies in Philosophy and Education*, *21*(6), 421-445.

Campbell, S. R. (2001). Enacting possible worlds: Making sense of (human) nature. In J. F. Matos, W. Blum, S. K. Houston, & S. P. Carreira, *Modelling and mathematics education* (pp. 1-14). Chichester, UK: Horwood Publishing.

Campbell, S. R., & Dawson, A. J. (1995). Learning as embodied action. In R. Sutherland & J. Mason (Eds.) *Exploiting mental imagery with computers in mathematics education* (pp. 233-249). Berlin: Springer.

Campbell, S. R., & Zazkis, R. (2002). Toward number theory as a conceptual field. In S. R. Campbell & R. Zazkis (Eds.) *Learning and teaching number theory: Research in cognition and instruction* (pp. 1-14). Westport, CT: Ablex Publishing.

CNS (Cognitive Neuroscience Society). On-line at http://www.cogneurosociety.org

Ebisawa, Y. (1998). Improved video-based eye-gaze detection method. *IEEE Transactions on Instrument and Measurement*, *47*(4), 948-955.

Gazzaniga, M. S. (2004). *The cognitive neurosciences III*. Cambridge, MA: MIT Press.

Geake, J., & Cooper, P. (2003). Cognitive neuroscience: Implications for education? *Westminster Studies in Education*, *26*(1), 7-20.

Hinrichs, H., & Machleidt, W. (1992). Basic emotions reflected in EEG-coherences. *International Journal of Psychophysiology*, *13*(3), 225-232.

Hutchinson, T. E. (1989). Human-computer interaction using eye-gaze input. *IEEE Transactions on System, Man, and Cybernetics*, *19*(6), 1527-1533.

John, E. R. (2002). The neurophysics of consciousness. *Brain Research Reviews, 39*(1), 1-28.

Jung-Beeman, M. J., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R. E., Reber, P. J., & Kounios, J. (2004). Neural activity when people solve verbal problems with insight. *PLOS BIOLOGY*, *2*(4), 500-510.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research Reviews, 29*(2-3), 169-195.

McVee, M. B., Dunsmore, K., & Gavelek, J. R. (2005). Schema theory revisited. *Review of Educational Research*, *75*(4), 531-566.

Niebur, E. (2002). Electrophysiological correlates of synchronous neural activity and attention: a short review. *Biosystems, 67*(1-3), 157-166.

NRC (National Research Council) (2000). *How people learn: Brain, mind, experience and school.* Washington, DC: National Academy Press.

NRC (National Research Council) (2002). *Scientific research in education.* Washington, DC: National Academy Press.

Pfurtscheller, G. and Aranibar, A. (1977). Event-related cortical desynchronization detected by power measurement of scalp EEG. *Electroencephalography and Clinical Neurophysiology, 42*, 817-826.

Sacks, O. (1995). *An anthropologist on Mars: Paradoxical tales*. New York, NY: Vintage.

Sacks, O. (1990). *The man who mistook his wife for a hat: And other clinical tales*. New York, NY: Harper Perennial Library.

Sacks, O. (1989). *Seeing voices: A journey into the world of the deaf*. Berkeley, CA: University of California Press.

Sugioka, A., Ebisawa, Y., & Ohtani, M. (1996). Nonconstant video-based eye-gaze detection method allowing large head displacements. *IEEE International Conference on Medicine and Biology Society*: 948-955.

Lutz, A., & Thompson, E. (2003). Neurophenomenology: Integrating subjective experience and brain dynamics in the neuroscience of consciousness. *Journal of Consciousness Studies*, *10*, 31-52.

Uttal, W. R. (2001). *The new phrenology: The limits of localizing cognitive processes in the brain*. Cambridge, MA: The MIT Press.

Varela, F. J. (1996). Neurophenomenology: A methodological remedy to the hard problem. *Journal of Consciousness Studies*, *3*, 330-350.

Varela, F. J., & Shear, J. (1999). First-person accounts: Why, what, and how. In F. J. Varela and J. Shear (Eds.), *The View from within: First-person approaches to the study of consciousness* (pp. 1-14). Thorveton, UK: Imprint Academic.

Zazkis, R., & Campbell, S. R. (Eds.) (in press). *Number theory in mathematics education: Perspectives and prospects*. Lawrence Erlbaum Associates.