Neuroscience in Mathematics Education

DONGJO SHIN

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Recently, I have often found the term ‘neuroscience’ in educational research studies. Moreover, many institutions for neuroscience research in education have recently opened in Germany (http://www.znl-ulm.de), England (http://www.educ.cam.ac.uk/neuroscience/index.htm), the U.S. (http://www.dartmouth.edu/~numcog), Canada (http://www.engrammetron.net), and elsewhere (Campbell, 2010). Then what is neuroscience? What is educational neuroscience?

Neuroscience is literally the scientific study of the nervous system. Unlike the traditional perspective, neuroscience is an interdisciplinary science that collaborates with other fields like linguistics, mathematics, psychology, and computer science as well as science, medicine, and so on. More specifically, Campbell (2010) mentions *educational neuroscience* as a new area of educational research that can be regarded as “an applied cognitive neuroscience, insofar as the tools, methods, and predominantly mechanistic and functionalist frameworks of cognitive neuroscience are applied to educational problems” (p. 315). Neuroscience perspectives on human learning have drawn increasing interest among researchers in education. Particularly, researchers in science and mathematics education have emphasized the utility of integrating a neuroscience or cognitive–science perspective into science and mathematics learning (Anderson, Love, & Tsai, 2014). Until quite recently, however, little research exists in mathematics education exploring some of the possible implications of neuroscience for mathematics education (Campbell, 2010). I would like to focus this paper on a) why neuroscientific methodology is meaningful in mathematics education, b) how neuroscientific methodologies have been used in mathematics education, and c) what further research studies of mathematics learning are possible using neuroscientific methodologies.

Campbell (2010) indicates that many mathematics education researchers remain largely unaware, uninterested, or uninformed by growing bodies of research into the nature and processes of mathematical cognition and learning, especially in the areas of cognitive neuroscience. So although the use of neuroscientific technologies in mathematics education research has been growing in recent years, most studies have been conducted in psychology and learning science related fields. In addition, combining research of neuroscience and mathematics education is also challenging because neuroscientific methods require a more or less artificial environment, while traditional classroom instruction takes place in a natural environment with a vast number of factors influencing learning processes. In other words, solving tasks using neuroscience methodologies is very different from solving paper and pencil tasks in the classroom. (Obersteiner, Dresler, Reiss, Vogel, Pekrun, & Fallgatter, 2010). Therefore, mathematics education research problems investigated with neuroscienctific methodologies may not be considered important to mathematics education.

Then why are many educational researchers focusing on neuroscience recently? What can we obtain from neuroscientific methodologies for the research studies in mathematics education? The discipline of neuroscience, compared to educational research, is a very young and so it is unreasonable to assume that such an innovative discipline will quickly resolve essential issues and problems in mathematics education. Even if progress is being made, neuroscience cannot be a panacea for mathematics education. (Smedt, Ansari, Grabner, Hannula-Sormunen, Schneider, & Verschaffel, 2011).

Campbell (2010) mentions that what we can gain from using neuroscientific methodologies, such as eye-tracking(ET), electroencephalography(EEG), functional magnetic resonance imaging(fMRI), and so on, is new means for operationalizing the psychological and sociological models that psychologists and (mathematics) educational researchers have developed for explaining learners' mental states and social interactions in mathematics education. Accordingly, the validity, reliability, and relevance of theories of teaching and learning in mathematics education studies may be corroborated, refined, or refuted through the use of neuroscientific methodologies (Campbell, 2010; Obersteiner et al., 2010). Lai, Tsai, Yang, Hsu, Liu, Lee, Lee, Chiou, Liang, and Tsai (2013) also cite the validity issues of the interview procedure that has been frequently used to probe cognitive activities during learning and hope neuroscientific methodologies present a complementary and validating point of view in the studies of learning process. Similarly, Smedt et al. (2011) claim that although neuroscientific methodologies only confirm what we have already developed from psychology and (mathematics) education studies, "this is still valuable information because convergent findings from different research methodologies provide a more solid empirical ground for a given hypothesis, model or theory, than findings obtained by only one research method" (p. 234). That is, many researchers expect neuroscience can play a role in a new methodology to complement and extend our available knowledge.

With regard to more essential role of neuroscienctific methodology in mathematics learning, Schlöglmann (2008) presents some problems in mathematics education that neuroscience could help us understand. The first problem in mathematics learning mentioned by Schlöglmann is "developmental dyscalculia", which is a seemingly insurmountable deficit in arithmetic acquisition. According to the work conducted by Cohen Kadosh, Cohen Kadosh, Schuhmann, Kaas, Goebel, Henik, and Sack (2007), neuroscientific methodology has given a clue of a physiological reason for dyscalculia. They used fMRI data and found dyscalculia could be due to an abnormality in the right parietal cortex. Such a discovery could help us distinguish between the physiological and developmental forms of dyscalculia (Schlöglmann, 2008). Second, Schlöglmann mentions the effects of "rote learning" could be illuminated by a neuroscientific concept of a *perceptual representation system*, which merely saves the form and structure of words and objects without saving the meaning of the words and the information of use from the objects. If we discover that the learners use their perceptual representation system to deal with mathematical tasks, we can understand why the students cannot solve the exercise, when just the symbols of the variable are changed. (Schlöglmann, 2008).

One of the challenges in using neuroscientific methodologies for educational studies is the difficulties of manipulating the tools and interpreting the results. Campbell (2010) recommends eye-tracking (ET) and electroencephalography (EEG) as tools for educational researchers for several reasons. First, ET and EEG instrumentation are affordable, relative to most other methods. With an increased demand for ET and EEG methodologies in many fields of academic research, the cost of ET and EEG gear has fallen in recent years. In addition, manipulating these tools and analyzing data are relatively easy for the researchers. This places fewer technical burdens on educational researchers to use such tools. Furthermore, "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" (p. 325).

With recent user-friendly advances in ET and EEG, we, as educational researchers, can use neuroscientific methodologies in mathematics education. I reviewed recent empirical studies in mathematics education where neuroscience methodologies have been used. In particular, these journal articles were published in the *International Journal of Science and Mathematics Education* and ZDM - *The International Journal on Mathematics Education* from 2010 to 2014. A total of 8 papers were selected including three eye-tracking and five brain-based studies. I briefly introduce them and finally investigate how neuroscientific methodology has been recently applied to studies of mathematics education.

Eye-tracking studies

The use of eye-tracker is effective in providing empirical evidence of how visual information is processing. Lin and Lin (2014) approached the challenging problem of better understanding student learning of geometry by combining analyses of eye movements with evidence of cognitive load when students were presented with computer-based geometry problems varying in levels of configuration. They investigated whether eye movements in comprehending geometry problems showed sources of cognitive loads and whether there were differences between successful and unsuccessful problem solvers with respect to eye movement indicators. Andrà, Lindström, Arzarello, Holmqvist, Robutti, and Sabena (2013) used eye-tracking techniques as a method to examine whether there is a meaningful difference in the eye movement between formulas and graphs and what causes such a difference when reading and understanding a mathematical text. Andrà and colleagues implicated the eye-tracker methodology provides us with suitable tools to characterize such differences in terms of different ways of navigating the stimuli. Susac, Bubic, Kaponja, Planinic, and Palmovic (2014) used eye-tracking to investigate students' strategies in simple equation solving. Susac and colleagues related the eye movement measures to participants' efficiency and the use of different strategies during solving equation. They also investigated whether there is a different pattern of eye movements between experts and non-experts. They indicated that the eye-tracking methodology provides insights into otherwise unavailable cognitive processes and may be used for exploring problem difficulty, student expertise, and metacognitive processes.

Brain-based studies

The neuroscientific technologies have improved the information and knowledge of the brain structure and function. A variety of neuroscientific methodologies have been used, such as fMRI, EEG, near infrared spectroscopy (NIS), and so on, for visualizing the brain activities. Thomas, Wilson, Corballis, Lim, and Yoon (2010) examined brain activity while ten university students translate between graphical and algebraic formats of both linear and quadratic functions using fMRI. Thomas and colleagues investigated which brain regions were involved in this translation, whether these regions were different from those involved in merely representing graphical and algebraic formats, whether brain activity was affected by the direction of translation (algebra to graph, or graph to algebra), and whether any areas appeared to represent function independent of format. They discussed fMRI methodology represented a promising initial attempt at identifying brain areas involved in the representation of mathematical function and representational fluency and presented some implications for the teaching and learning of functions. Stavy and Babai (2010) focused on difficulties students encounter in geometric problem solving and explored reasoning processes associated with overcoming these difficulties. They indicated that adding a cognitive neuroscience perspective to mathematics education research can contribute to a better understanding of students' difficulties and reasoning processes. Obersteiner et al. (2010) addressed aspects of arithmetic problem solving and used brain imaging to gain insights into mental processes. In particular, Obersteiner and colleagues investigated the influence of age, task characteristics (format, complexity), and mathematical competency on students' performance and parietal brain activation. Norton and Deater-Deckard (2014) used EEG and fMRI methodologies to investigate what were the neurological correlates for dynamic mathematical operations, such as partitioning, iterating, and splitting and whether there was neurological evidence for splitting as the simultaneous composition of partitioning and iterating. In addition, they analyzed whether various levels of units coordinating were represented in hierarchical structures within the intraparietal sulcus and whether activity in the intraparietal sulcus functions similarly across contexts: whole number, integers, fractions, algebra. Waisman, Leikin, Shaul, and Leikin (2014) examined the impact and the interplay of general giftedness and excellence in mathematics on high school students' mathematical performance associated with translations from graphical to symbolic representations of functions. Waisman and colleagues used the ERPs (event-related brain potentials) that are electrophysiological measures reflecting changes in the electrical activity of the central nervous system related to external stimuli or cognitive processes occurring in the brain. The electrical activity in the study was used as an indicator of increased cognitive load. They indicated that combining ERP techniques with more traditional educational research methods enabled obtaining reliable measures on the mental processing involved in learning mathematics and mathematical problem solving. In other words, functional brain imaging techniques may play a meaningful role in offering a complement to the existing methods.

Table 1 Research purpose and indication for learning in each reviewed study

Methodologies	Authors	Research Purposes
Eye tracking	Andrà et la. (2013)	· Difference in the eye movement between formulas and graphs
〃	Susac et al. (2014)	· Students' learning strategies during solving equation · Difference in eye movements between experts and non-experts
〃	Lin & Lin (2014)	· Correlation between eye movements in geometry problems and cognitive loads. · Differences in eye movements between successful and unsuccessful problem solvers
Brain-based (fMRI)	Thomas et al. (2010)	· Difference in brain activation while translation between graphical and algebraic formats of both linear and quadratic functions
〃	Stavy et al. (2010)	·Reasoning processes associated with overcoming the difficulties in geometric problem solving and implication of an effective teaching
Brain-based (NIRS)	Obersteiner et al. (2010)	· Difference in parietal brain activation of age, task characteristics, and mathematical competency on students' performance
Brain-based (EEG & fMRI)	Norton & Deater-Deckard (2014)	· The link between neo-Piagetian approaches and neurological hypotheses · Reexamination of existing research studies
Brain-based (ERP)	Waisman et al. (2014)	· Giftedness and excellence in mathematics · Translation between graphical and symbolic representations

Table 1 shows research purposes and indications for learning in each reviewed study. In this review, mathematics education research studies using neuroscientific methodologies have mostly focused on examining individual difference among learners. The studies of individual difference involved the levels of mathematical performance (Lin & Lin, 2014; Obersteiner et al., 2010; Susac et al., 2014; Waisman et al., 2010) and representations (Andrà et la., 2013; Obersteiner et al., 2010; Thomas et al., 2010; Waisman et al., 2014). Based on this result, it appears that pattern of eye movements and brain activities are good measures to reveal cognitive processes of distinct level of student groups as well as different visual stimuli. Thus, educators can make use of the information about individual differences to develop proper learning systems that take into consideration learners' characteristics. Others dealt with students' learning strategies (Susac et al., 2014), effect of instructional strategies (Stavy et al., 2010), reexamination of existing research studies (Norton & Deater-Deckard, 2014), and giftedness and excellence in mathematics (Waisman et al., 2014). In addition, neuroscientific research methodologies may provide a more solid empirical ground for a given educational model or theory as well as for effect of learning and teaching strategies. However, I could not find mathematics education research studies using neuroscientific methodologies in terms of social cognition, gender difference, and so on. Because I have reviewed only a few research studies, more efforts and systematic analysis are needed to understand the potential for integrating neuroscientific methodologies into mathematics education.

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