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Can Cognitive Neuroscience Ground a Science of Learning?

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Abstract

In this article, I review recent findings in cognitive neuroscience in learning, particularly in the learning of mathematics and of reading. I argue that while cognitive neuroscience is in its infancy as a field, theories of learning will need to incorporate and account for this growing body of empirical data.

Keywords: cognitive neuroscience, learning, mathematics, reading

Why is there a current interest in cognitive neuroscience findings? In spite of the pessimism of Bruer (1997) and the more recent caveats of Varma, McCandliss, and Schwartz (2008), and Willingham (2008), the past decade has seen an upsurge in studies focusing on the brain-basis for learning (see OECD, 2007 for a comprehensive review of brain-related research in education). The following factors appear to be contributing to this interest:

- A desire to scientifically debunk popular 'brain-based' claims about learning and teaching (i.e. 'neuromythologies');
- A growing set of studies on the neural bases for mathematical thought;
- The establishment of recent gains in understanding the brain bases for processes of decoding in reading;
- Decades of behavioral and cognitive science findings on both reading and learning mathematics upon which to base brain studies in these areas;
- Frustration with vague theories of learning and the desire to disambiguate and constrain research hypotheses at the behavioral, cognitive and social levels of analysis;
- Frustration with broad measures of achievement (often paper-and-pencil standardized tests) that do not allow the ability to sharpen and ground diagnosis and remediation of learning difficulties;
- A desire to introduce and explore new mixed-methods research methodologies in the social sciences;
- A sense of urgency to address emerging ethical issues that pertain both to neuroscience and to learning;
- The ongoing goal to improve methods of teaching worldwide, including the quality of educational materials;

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- The emergence of more comprehensive and testable models of learning emerging from cognitive science that can bridge learning and cognitive psychology;
- A desire to understand and promote creativity, and to explore cognition in music and other areas;
- The challenges neuroscientists face in modeling learning phenomena continue to push the boundaries of imaging technologies, and of the expertise required co-formulate clinical learning tasks with learning scientists.

Part of the difficulty that educational psychology has faced in the study of learning is that, too often, learning constructs exist as psychometric objects measured by tests (cf. the treatment of intelligence, Sternberg, 2007). At the behavioral level, particularly in ethnographic studies of learning in classrooms, researchers typically lack the knowledge to differentiate between activity that is essentially accidental or contingent (i.e. behavior A happened as a result of behavior B, but the results are transitory and the implications for understanding are fleeting) and behaviors that point to more fundamental processes or constraints that are necessary to a scientific understanding (e.g. Kelly, 2004; Kelly, 2008). I argue that a science of learning can be grounded in a set of empirical primitives and that these primitives are becoming known via cognitive neuroscience-based analyses.

I recognize that the state of the art in cognitive neuroscience research is still in its early stages (OECD, 2007; Frith & Blakemore, 2005), and that cognitive neuroscience will take decades to mature. Nonetheless, important questions are being addressed, and new ones will be answered, by advances in functional imaging technology such as near infrared spectroscopy (Koh *et al.*, 2007).

Moreover, there already is evidence that general abilities that define learning, such as studies of general understanding of concrete and abstract concepts, are linked to specific brain systems (Binder *et al.*, 2005). Other studies have focused on attention (e.g. Rueda *et al.*, 2004), and executive function, attention and memory (Fan *et al.*, 2003; Fan *et al.*, 2005; Fossella *et al.*, 2002). Interestingly, the attention capacity may have genetic triggers (Parasuraman *et al.*, 2005).

New work is appearing on long-term memory consolidation as a complex neurobiological process, involving synaptogenesis and neurogenesis (Shors, 2008). For related studies on memory see Kesner, 2009; Reder, Park & Kieffaber, 2009; and Weinberger *et al.*, 2009.

Specific abilities such as mathematics are also apparently rooted in and require brain circuitry to support simple function and these circuits also underlie significant performance deficits. For example, mathematical ability not only appears quite early in life (e.g. Berger, Tzur & Posner, 2006; Wynn, 1992), but is also being found to have phylogenetic roots and may not be 'uniquely human' (e.g. Diester & Nieder, 2007; Nieder, Diester & Tudusciuc, 2006).

When mathematical ability is impaired in humans, growing evidence points to a brain basis, especially in extreme cases such as in dyscalculia (e.g. Butterworth, 2005). Or in cases of dementia, cognitive decline appears to be related to specific dissociations in numerical ability (Cappelletti *et al.*, 2005, see also, Tang, Ward & Butterworth, 2008). On the positive side, intensive instruction in multiplication and subtraction appears to impact different neural circuitry (Ischebeck *et al.*, 2006). In fact, Dehaene and colleagues argue for a brain basis for 'number sense', generally (Dehaene, 1997; Feigenson, Dehaene & Spelke, 2004; Hubbard, Piazza, Pinel & Dehaene, 2005), which they contend is the result of evolutionary pressures.

The brain circuitry for reading is already well established, building on decades of behavioral work. Like mathematics research, there is growing evidence of very early circuitry development to support reading skill (e.g. Guttorm *et al.*, 2005; Molfese, 2000; Schlaggar & McCandliss, 2007). For example, there are studies implicating the posterior cortex in development dyslexia (e.g. Pugh, Mencl, Shaywitz *et al.*, 2000; Pugh, Mencl, Jenner *et al.*, 2000; Pugh *et al.*, 2005; Shaywitz *et al.*, 2002). It is important to note that neural studies go beyond simply mapping areas of the brain to behavioral activity. Studies are now appearing that attempt to design learning based on brain studies such as executive attention (Rueda *et al.*, 2005), reading (e.g. Eden & Moats, 2002; McCandliss *et al.*, 2003; Sarkari *et al.*, 2002), and number sense (e.g. Wilson, Dehaene *et al.*, 2006; Wilson, Revkin *et al.*, 2006). Dehaene (2009) is a superb review of the neural basis for reading.

Significantly, studies are now appearing linking learning to changes in the brain via training interventions, completing an observational-correlational-experimental loop (e.g. Sandak *et al.*, 2004; Simos *et al.*, 2002; Temple *et al.*, 2003). The drivers in these studies are the tasks, which can be simultaneously tested within the limitations of current imaging technology, yet are informative about model building in learning (see Dehaene, 2008, for pointers on task design in arithmetic). New neuroscience studies are also emerging that link learning to more traditional factors such as socioeconomic conditions (Noble, McCandliss & Farah, 2007).

Most importantly, funding agencies are beginning to support research at the intersection of brain-based studies and learning. In 2008, the Research and Evaluation on Education in Science and Engineering (REESE) program at the US National Science Foundation targeted studies on the neural basis for mathematics learning. In 2009, the REESE call for proposals has been extended to all science, technology, engineering, and mathematics (STEM) learning:

> 1. *Neural basis of STEM learning*
>
> Fundamental aspects of STEM learning are beginning to be understood in terms of neural processes and biological context. Discoveries in these and other areas are influencing our understanding of behavior, cognition, and the nature of human learning. REESE will support studies focused on human learning in the STEM fields drawing on a wide range of theoretical approaches and empirical techniques. It is incumbent upon those submitting proposals to make explicit the implications their work has for current theories of learning and instructional methods, however long-term and indirect they may be. For example, neuroscientific studies of attention or inhibition could constrain theories about the learning of specific STEM content or help explain why some misconceptions are robust and difficult to overcome. They could similarly inform the creation of principles of design for the development of instructional materials, informal learning opportunities, or the education of teachers in the STEM fields.

> In order to gain traction on fundamental questions of mind and brain as related to STEM learning, REESE supports innovative combinations of theory, methods, and levels of analysis from a wide range of disciplines. An important aspect of these activities is to build capacity in neuroscience related to complex human learning and education, and to identify trajectories by which multidisciplinary research anchored in the biological basis of human learning can inform STEM educational practice. The involvement of researchers familiar with STEM educational practice will be of benefit both in helping to set the cognitive and neuroscientific research agendas in learning as well as in helping to disseminate relevant literatures across disciplines. (REESE Program Description. Available online at: http://nsf.gov/pubs/2008/nsf08585/nsf08585.htm)

Taken together, I contend that we are beginning to see, across these factors, the basis for a revolution in theorizing about learning that designs and refines its measures, guides its hypotheses, informs its analyses and grounds its conclusions using data from cognitive neuroscience studies. I expect that current, apparently incommensurate, theories or general descriptions about learning will be decided more and more on the basis of this growing empirical record. Theories are never abandoned easily, of course, but the disambiguation of claims at the hypothesis testing level using cognitive neuroscience data is likely to place upward pressure on theories, which are too often contingent descriptions of learning with little specification of mechanism or grounding in the larger set of findings in science.

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