

CONSTRUCTING A DEVELOPMENTAL TRAJECTORY OF EDUCATIONAL
NEUROSCIENCE: GROUNDED PERSPECTIVES FROM PIONEERS

by

Charles Gillmarten
A Dissertation
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
Doctor of Philosophy
Education

Committee:

_____ Chair

_____ Program Director

_____ Dean, College of Education and Human
Development

Date: _____ Spring Semester 2015
George Mason University
Fairfax, VA

Constructing A Developmental Trajectory of Educational Neuroscience: Grounded
Perspectives From Pioneers

A Dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy at George Mason University

by

Charles Gillmarten
Master of Science
George Mason University, 2010
Bachelor of Arts
St. John's College, 2008

Director: Dr. Layne Kalbfleisch, Associate Professor
College of Education and Human Development

Spring Semester 2015
George Mason University
Fairfax, VA



This work is licensed under a [creative commons attribution-noncommercial 3.0 unported license](https://creativecommons.org/licenses/by-nc/3.0/).

DEDICATION

This dissertation is dedicated to my grandfather, my friend, and my roommate for much of the dissertation journey: James F. Marten.

ACKNOWLEDGEMENTS

I would like to thank my family, friends, and supporters who have made this possible. First, my parents, Mary and Dave and my sister, Sarah for their support and encouragement every step of the journey. My wonderful girlfriend, Raquel, for handling the day-to-day chaos that was this project with grace and a smile. My best friends, Adam and Erik for being there in all the ways I needed. Dr. Joe Maxwell and Dr. Anastasia Samaras for their participation on my committee and their invaluable methodological expertise and guidance. And, finally, my advisor, Dr. Layne Kalbfleisch for the opportunities, the scaffolding, and the guidance through this project and throughout my graduate studies.

TABLE OF CONTENTS

| | Page |
|--|------|
| List of Tables | vii |
| Abstract..... | viii |
| Introduction..... | 1 |
| Conceptual FrameWork | 13 |
| • Building Bridges | 15 |
| • Establishing Value..... | 21 |
| • Defining a Discipline | 25 |
| • Content Knowledge..... | 28 |
| • Personal Interest | 38 |
| • Current Study | 41 |
| Methods..... | 44 |
| • Data Collection..... | 45 |
| • Participants | 49 |
| • Data Analysis | 50 |
| • Ethical Concerns | 55 |
| • Issues of Validity..... | 56 |
| Results..... | 60 |
| • Conference Presentations | 60 |
| • Interviews | 69 |
| Discussion..... | 83 |
| • Interpretations..... | 108 |
| Appendix A: Interview Protocol..... | 118 |
| Appendix B: Analytic Memo Example..... | 119 |
| Appendix C: Reflective Memo Example..... | 126 |
| Appendix D: Knowledge Menu | 128 |

| | |
|--|-----|
| Appendix E: Knowledge Menu Example | 132 |
| Appendix F: Recruitment Emails..... | 136 |
| Appendix G: IRB Approval Letter | 141 |

LIST OF TABLES

| Table | Page |
|---------------|------|
| Table 1 | 46 |

ABSTRACT

CONSTRUCTING A DEVELOPMENTAL TRAJECTORY OF EDUCATIONAL NEUROSCIENCE: GROUNDED PERSPECTIVES FROM PIONEERS

Charles Gillmarten, Ph.D.

George Mason University, 2015

Dissertation Director: Dr. Layne Kalbfleisch

This study begins with video of the *Cognitive Neuroscience and Education: Brain Mechanisms Underlying School Subjects* conference held in 1995, hosted at the University of Oregon by Dr. Michael Posner and sponsored by the James S. McDonnell Foundation, that marked a beginning in how to discuss potential contributions from cognitive neuroscience to improve educational practice. It concludes with the modern perspectives and interpretations of some of those speakers. This study attempts to construct a developmental arc of the discipline of educational neuroscience according to these pioneering voices. The intermediate nineteen years involved an almost immeasurable amount of activity within the discipline, both in terms of progress and regression. This study used qualitative, constructivist grounded theory methods to articulate an interpretation of this activity. This study is framed – as the discipline is itself – in the fundamental conceptual, methodological, and practical obstacles that pose a

potential hindrance to the efficacy of the field. The ebb and flow of the development of the field contextualize my interpretations of the perspectives from these primary sources. This investigation demonstrated the conference in 1995 to be an attempt by scientists from disparate fields of research to explore the potential for common ground. Further, the optimism present in 1995 continues today among many of the presenters, though their emphasis on caution despite progress is strong as well. Recommendations for continued progress are discussed as they emerged.

INTRODUCTION

As society moves forward and new knowledge is created, it is necessary to develop new fields of study with new vocabularies, new goals, and new mores. These new disciplines, or fields, are not constructed from the ground up; rather they are cultivated at the intersections of familiar and more time-honored disciplines, influenced by both revolutions in thought as well as in capabilities of observation and measurement. This path to new knowledge is a corner stone of the western world, from oral histories, to philosophies, which in turn gave rise to scientific study of the world's phenomena. Humans eventually turned this scientific method inward as psychology split off from philosophy (Bower & Hilgard, 1981; Driscoll, 2005). In this paper, I use the term 'discipline' to mean 'field of study' and, therefore, use it interchangeably with the term 'field'.

Psychology, or 'the science of mental life' (Bower & Hilgard, 1981), played an instrumental role in articulating these new theories of general human behavior. As these different perspectives grew, the emphases switched to understanding internal processes, such as how humans process information or develop cognitive skills. Ultimately, the discipline of psychology gradually advanced many ways to comprehend human behavior, though these cognitive perspectives continue to be the most prevalent accounts of how

and why individuals think and act the way they do (Herrnstein & Boring, 1965; Leahey & Harris, 1997).

Ideas about learning and the processes of education have always engaged the attention of thinkers in many of these previously established disciplines: from Plato's *Meno* (Plato, trans. 1997), to the behaviorisms of Aristotle, Thorndike, and Pavlov (Woolfolk, 2010), and more recent theories of learning such as information processing theory (Atkinson & Shiffrin, 1968), Piaget's cognitive development theory (Piaget, 1964, 1970; Zwingmann, Inhelder, & Chipman, 1976), and constructivism (Vygotsky, 1928, Bruner, 1960, 1990). This is, in part, due to the essential role of education in the progress of human society. This emphasis naturally led to the establishment of educational research as a discipline of its own and, as with any field of study, education soon developed its own subdivisions, or branches of inquiry, within the discipline.

One of the earliest major theories of education and learning, adapted from the more general discipline of psychology, emphasized the role of external motivators as the primary cause of human behavior (Skinner, 1938, 1974). This perspective stemmed from the conceptualization of all learning as habit formation, and therefore cast these external motivators as the only cause of consequence for modifying behaviors. Traces of this approach are still recognizable in some educational research and classroom practices, though in a more developed articulation. That being said, the alternative models of learning that emphasize internal processing, as opposed to external behaviors, were more appealing to the educational community, and they now comprise many of the theories and foci of educational research (Elliot & Dweck, 2005; Woolfolk, 2010). Due to this

increased recognition and investigation of various cognitive psychological theories as applied to educational contexts, a new domain of research emerged at the intersection of the disciplines of education and psychology, namely, educational psychology.

In a very similar way, the study of intelligence passed through many phases of inquiry. Beginning with the days of limited understanding that constituted phrenology, the head was thought to be the seat of this elusive construct (Gould, 1996). Despite the ways in which early research misconceived the relationship between physical structure and cognitive ability, these investigators were responsible for directing attention to the important role of the human brain. This physical study of the brain, like behaviorism, has not gone away, nor is it irrelevant. Instead, the study of the relationship between the brain and behavior has been reorganized to reflect a more nuanced understanding. As the tools became available, animals were used as research subjects as scientists began to explore the inner connectedness of this complicated organ within the bounds of a new discipline called neuroscience. As our ability to measure the human brain increased, enabling the study of living humans, a branch of specialized neuroscience took shape. This new field of study, specifically interested in parsing the relationship between the human brain and cognition, was termed 'cognitive neuroscience' (Gazzaniga, 1992; OECD, 2002, 2007).

Furthermore, as the knowledge base of this discipline increased and gained traction in the larger context of studying human behavior and physiology, so did another unique, interdisciplinary field of study. Educational neuroscience sits at the fulcrum of the research interests of cognitive psychology, cognitive neuroscience, and education.

One caveat to keep in mind: this narrative of the genesis and development of these research disciplines into educational neuroscience is not meant to be comprehensive. This description is meant to be an overview of the emergence of educational neuroscience from the intersection of cognitive neuroscience, psychology, and education, informed by a conference held nearly 20 years ago.

In 1995, a group of cognitive neuroscientists and cognitive psychologists converged at a conference at the University of Oregon hosted by Dr. Michael Posner and sponsored by the James S. McDonnell Foundation. Their goal was to come together, share ideas, and assess the implications and potential contributions of a collaborative research agenda for educational practice. While I was not able to determine if this was *the* first conference in the field of educational neuroscience, it does provide insight into the formation of the field and an enlightening reference point in time.

1995 sits right in the middle of the ‘Decade of the Brain’ (1990-1999), as proclaimed by then President of the United States, George H. Bush (Jones & Mendell, 1999). This explicit campaign to publicize the discipline of neuroscience had very significant consequences. First, the public became much more aware of the ideas and the research in the field, partly due to a significant increase in media coverage of these topics. This media coverage garnered an overwhelming enthusiasm for applications of neuroscience that is still being felt today. Relatedly, this campaign motivated both policymakers and scientists to incorporate the latest research findings into the rationale for certain policy programs.

This conference titled: *Cognitive Neuroscience and Education: Brain Mechanisms Underlying School Subjects* was held in the middle of this exciting and lively time for neuroscience research. Dr. Posner, as he introduced the meeting, stated the meeting's goal: "considering research related to the brain mechanisms underlying cognitive processes, of cognitive neuroscience, and how the plasticity of the human brain and new facts about cognition can together be applied to further our understanding of what children do in schools and how their learning can best be improved" (S. Posner, 1995). In other words, these researchers were invited to present their research and to think about the ways that facts about human brain function and facts about human cognitive function could together be of service to understanding students and improving their learning in school. With the ever-increasing reliance on empirical evidence in our society, combined with the rapid technological developments providing new tools for inquiry, it is not surprising that neuroscientific research has continued to receive the attention of the media and public. In fact, last year, the President of the United States, Barack Obama launched a new brain research campaign, called the BRAIN Initiative (Brain Research through Advancing Innovative Neurotechnologies), with the ultimate goal of mapping every neuron in the human brain (Kandel, Markram, Matthews, Yuste, & Koch, 2013).

In education, there is a desire for information about the neural underpinnings of cognitive development, learning processes, and the psychological aspects related to education and learning (Goswami, 2006). Additionally, teachers remain enthusiastic about the role of neuroscience in education (Dekker, Lee, Howard-Jones, & Jolles, 2012;

Hook & Farah, 2012; Pickering & Howard-Jones, 2007). There is also evidence that the discipline has made significant progress toward the goal of understanding of the neural bases of educational domains, such as reading and mathematics, as well as domain-general topics like memory, attention, and reasoning ability (Byrnes, 2012; Goswami, 2004; OECD, 2007).

While there are significant reasons to be optimistic about the progress and direction of the field, other developments since 1995 suggest a measured optimism and, more than that, warrant a reflective analysis of the position of the field in terms of not just the starting line, but our end goals as well. In 1997, Dr. John Bruer published a well-documented critique of the ability of neuroscience to inform educational practice. The issue he articulated is one of scale commensurability. In other words, the fine-grained level of analysis necessary to understand brain function at the neural level cannot address the macro-level problems that education is interested in. Bruer suggested that neuroscience is better suited to trying to understand the relationship between the brain and cognition, while education is looking to understand the relationship between cognition and behavior (Bruer, 1997). His critique was aimed primarily at the ideas of synaptogenesis¹, critical periods², and environmental enrichment³ based on

¹ Synaptogenesis is the formation of new synaptic connections (Bruer, 1997; OECD, 2007).

² A critical period is a time when synaptogenesis is abnormally high, suggesting efficiency in learning (Bruer, 1997). It was thought that if these ‘windows’ were missed, children were subsequently at a disadvantage.

³ Environmental enrichment, or stimulating learning environments, was thought to be vital for children’s learning during these critical periods of increased synaptogenesis (Bruer, 1997).

neuroscientific information. These issues clearly need to be fully addressed before educational neuroscience will be able to contribute to the classroom.

A short time later, Byrnes and Fox (1998) presented their argument for the relevance of cognitive neuroscience research in education. Their paper was quite extensive, including a detailed account of the nature and limitations of the most popular methods in cognitive neuroscience at the time, reviews of four topics they saw as most relevant to education at that point: attention, memory, reading, and mathematics, as well as implications from these sections and direct refutations of well-known positions. At several points, Byrnes and Fox (1998) called for cautious interpretations of neuroscientific data, while maintaining the usefulness of cognitive neuroscience in education. The main reason they gave for this usefulness is the fact that “the brain constrains the nature of cognition that it makes possible.” (p. 308). In other words, the extent of human cognitive abilities is delimited by the physical properties of the brain (that produces them). For this reason, the authors suggested psychologists would be remiss to ignore brain function when considering their theories of cognition.

The Byrnes and Fox (1998) article was published in the *Educational Psychology Review Journal*, and the next issue of this journal invited six other researchers to comment on their account for educational neuroscience. The majority of the commentaries agreed with Byrnes and Fox (1998) with some slight modifications or extensions in certain areas. However, two of the respondents articulated two notable difficulties with the Byrnes and Fox (1998) account for the relevance of cognitive neuroscience in education.

First, Mayer (1998) commented systematically on the argument Byrnes and Fox (1998) formulated. He began by demonstrating that current psychology is negligibly influenced by cognitive neuroscience, and further, it was a mistake in the history of psychology to focus on the nervous system as the seat of human mental life. The author stated that cognitive neuroscience fails to produce any theory-driven research and therefore largely serves to corroborate what psychology has already discovered. Mayer (1998) stated, “Knowing how the brain works is not the same as knowing the best way to help students learn.” (p. 395). He recognized the potential of the field, but that the potential was not yet actualized as educational applications. The author suggested that the relationship between the two disciplines (educational psychology and cognitive neuroscience) will be mutually beneficial, but he states, at this point, much of the research is driven by impressive technologies, not findings. The takeaway from this commentary was the practical question of, ‘now we know the brain areas. So what?’

In another response commentary, Stanovich (1998) articulated a conceptual difficulty in the account of Byrnes and Fox (1998). The author proceeded through the argument, praising Byrnes and Fox (1998) for many things they agree upon. For example, Stanovich (1998) praised the emphasis on appropriate caution in interpreting from neuroscience findings to classroom applications. The author articulated the conceptual difficulty with how the brain constrains cognition. He agreed with the claim in principle, though his concern is “how strongly the neurophysiological findings constrain the psychological level – given the current levels of knowledge.” (p. 423). The logic behind this remark is that in order for the physical constraint on cognitive processes to manifest,

we must have a certain level of knowledge about the physical constraint itself and how it produces the cognition. Stanovich (1998) advocated for patience with the cognitive neuroscience applications to education because as he saw it, they currently only happen indirectly and “the field tends to run into trouble when it attempts to leap directly into education” (p. 424). Here, Stanovich was referring to the misapplication of neuroscience information in educational contexts that has happened prevalently in the past. He specifically mentioned the left-brain-right-brain theories still circling in educational contexts.

This hesitancy for application due to previous missteps is the result of another obstacle that educational neuroscience must overcome in order to responsibly and meaningfully contribute to improving educational contexts. That obstacle is the breakdown in the communication of research findings from the field to educational practitioners. Evidence of this communication gap can be seen in the pervasiveness and availability of information claiming to be brain-based educational references and guides for classroom practice, for which there is no central, organized quality control. This gap between the producers and consumers of neuroscience information is multifaceted and has led to a prevalence of misconceptions and misunderstandings among the general public, and the educational community in particular. These unchecked misconceptions have, in turn, led to inappropriate programs and curricula that claim to be based on brain science (Goswami, 2006), which heightens concern and skepticism about the viable and responsible application of neuroscience information to the field of education.

In 2002, the Organization for Economic Cooperation and Development's Center for Educational Research and Innovation (OECD-CERI) coined the term 'neuromyth' to describe any misconception about the use of brain research in education that is the result of misunderstanding, misreading, or overgeneralization of established neuroscientific facts. Many papers have been written to address and refute the most widespread neuromyths (Bruer, 1997; Dekker, Lee, Howard-Jones, & Jolles, 2012; Geake, 2008; Hyatt, 2007; Kalbfleisch, 2008; Kalbfleisch & Gillmarten, 2013; Lindell & Kidd, 2011; Pasquinelli, 2012; Purdy, 2008; Stephenson, 2009) but despite this effort, these myths continue to overshadow the significant contributions of cognitive neuroscience to many areas of education (Goswami, 2006).

Many people in the discipline of cognitive psychology today believe that these obstacles between neuroscience and direct educational application are still relevant and unanswered. Part of this belief seems to be due to this history of numerous misapplications and neuromyths. However, there is also a large body of literature, written by researchers in the field of educational neuroscience aimed to address the criticism and skepticism about educational neuroscience. These articles take one of three approaches: (a) they directly address the criticisms presented by Bruer (1997) and similar perspectives; (b) they address the practical concerns expressed first by Mayer (1998) by articulating the value of neuroscience information for educational application; or (c) they intend to address the criticisms indirectly by focusing more on defining the discipline of educational neuroscience.

In short, there are certainly reasons to be optimistic about the potential impact of neuroscience on education, however there are also significant impediments limiting the actualization of this impact. While the discipline has grown significantly, some believe that there has been minimal progress toward overcoming these impediments from the time they were first voiced. There is a significant body of literature within the field directed toward these goals. Despite this, no one has approached the understanding of the field and its development from the perspective of the researchers. The criticisms appear largely the same now as they were in the mid-1990's, shortly after the Cognitive Neuroscience and Education conference in Oregon. For that reason, I think the perspectives of those cognitive psychologists and cognitive neuroscientists who participated in one of the initial conversations about the possibility of the field would allow me to start from a historically relevant time point to examine the development of educational neuroscience and its role in educational research.

The primary goal of this study was to propose a developmental trajectory of educational neuroscience informed by: (a) videotapes of an early conference; and (b) perspectives of some of the presenters at that conference about the discipline at the time of the conference (1995) compared and contrasted against some of their contemporary opinions and professional contributions to-date, and how these things have influenced the current shape and development of the field. Relevant literature from the field provides a background from which to understand these perspectives and assess the progress of the discipline in bridging the gaps between neuroscience research and educational applications. I conducted a qualitative study of the discipline of educational neuroscience

from the perspectives of early, pioneering contributors to the field in order to answer questions about their interpretations of the development and growth of the field.

CONCEPTUAL FRAMEWORK

Educational neuroscience is a highly interdisciplinary field of study. It resides at the intersection of cognitive neuroscience, psychology, and education. This multidisciplinary characteristic can make the boundaries and motives of the discipline seem permeable and cloudy, which can make assessing progress seem difficult. Further, the discipline was conceived almost simultaneously in numerous locations around the world (Fischer, 2009), which has led to a variety of names, emphases, and stated goals. The most common names given to what amounts to the same discipline are: (a) Mind, Brain, and Education Science (MBE), (b) Neuroeducation, and (c) Educational Neuroscience. These various emphases and goals are, naturally similar in some respects, though the ways in which they differ make it increasingly difficult to assess the discipline's status as a whole. While some focus on these differences in an attempt to make distinctions between the three names, in this paper I treat these terms as synonymous and therefore interchangeable.

Educational neuroscience is also a relatively new discipline. For this reason, despite the availability of numerous stated goals and intents, the most palpable and most essential purpose of educational neuroscience is to grow the knowledge base of the discipline through empirical inquiry. The continued development of neuroimaging methods and data analysis techniques allows for parallel advances in our understanding

of the typical relationships between brain structure, brain function, and cognitive processes, as well as our understanding of the nuances and intricacies that are introduced by development, individual differences, and atypical populations. This is most likely a never-ending project, however, the recent genesis of the field, from which much is expected, makes this goal pertinent.

Nevertheless, educational neuroscience, in its early life, has faced a fair share of skepticism and critique. This is, in part, due to the prevalence of neuromyth in educational contexts and in society. Because of the concerns surrounding potentially viable and relevant applications of neuroscience to education, the discipline has created quite a large body of literature, aimed to quell the various critics and skeptics, while also recognizing the validity and appropriateness of some of these concerns put forth by Bruer (1997), Mayer (1998), and Stanovich (1998), among others.

As these concerns are multiple, papers written in response did so from a number of different perspectives. I categorized some of these articles by their shared approach. One common approach to these issues is to respond directly to the issues raised by Bruer (1997) and others. I call this category ‘building bridges’ (Ansari & Coch, 2006; Atherton, 2005; Geake, 2004; Howard-Jones, 2005; Mason, 2009; Samuels, 2009; Sigman, Peña, Goldin, & Ribeiro, 2014; Tommerdahl, 2010; Varma, McCandliss, & Schwartz, 2008). A second common approach to addressing these concerns is what I call ‘establishing value,’ in which the authors demonstrate the specific practical applicability of educational neuroscience (Cameron & Chudler, 2003; Christodoulou & Gaab, 2009; Devonshire & Dommett, 2010; Dommett, Devonshire, Plateau, Westwell, & Greenfield, 2011; Ferrari,

2011; Geake & Cooper, 2003; Howard-Jones, 2011; Howard-Jones, Washbrook, & Meadows, 2012; Kalbfleisch, et al., 2013; Kim, 2013; Stern, 2005; Szűcs & Goswami, 2007; Willingham & Lloyd, 2007). A third category, which I name ‘defining a discipline’, includes articles that attempt to establish clear boundaries, motives, and implications of educational neuroscience as a discipline in order to indirectly allay the conceptual, theoretical, or practical concerns (Ansari, Coch, & De Smedt, 2011; Ansari, De Smedt, & Grabner, 2012; Campbell, 2011; Cerruti, 2013; Fischer et al., 2007; Fischer, 2009; Goswami, 2005; Schwartz & Gerlach, 2011).

Building Bridges

In their opinion article, Ansari and Coch (2006) offered to “advance the debate beyond both recitation of potentially education-related cognitive neuroscience findings and the claim that a bridge between fields is chimerical” (p. 146). The authors focused on the idea of multiple bridges, not only the traditional, direct-to-classroom application of neuroscience research. The two additional bridges they proposed connect (1) teachers to cognitive neuroscience, as well as (2) cognitive neuroscience researchers to the classroom.

Including cognitive neuroscience in teacher training programs would provide a space for teachers to investigate how to link the research to their classrooms, as well as providing them the much-needed tools to effectively evaluate research findings. The authors suggested, “training in cognitive neuroscience will influence teachers’ thinking about their practice and students in ways that are indirect and unpredictable a priori, but eventually measureable” (p. 148). In other words, knowledge of the interactions between

environment, brain, and cognition can provide a background, or context for the teachers' development of instructional techniques and other classroom practices. The authors provided examples from both math and reading, and emphasize that these benefits apply beyond specific academic domains to areas such as sleep, nutrition, and the particulars of brain development at relevant ages (Ansari & Coch, 2006).

Further, the authors highlighted the importance for cognitive neuroscience researchers to gain experience in classroom contexts. This would allow researchers to better connect their studies to more ecologically valid classroom practices and concerns. The authors also emphasized the value of the opportunity for dialogue with teachers, which can help "to see new connections and lines of inquiry related to real-world questions and solutions" (Ansari & Coch, 2006, p.149). The recommendation to consider multiple bridges between the disciplines of cognitive neuroscience and education seems to be an important step in shaping a bidirectional, mutually beneficial, and optimally effective relationship between the related, but distant fields. This approach, "will not only lead to a better understanding of 'what works', but also an understanding of *why* and *how* [Author's emphases] it does or does not work" (p. 149).

In another article Varma et al. (2008) provided a window into the issues of cognitive neuroscience in order to suggest specific ideas for the prospects of a multidisciplinary collaboration called educational neuroscience. The authors first described many concerns that are commonly expressed about bridging education and neuroscience, and then reframed these concerns in terms of opportunity for mutual

benefits and understanding. The concerns were categorized into either scientific or pragmatic differences between the two disciplines.

Two of the scientific concerns included: (1) the incommensurability of the artificial laboratory contexts necessary for neuroimaging and the more complex classroom environment; and (2) that the knowledge of brain activations associated with cognitive tasks does not inform educational practice. The authors reframed these issues by highlighting some of the ways that neuroimaging has deepened the way we understand these cognitive processes and their contextual influences. They offered three examples of this: understanding the influence of different instructional strategies on brain activation patterns (representing different problem solving strategies); deepening understanding of developmental improvements in performance by “opening the hood” (p.144); and illuminating the effects of cultural variables on the use of specific problem solving strategies. Further, the authors claimed, neuroscience data can suggest new insights and analyses of cognition, implying new theories for instruction (Varma et al., 2008). In other words, using neuroscientific data to describe a specific behavioral difference observed in educational contexts can provide an avenue to further explore the causes of these differences, potentially leading to utilizing that knowledge to elicit desired behavioral outcomes.

The pragmatic concerns that the authors addressed are: (1) cost/benefit analysis of neuroimaging experiments; (2) we need to know more about how the brain works before using that information to inform education; (3) education should not “cede control to

neuroscience” (p.143); and (4) the prevalence of neuromyths is having a significant, negative impact on educational communities.

The authors responded to the cost/benefit concern by stating that this concern assumes an independence of research agendas between education and neuroscience, and that funding for the two disciplines is “jointly fixed” (p.146). The authors suggested neither of these assumptions hold and, in fact, educational neuroscience would provide new opportunities for funding, to which neither discipline currently has access. Further, there are research questions of interest to both fields. In terms of increasing the knowledge base about the brain before applying it to educational contexts, the authors simply cited the progress that has been made thus far. Understanding the *why* of things like dyslexia, as well as the effects of specific educational interventions aids in determining curricular and remediation decisions.

As for concerns about control, the authors emphasized the importance of education and psychology contributing to the neuroscientific inquiries. These former bodies of research are much more extensive than the newer neuroscience literature, so it is of the utmost importance that these fields communicate, so as not to ‘reinvent the wheel’ in context of the learning brain. In terms of the prevalence of neuromyths, the authors suggested that this indicates enthusiasm about the field. They recognized the issue as real, and suggest more “plain text translations of neuroscience findings that report clusters of studies in accessible ways without trying to sell them” (p.148). This seems like an uphill battle that will require efforts from both the neuroscience and the educational community.

The authors concluded by suggesting a “cautious optimism” (p. 150) as we move forward in the direction of educational neuroscience. They recommended a “focus on domains, not on disciplines” (p. 149) in order to help bridge the two communities. In other words, identifying your interest in terms of the problem you study (i.e. understanding multiplication reasoning), as opposed to the larger domain (i.e. mathematics) (p. 149), will open a space for communication across discipline boundaries and aid in collaborative solutions to these educational problems.

Additionally, Sigman et al. (2014) discussed specific areas of education where neuroscience may contribute. In the first area, physiology, they emphasized the importance of sleep and nutrition for academic success. Neuroscience evidence demonstrates that the brain is the largest consumer of glucose in the body and that supplementing glucose before training boosts both short- and long-term memory (Sigman, et al., 2014). While this is not a prescription that students should be administered glucose before each lesson, it does highlight the importance of diet for brain development and learning. The authors conceded that the specific details relating meal composition to learning are not yet understood, but it does support the provision of an adequate breakfast for students before school (Sigman et al., 2014). On the other hand, research on this topic is inconclusive (Brindal et al., 2012; Cooper, Bandelow, Nute, Morris, & Nevill, 2012; Edefonti et al., 2014; Kral, Heo, Whiteford, & Faith, 2012; Liu, Hwang, Dickerman, & Compher, 2013; Micha, Rogers, & Nelson, 2011) and, therefore, any claims about the specific effects of breakfast on students’ cognition need to be replicated before implemented in educational contexts. The authors also mentioned that

neuroscience could inform the optimal schedules for exercise throughout the school days, based on the neuroscientific evidence of the importance of physical activity to cognition (Sigman et al., 2014).

Sleep is also an area in which neuroscience has informed educational practices, specifically with respect to the adolescent sleep cycle (Boschloo, et al., 2013; Kelley, Lockley, Foster, & Kelley, 2014). The recommendation from this literature to start school later for adolescents has been met with an understandable resistance from parents who need to be at work at certain times in the morning (Sigman et al., 2014, p. 498). That being said, sleep is of fundamental importance to cognitive performance, and evidence is beginning to encourage the need for middle ground.

Another area in which neuroscience can inform educationally relevant topics is education outside of the classroom. According to Sigman et al. (2014), neuroscience research has developed signatures that may aid in the diagnosis of cognitive impairments before they can be observed behaviorally. This possibility, combined with the literature stating the importance of early intervention, could result in significant improvements of these populations by the time they reach school age. Further, understanding the cognitive capabilities of infants may inform curriculum development in order to build from these early skills.

The authors also discussed the neuroscience information about the content domains of reading and mathematics. The literature on these areas is significant and increasingly suggests interventions for conditions such as dyslexia, and provides context for understanding how these subjects are learned. Because these tasks are ‘new’, the brain

has had to evolve specific neural circuitries for these cultural traits, and given variability at the individual level, the authors recommended caution and emphasized the importance of distinguishing between inferences from single studies with low sample sizes and those from larger independently replicated studies.

In conclusion, Sigman et al. (2014) drew attention to the broader context, stating, “efforts to make change may be wasted if they are not accompanied by a reflection on how the translational process can be efficiently organized” (p. 500).

Establishing Value

Geake and Cooper (2003) argued for implications and contributions of cognitive neuroscience research to educational practice. They outlined the field of cognitive neuroscience, reminding the reader that cognitive neuroscience is already studying topics of interest to educators such as learning and memory, literacy and numeracy, but that only a portion of the cognitive neuroscience research will be influential for educational contexts. They posited that it is important for educators to “appropriate this research with regards to implications and applications for teaching in formal educational settings, especially classrooms” (p. 11). Their language highlights their intention to empower classroom teachers and provide them with tools to determine the most efficacious pedagogical practices.

The authors pointed to areas of research in cognitive neuroscience that may inform educational practice. The concept of “adaptive plasticity” of the brain is centrally important to their thesis (p. 14), the longstanding idea that neural circuits that ‘fire together, wire together’ (Hebb, 1949). The authors discussed how this concept might

influence educational practice: the necessity of repetition for learning, the troubling effects of distractions and misleading concepts, and why it can be so difficult to undo previously learned misinformation.

Importantly, Geake and Cooper (2003) argued that over-simplification of neuroscientific findings in the past does not exclude neuroscience from influencing education. They remained cautious and conjectural in their analysis, and emphasized the need for educators to be involved in neuroscientific research in order to improve the appropriateness of research questions.

In a later article, Devonshire and Dommett (2010) rearticulated some of the theoretical barriers between neuroscience and education and suggested that these are motivated by two practical ideas. The first theoretical barrier the authors discussed is the “goal barrier” (p. 350), or the fact that the overall objective of neuroscience is to understand how the brain and mind map together, whereas education aims to improve the artifice of classroom pedagogy. They suggested collaboration on research between practitioners in these fields in order to find common goals and overcome this barrier.

The second barrier that Devonshire and Dommett (2010) presented pertains to the differences in the scale of investigation between the fields. They elaborated on the many levels of analysis associated with neuroscience and suggested that the most appropriate levels for educational implications are “the functional circuitry level”, the “syndrome level” and the “observing normal/healthy behavior” level (p. 351). These levels have contributed to our understanding of reading and arithmetic as well as disabilities associated with those content domains. The authors suggested, “work at the circuitry

level can be used to develop or test the effects of specific interventions.” (p. 352). The third theoretical barrier discussed is that of translation between fields of study.

At this point, the authors connected these theoretical issues with the more practical barriers, namely: the difference in working vocabulary between education and neuroscience and finding the time and appropriate environment for collaborative work. Devonshire and Dommett (2010) focused on the language barrier, describing instances where terms such as ‘learning’ can mean very different things depending on the context of either neuroscience or education. Their recommendation for overcoming this barrier was through mutual training and familiarity. Neuroscientists should present findings not only in peer-reviewed journals, but also in a simpler form that contains all key information for educators (Devonshire & Dommett, 2010). On the other hand, teachers would benefit from becoming more fluent in terms of research practices and interpreting findings. This would combat the prevalence of neuromyths as well as enable the communication of more educationally relevant research questions to neuroscientists. (p. 353).

Ferrari (2011) took a broader view of the potential impacts of neuroscience on educational contexts in order to suggest an avenue of success for the discipline of educational neuroscience. The author highlighted that the contributions thus far have been particularly successful in understanding atypical developments and academic performances, but, while this advancement in our understanding of the embodiment of knowledge in the brain is helpful, educational neuroscience must do this “in ways that promote personal learning and development” (p. 32). In other words, the author

suggested that educational neuroscience participate in the conversation about the goals and outcomes that we desire from our educational systems.

Ferrari (2011) acknowledged that content learning is part of this, but that there are more global, societal purposes as well and that educational neuroscience would be well served to inform these areas as well. The author discussed some of the dangers of applying neuroscience to education: the danger that neuroscience does not add anything new, that lab results are generalized to classroom contexts in inappropriate ways, or worse, that we begin to understand the root of learning disabilities – and learning in general – as mechanistic failures on the genetic or neural level. Ferrari (2011) emphasized the importance of maintaining the value of agency in educational contexts (p. 33). The author also mentioned the ability of neuroscience to reinforce the importance of diet and nutrition, especially during the prime years of brain development, and to help design educational programs based on differences in brain functioning underlying academic performance difficulties.

Ferrari (2011) emphasized the role of educational neuroscience as a “tool that is part of a broader conversation” (p. 31). The author recommended educational neuroscience research inform practice, especially for atypical cases, but also that it inform discussions about how people choose to live and how those lives can be shaped by cultural and environmental influences to which they are exposed (p. 34). Ferrari (2011) concludes, “educational neuroscience can help fulfill the mandate of public education, but only as a tool that is part of a broader conversation . . . about what schools should strive to achieve for the millions of students who attend them” (p. 35).

Defining a Discipline

Campbell (2011) set forth his working definition of educational neuroscience. He presented educational neuroscience as a new area of educational research that is more than simply cognitive neuroscience applied to educational contexts. The key difference is that while educational neuroscience is certainly informed by the theories and methods of cognitive neuroscience, it is not restricted to them. The author took a very philosophic approach to defining the field, but emphasized, “the focal points of educational neuroscience are living human beings, not *just* [author’s emphasis] physiological and biological mechanisms underlying them” (p. 8). Campbell (2011) drew distinctions between the terms multidisciplinary, interdisciplinary, and trans-disciplinary, and identified educational neuroscience as trans-disciplinary because it requires new philosophical frameworks and research methodologies in order to bridge education with neuroscience (p. 8). The author stressed that educational neuroscience is concerned not only with how the brain learns, but also with the interactions between the learner and various aspects of their environment.

Schwartz and Gerlach (2011) described “the birth of a field” and introduced the potential of laboratory schools. The authors discussed MBE as an emerging new field that is a confluence of education, cognitive science, and neuroscience. They started by discussing the challenges of this field, such as discovering the ways these larger, individual disciplines may reorganize their boundaries and delineations to provide the space for a new, interdisciplinary field. Further, the authors acknowledged that conclusions about educational practice have not always been linearly connected to

research findings from educational neuroscience, and it is therefore a responsibility of the field to monitor these interactions and expectations, while clarifying previous findings. Schwartz and Gerlach (2011) also discussed the ethical challenges of MBE, and specifically in conceptualizing learning in terms of biology and genetics. In order to meet these challenges, the authors recommended bidirectional and respectful communication between practitioners and researchers. They concluded by presenting a model for establishing a laboratory school that would facilitate the transfer of ideas and information, as well as promote collaboration.

In another article, Ansari, De Smedt, and Grabner (2012) offered an overview of the emergent field of neuroeducation. They also recognized this term as interchangeable with MBE and educational neuroscience. The authors first contextualized the field within overwhelming enthusiasm for neuroscientific applications and approaches to education, coupled with the rapid development of neuroimaging techniques. The authors stated, “the possibility of imaging neural effects of learning is helping us to understand both the typical and atypical trajectories of development and to better characterize the limits of plasticity of brain circuits underlying cognitive functions that are shaped by education” (p. 106). In other words, these technological developments allow for educational neuroscience to measure which areas of the brain are involved in academic skills and how these networks of activity develop over time. Ansari et al. (2012) expressed the aim of this inquiry as helping to structure learning environments and educational interventions in ways that will foster learning.

The authors went on to discuss current contributions from neuroeducation to understanding educational processes, such as reading and mathematics. They also discussed the current state of the “brain training” (p. 110) literature, suggesting that although this work has been exploited in order to market certain mental practice programs and that the evidence for the transferrable cognitive benefits of ‘brain training’ is mixed at best. Still, Ansari et al. (2012) claimed that this literature might offer insights into how the brain learns and therefore, “there need to be greater efforts to design educational interventions to train skills that are reflected in performance” (p. 111).

Additionally, the authors discussed the challenges facing the field of neuroeducation. Specifically, they addressed issues of communication, an affinity to biological explanations of behavior, and the limitations of neuroimaging methods. They attributed the prevalence of neuromyths to a lack of bidirectional communication between researchers and educational practitioners and suggested neuroscientists acquire more knowledge of educational contexts and problems, while teachers gain a literacy and understanding of how to discern responsible research results from over-generalized misconceptions (p. 112-113). The methodological issues in educational neuroscience are twofold. First, the requirements for control and clear data acquisition in these studies are very far from ecologically valid. Further, due to the cost of neuroimaging equipment, the sample sizes in a typical neuroimaging study are very small, which does not enable or facilitate generalization to larger populations – a necessity in the realm of educationally relevant research. Despite these issues remaining largely unresolved, the authors claimed

that neuroeducation is primed to contribute to the conversation about how students learn and how best to teach them.

In addition to these meta-cognitive accounts and assessments of the discipline of educational neuroscience as a whole, there is also the knowledge base, or content of the research being conducted in the field.

Content Knowledge

In order to contextualize this study, I present brief overviews of the academic domains that were addressed during the Cognitive Neuroscience and Education conference in 1995. There are certainly other areas of inquiry in the field, but reading and mathematics are the most popular areas of study and the large majority of the presentations in 1995 addressed these two subjects. For that reason, I summarize the educational neuroscience literature of these areas here to provide a basic picture of how educational neuroscience approaches and understands these processes. This approach enriches the context and purposes of the present study.

Reading. The reading subdivision of educational neuroscience has historically been the favorite subject of researchers in the field and consequently has the largest body of literature of the different subdivisions in educational neuroscience (Byrnes, 2012). In fact, researchers have used positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) for over 20 years to investigate the neuroanatomy of language and reading – and the conclusions have remained relatively stable the entire time (Price, 2012). This is not surprising since once reading proficiency is achieved educational practices rely heavily on text to communicate information across academic domains.

Because of this widespread utilization of reading in schools, many studies have focused on understanding reading deficits and impairments (Landi, Frost, Mencl, Sandak, & Pugh, 2013; Pugh, et al., 2000; Raskind, Peter, Richards, Eckert, & Berninger, 2013; Shaywitz, et al., 1998). With that in mind, in order to fully comprehend and properly address these deficits in educational contexts, the typical process of reading must first be parsed and understood.

While reading itself involves a collection of complex skills, the foundation of literacy is the capacity for language. The primary brain regions associated with language are: (a) the left inferior frontal gyrus, commonly referred to as Broca's area, supports language production and (as we will discuss) a broad range of linguistic processes; and (b) the posterior middle gyrus, commonly called Wernicke's area, which supports semantic processing (OECD, 2007; Posner & Raichle, 1994). These structures are certainly primed for language, however prolonged auditory experience is necessary for language acquisition. The language-specific auditory units that make up speech are called phonemes. Analogous to the process of synaptogenesis and neuronal cell death in the brain, the experience of a particular language enhances the perception of some phonemic distinctions and eliminates others.

While language is essential to the development of reading ability, the human brain is not 'biologically prepared' to read. In other words, there are no brain structures specifically tuned to support reading as a unitary skill, as opposed to motor tasks, for example. For this reason, Dehaene (2009) labels the neural process of reading: "neuronal recycling", as the brain must use neurons and regions intended for processes other than

reading in order to achieve literacy. This ‘improvisational’ quality of the brain processes associated with reading affirms that, even more so than language, the process of reading is almost exclusively driven by experience. The role of neurobiology in the acquisition of this ability, namely the extraordinary capability of the human brain to reorganize and adapt to novel cognitive demands, is less of an instigating factor, though no less impressive.

The variety of complex skills required for reading lends itself to being summarized sequentially. First, letters and syllabic symbols, called morphemes, are perceived and differentiated in the primary visual cortex, located in the occipital lobe (Byrnes, 2012). This information is then converted into orthographic symbols, or labels that follow the rules of the language-appropriate writing system. In other words, morphemes are simply arbitrary shapes until they are filtered through the rules of the writing system of a language. The resulting symbols are contextualized labels that can be mapped onto sounds. Then, according to the dual route theory (Jobard, Crivello, & Tzourio-Mazoyer, 2003), because English is considered to have a ‘deep orthography’ (meaning the grapheme-phoneme combinations are variable and numerous), the orthographic information (graphemes) continues on one of two complementary pathways. The first of these pathways is a dorsal circuit involving temporo-parietal areas, while the second, a ventral circuit, relies on occipito-temporal areas of activation (Pugh et al., 2000). When information continues on the dorsal pathway, graphemes are converted into corresponding phonemes in Broca’s area and other regions in the left temporal and frontal areas (Pugh, et al., 2001). This phonemic information then travels to Wernicke’s

area where phonemes are assigned semantic associations, or meaning. Graphemes that travel along the ventral pathway are not converted into phonemes in Broca's area and instead are transmitted to Wernicke's area via the visual word form area (VWFA) in the ventral occipital lobe (Byrnes, 2012). The VWFA supports immediate, whole word recognition in skilled readers – a valuable capability for languages with deep orthographies (Pugh, et al., 2000).

The final component of reading is syntactic processing. Syntax is a system of implicit rules that govern the arrangement of words in order to convey information beyond the word meaning. Neuroscientific studies have corroborated behavioral data that suggests syntactic processing is highly context dependent and therefore supported by a combination of multiple brain areas (Caplan, 2009). The distributed nature of syntactic processing brings to light the prevalent, but misguided assumption of the modularity of brain function (Goldberg, 2009). In other words, the idea that specific cognitive functions are localized to discrete, bounded brain regions is not able to account for all cognitive processes. This is partly because the relationship between cognition and discrete brain areas is malleable both within and between individuals. Because this discussion of reading processes has relied heavily on the notion of modularity, it is important to express that this conceptual model finds its utility as a theoretical simplification of actual neural phenomena. The reliance of educational neuroscience, to this point, on this method of explanation has hindered the goal of promoting scientific literacy, as many fail to communicate the difference between the conceptual model of an isolated cognitive

process, and the much more complex reality of extreme interactivity of in vivo brain functions.

The neuroscientific study of reading is important to education in more than one way. First, the reliance on reading (e.g. textbooks) spans across academic domains, so an in depth understanding of this process will provide helpful insight into the design of effective instructional methods. For example, the classic debate in the educational literature between teaching students to read via phonics versus whole-word learning is informed by neuroimaging studies. These studies have refined our knowledge of the role of the component processes involved in reading, and highlighted the significance of both phonological and semantic processing, suggesting that instruction would be best served to focus equally on both of these processes (Landi et al., 2013).

Further, a topic of significant interest in this subdivision is developmental dyslexia. Developmental dyslexia is considered a multifaceted neurobiological language impairment primarily involving a letter-to-speech integration deficit that manifest most commonly in severe reading difficulty (Gori & Facoetti, 2013). Neuroimaging techniques have been able to complement and extend the existing knowledge and understanding of dyslexia (Ansari et al., 2012). For example, research has identified specific brain circuits that are disrupted in students with dyslexia (Gabrieli, 2009). Additionally, neuroimaging has shown the efficacy of phonologic intervention in increasing activation in the brain areas involved in these circuits (Shaywitz, et al., 2004; Temple, et al., 2003), thereby corroborating and confirming the efficacy of interventions developed behaviorally. Further, these studies have shown post-intervention normalization of activity in brain

regions that were found to be under-activated in students with dyslexia, but that additional brain regions not typically associated with reading processes are involved in students with dyslexia (Ansari, et al., 2012). This recognition of the various possible developmental pathways to construct the ability to read offers an inclusive conception of literacy in the brain and offers potential implications for reading instruction for struggling students.

Mathematics. Within educational neuroscience, the mathematics subdivision is the second most prominent area of study. With that said, most research has focused on basic mathematic concepts and operations in addition to severe deficits in math ability. The evolution of mathematical processes in the brain is similar to that of reading as discussed in the previous section. Namely, numeracy emerges from a combination of (a) the neuronal recycling of compatible brain regions into supplemental numeracy circuits and (b) the brain structures biologically developed to support quantitative sense.

Research has divided this quantitative sense into two distinct systems that are present in infants. One is called the object-tracking system, and the other is called the number estimation system (Xu & Spelke, 2000; Xu, 2003), or more commonly, the approximate number system (ANS)(Ferigenson, Dehaene, & Spelke, 2004) The ANS is a ratio-dependent, approximate representation of number. In other words, the ANS is a system that allows for the distinction of large numbers (> 4) from one another given enough of a discrepancy between them (Ferigenson, et al., 2004; McCrink & Wynn, 2004). On the other hand, the object tracking system supports the differentiation and manipulation of a small number of individual objects (< 3) from each other (Ferigenson,

et al., 2004). Infants are reportedly able to distinguish quantities from one another, abstract the stability of these concepts across modalities, and perform some basic addition with them. However, it has been suggested that this small number discrimination is the result of variables continuous with numerosity (i.e. area occupied, contour distinctions), not the differences in number per se (Van Herwegen, Ansari, Xu, & Karmiloff-Smith, 2008).

Neuroimaging studies have been able to identify the neural substrates supporting both core systems of number sense (ANS and object-tracking system) as well as those involved with simple mathematical operations (addition, multiplication, etc.). Many regions in the parietal cortex have been implicated in several mathematical processes and operations, for the most part lateralized in the left hemisphere. Number processing is supported by the bilateral horizontal intraparietal sulcus (HIPS) (Ansari & Dhital, 2006), while the left angular gyrus has been linked with arithmetic fact retrieval (Grabner, et al., 2009). The activation of the HIPS is observable from infancy to adulthood, despite significant structural and functional reorganization that results in the formation of experience-dependent supplemental numeracy circuits, as previously explained, suggesting the HIPS play a primary role in general number sense (Ansari & Dhital, 2006).

All mathematical processes are supported by a collection of distributed neural networks. This necessitates the coordination and cooperation of multiple brain structures even for simple numerical operations. For example, the most widely accepted account of number representation is called the triple-code model of number processing (Dehaene &

Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003). This model asserts three categories of number processing: magnitude representation, visual representation, and verbal representation. Magnitude representation, or the abstract number concept (e.g. ‘twoness’), involves the inferior parietal circuit, which is believed to be the core of mathematical processing, as mentioned previously. The inferior occipito-temporal cortex supports visual representation. More specifically, the numerical-visual representation recruits the inferior occipito-temporal cortex bilaterally, while the linguistic-visual representation recruits only the left inferior occipito-temporal cortex. Finally, verbal representation is associated with perisylvian areas in the left hemisphere (Dehaene & Cohen, 1995; Dehaene, et al., 2003).

Further, research has begun to examine the neural correlates underlying basic mathematical calculations such as addition, subtraction, and multiplication, though higher-level operations are still largely unexplored. In fact, these circuits have been seen to be extremely malleable and, as mentioned previously, subject to significant reorganization via influence of newly learned knowledge, on-task training, and specific instructional methods (Ischebeck, et al., 2006). In their study, Ischebeck et al. (2006) used functional magnetic resonance imaging to examine the brain activation patterns associated with multiplication and subtraction and how training influenced these circuits. The authors found distributed networks of activation for both multiplication and subtraction when contrasted with a control number-matching task.

The network supporting multiplication included frontal areas (bilateral inferior frontal gyrus, supplemental motor area (SMA), bilateral insula, right precentral gyrus),

occipital areas (bilateral occipital gyrus), temporal areas (left inferior temporal gyrus and right fusiform gyrus), and the left cerebellum along with bilateral intraparietal sulcus. The subtraction circuit included bilateral intraparietal sulci, frontal areas (bilateral inferior and middle frontal gyri, SMA, insula, and precentral gyrus, right superior frontal gyrus), basal ganglia (caudate/putamen nucleus), occipital areas (inferior occipital gyrus, calcarine gyrus, bilaterally), and the cerebellum (Ischebeck et al., 2006). When examining the results of training on these circuits, decreases in activation of frontal areas associated with general purpose cognitive processes (working memory, executive control) were found for both multiplication and subtraction. This decreased reliance on general cognitive processes indicates learning, which was supported by accuracy and response time data. Interestingly, in multiplication only, training resulted in a shift of activation from the intraparietal sulcus to the left angular gyrus – which suggests a cognitive shift in strategy from quantity-based processing to automatic information retrieval (Ischebeck et al., 2006).

These findings first suggest differentiation between the various processes within the domain of mathematics from one another. In other words, a student may excel with one mathematical skill, but struggle to master another, indicating the need for educators and educational researchers to reconsider the value and meaning of categorizations such as ‘high-math ability’. Further, this study demonstrates the plasticity of these mathematical processing circuits, which suggests the efficacy of intervention for students with math processing deficits.

Another study examined whether different learning methods influenced the modification of brain activations due to training (Delazer, et al., 2005). One method of learning was the application of a sequence of arithmetic operations (strategy condition), and the other was learning by association of operands and the result, i.e. memorization (drill condition). The authors found that, after training, the drill condition was associated with activation in medial parietal regions including the left angular gyrus and the strategy condition more strongly associated with activation of the precuneus (Delazer et al., 2005).

These findings demonstrate that different instructional techniques (drilling or arithmetic strategy learning) result in the different influences on the neural circuitry underlying the same mathematical process. In other words, in addition to the idea that instruction influences the way students encode information, different ways of instruction result in different methods of encoding information. The implications of this are at least twofold. First, it is important that teachers provide a variety of representations of mathematical knowledge and an equal variety of assessment styles in order for students to best acquire the skills. Second, the specifics of mathematical interventions must be carefully monitored, as these instructional techniques have varying influences on the architecture of mathematical processing in the brain that may represent more or less efficacious problem solving strategies.

Further, neuroscience research is beginning to understand how the brain mechanisms associated with calculation change over time in both children and adults. (Ansari, et al., 2012). These results can partially be attributed to training effects, as the

activation patterns revert when the participant is presented with problems they were not trained with. Nonetheless, these data show that during novel calculations, participants recruit more frontal areas as compared to trained participants (Rivera, Reiss, Eckert, & Menon, 2005). The combination of variable strategies, training effects, and developmental influences all have the potential to influence math instruction and remediation. The applicability of this subdivision lags behind that of the reading literature, but the current evidence gives reason for optimism.

In sum, these aspects of the literature remain important for the conceptualization and assessment of the discipline of educational neuroscience and will continue to benefit the field. While these are not the only subdivisions of research within educational neuroscience, they are the two pillars of content knowledge in the field. This study aimed to use this landscape as a background for examining a developmental trajectory of educational neuroscience from the perspectives of some of the pioneering researchers in the field.

Personal Interest

My interest in this topic was influenced by my previous and current educational experiences, my basic knowledge of key concepts and issues of the discipline, and my future goals as a professional. Growing up with an elementary school teacher as a father provided me with an insight into teachers' perspectives on a wide range of hot topic issues, and listening to my father discuss the state of education resulted in my own intrinsic interest in improving education generally and the communication between researchers and practitioners, specifically. Further, my undergraduate studies in

philosophy, steeped in the Western canon, shaped my thinking toward large-scale concepts and ideas. Even while obtaining my scientific training, my inclinations continued toward conceptual research problems and big-picture narratives.

As a graduate student in education, with an emphasis on educational neuroscience, and with my research training in a neuroimaging lab, my interest in the developmental directions of the discipline also underlie the motives for this project. I began my graduate education studying the concepts, principles, and research methodologies of educational psychology. This terminal Master's degree allowed me to explore the complexities of educational theory as well as practice. During this time, I studied theories of learning and motivation and investigated the many complexities and nuances of the construct of 'intelligence'. It was during this time I discovered my interest in the neuroscience of learning and cognition as well. These two interests led to my Master's degree capstone project, advised by Dr. Layne Kalbfleisch, contributing to a book chapter titled: The Neuroscience of Giftedness (Kalbfleisch & Gillmarten, 2011). This chapter synthesized the literatures on intelligence, reasoning, and working memory in order to present a neuroscientific account of giftedness that was accessible to school counselors of gifted populations.

Following this, I began my doctoral work in education with an emphasis in educational neuroscience. Throughout my doctoral studies, continuing under the mentorship of Dr. Kalbfleisch, I worked as a research assistant in her laboratory, KIDLAB, housed in the Krasnow Institute for Advanced Study at George Mason University, and was apprenticed in the many aspects of conducting neuroimaging

research. At first, training involved the recruitment of new participant volunteers, coordinating participant visits and administering psychometric assessments. This experience allowed me to interact with participants and their families as well as become familiar with the specific requirements and boundaries of common psychometric assessments.

I trained in the methods of fMRI data analysis, both with real data in the laboratory, and through coursework at George Mason University, George Washington University, and the University of Maryland, College Park, as these institutions are participants in the consortium of colleges and universities in the metro Washington, D.C. area. This led to my role in an fMRI study from start to finish. I participated in the design of the task, the recruitment and psychometric assessment of participants, neuroimaging data collection, and data analysis.

During this time, I co-authored an article dispelling the neuromyth of left-brain/right-brain localization of specific cognitive abilities, with specific attention to visuospatial skills (Kalbfleisch & Gillmarten, 2013). I presented this paper as part of an international symposium of the Brain, Neuroscience and Education Special Interest Group at the annual meeting of the American Educational Research Association in April 2014.

Naturally, these training and publication experiences in educational neuroscience reflect my personal investment in the progress of the field and achieving successful communication and application of neuroscience knowledge to educational contexts.

Coupled with my penchant for a meta-cognitive perspective, these experiences motivated my interest in examining educational neuroscience from a ‘bird’s eye view.’

In addition, Dr. Kalbfleisch made the videotapes of the complete proceedings of the 1995 Cognitive Neuroscience and Education conference available to me. I discuss this in more detail in the methods section, but the opportunity to observe these early presentations cultivated my interest in this research project. In sum, the combination of my intellectual history, my inclination toward contributing to improvements in education, and my serendipitous access to the videotaped proceedings of a very early conference concerned with the intersection of cognitive neuroscience and education all contributed to my interest in this topic.

As a student in the field, I am positioned as a peripheral participant in the discipline of educational neuroscience and this study helped shape my impending entrance into the field. I am an insider in that I am familiar with much of the literature, research techniques, and important concepts. However, I am an outsider in that I have yet to launch my career in the field and therefore do not have a full sense of its shape. My personal goal for this study was to gain a panoramic perspective and overview of educational neuroscience from some of the pioneering researchers in the field, in order to assess my own role and value as a future contributor to the discipline.

Current Study

The purpose of this study was to explore the trajectory of educational neuroscience from perspectives of pioneering researchers in the field who participated in the 1995 conference at the University of Oregon. I wanted to compare and contrast the

information they presented in this early stage of the field with the developing knowledge base, and the goals, aspirations, and obstacles of the field, as perceived by this group of researchers. To support this goal, the perspectives and interpretations of the participants are framed by literature reviews that relate to the topics the conference featured most prominently, reading and mathematics. This literature provided a background that enabled me to understand the perspectives of these foundational researchers and to assess the development of educational neuroscience with respect to relevant topics.

Research Design. This qualitative study was informed by an interpretivist conceptual paradigm (Glesne, 2011), as I sought the interpretations of the participants about the disciplines of educational neuroscience at two time points, from their presentations in 1995 and from interviews conducted in the last half of 2014. Glesne (2011) states that the goal of an interpretivist investigation is “understanding human ideas, actions, and interactions in specific contexts or in terms of the wider culture . . . what is of importance to know, then, is how people interpret and make meaning of some object, event, action, perception, etc.” (p. 8). This perspective allowed me to conceptualize a developmental trajectory of the field and better understand some of the early goals and influences. Finally, this paradigm fit my study because “accessing the perspectives of several members of the same social group about some phenomena can begin to say something about cultural patterns of thought and action for that group” (Glesne, 2011, p. 8).

Beyond this conceptual paradigm, I adopted Constructivist Grounded Theory (Charmaz, 2014) methods to frame the process of my study. Charmaz (2014) explains the

approach -- “we start with the assumption that social reality is multiple, processual, and constructed . . . [therefore] relativism characterizes the research endeavor rather than objective, unproblematic prescriptions and procedures” (p. 13). This framework helped me stay close to the data as I constructed meaning from the “views, values, beliefs, feelings, assumptions, and ideologies of individuals” (Creswell, 2008, p. 439) about the discipline of educational neuroscience.

Research Questions. Working within this paradigm and framework, I explored the following research questions:

1. How do the presenters in the Cognitive Neuroscience and Education conference in 1995 conceptualize the discipline of educational neuroscience?
2. How do these conceptualizations compare to their understandings of the state of the field in 1995?
3. How do these pioneering researchers interpret how the discipline of educational neuroscience has taken shape since the time of the conference?
4. What do these researchers consider productive directions and avenues of inquiry for the discipline of educational neuroscience?

METHODS

This qualitative research paradigm allowed me to explore the experiences and perspectives of my participants. I aimed to examine the development of educational neuroscience from 1995 to the present, as understood by some of the pioneering researchers of the field. This goal led me to grounded theory methods (Charmaz, 2000, 2002, 2014; Glaser & Strauss, 1967; Strauss & Corbin, 1998) for the project which made it possible for me to flexibly interact with my data in order to develop my interpretations and form meaning.

More specifically, I found the constructivist grounded theory, as presented in Charmaz (2014), to fit the purposes of this study because of the initial assumption that “social reality is multiple, processual, and constructed” (Charmaz, 2014, p. 13). Another reason I chose constructivist grounded theory over the more classic grounded theory methods of Glaser and Strauss (1967), or Strauss and Corbin (1998) is the difference in expected relationship of the researcher to the data and theories that emerge. Specifically, the classic iterations of grounded theory expect the emergent theory to be grounded in the data, and necessarily separate from the researcher; whereas constructivist grounded theory assumes no such separation of researcher and researched: “Rather, we are part of

the world we study, the data we collect, and the analyses we produce. We *construct* [author's emphasis] our grounded theories through our past and present involvements and interactions with people, perspectives, and research practices" (Charmaz, 2014, p. 17).

Data Collection

Data for this study was collected from three different sources: (a) VHS recordings of the complete proceedings of a national conference held in 1995 about the intersection of cognitive neuroscience and learning; (b) present-day interviews with four of eleven presenters featured at the conference; and (c) focused reviews of the relevant literature in educational neuroscience.

Conference Proceedings. I was granted access to VHS tapes of the entire proceedings of a conference hosted by the James S. McDonnell Foundation in Eugene, Oregon in 1995, entitled: *Cognitive Neuroscience and Education: Brain Mechanisms Underlying School Subjects* (Posner, 1995). Dr. Posner gave the videotapes to Dr. Kalbfleisch in 2000 at the end of her post-doctoral studies at the Sackler Institute for Developmental Psychobiology, Weill Medical College of Cornell University. After consulting with Dr. Posner, Dr. Kalbfleisch provided me with access to the videotapes for the purposes of this dissertation. The tapes included the eleven presentations from the conference that introduced a range of topics related to the contributions of cognitive neuroscience to the understanding of learning and education (see Table 1). The tapes were digitized in order to preserve the original recordings and aid in transcription. After digitization, I made duplicate copies and backups of the digital data to prevent data loss. The digital versions of these videos were stored on a password-protected computer.

Table 1

Presentation Schedule from the Cognitive Neuroscience and Education Conference, 1995

| Presenter | Topic |
|---------------------------------|--|
| Dr. Michael Merzenich | Plasticity mechanisms of the Brain & Implications for Training & Processing Deficits |
| Dr. Marc Raichle ^a | Neuroanatomy of Single Word Recognition |
| Dr. Michael Posner ^a | Neural Circuitry of Single Word Recognition and Reading |
| Dr. Tom Carr | Reading from the Perspective of a Brain: A Problem to Solve |
| Dr. Helen Neville | Effects of Experience & Environment on Visual & Language Systems |
| Dr. James Stigler ^a | The Effects of Non-Universal Representations on Future Numerical Processing |
| Dr. Stanislas Dehaene | Brain Networks for Number Processing and Calculation |
| Dr. Karen Wynn | Number Representation in Infants |
| Dr. Robbie Case | Facilitating the Development of Children's Mathematical Understanding with Educational Interventions |
| Dr. Robert Siegler | Variation and Change in Children's Strategies in Arithmetic |
| Dr. John Bruer ^a | Real Educational Problems: How Cognitive Psychology and Cognitive Neuroscience has Contributed |

Note. ^a = interview participant

Interviews. I conducted semi-structured, in-depth interviews (Johnson, 2001) with four of the eleven researchers featured at the 1995 conference, Drs. Jim Stigler, Michael Posner, Marc Raichle, and John Bruer. One presenter, Dr. Robbie Case, was deceased in 2000. The remaining ten individuals were recruited to the study via email. I received five positive responses and was able to schedule and complete interviews with four of those five. The fifth respondent, after expressing an initial interest in participating, failed to reply to my attempts to schedule the interview. I received one email expressing an inability to participate because of scheduling issues.

Interviews ranged from 36 minutes to 70 minutes and were conducted via telephone. Interviews were recorded using the TapeACall application for iPhone. These recordings were immediately uploaded to a local, password protected computer, via Dropbox, and once saved on the computer, the recordings were deleted from the phone.

The interview protocol is provided in Appendix A. The questions were predominantly open-ended and aimed to explore: (a) past and present research interests, (b) perspectives on important issues and concepts within the field, (c) evaluation of the goals and efficacy of the discipline in meeting those goals to this point, and (d) ideas about improvement moving forward and potentially fruitful research directions.

Literature Reviews. In order to provide a background and context for the perspectives of my participants I conducted reviews of the educational neuroscience literature about relevant and influential topics to educational contexts. I initially incorporated reviews of the reading and mathematics subdivisions of educational neuroscience (found in Conceptual Framework) because these domains were at that time,

and continue to be the most-researched domains in the discipline of educational neuroscience. Additionally, eight of the eleven presentations at the conference in 1995 addressed various processes associated with either reading or mathematics and I felt that these reviews could provide a necessary context for my interpretations of the field in 1995 as well as the conference itself. I conducted literature searches using the National Library of Medicine's PubMed database. I searched using various combinations of domain-specific keywords: reading, language (or: mathematics, number processing), neuroscience, neuroimaging, education, cognition, and educational neuroscience. I reverse-searched references of relevant articles and drew from the bibliographies of articles I had previously discovered.

I included an additional review of some of the mathematics research (found in Discussion) in order to provide a glimpse of current topics of interest and methods of investigation. I intended to provide a background of the progress within the literature in order to add depth to my interpretations of the participants' perspectives on the current state of the discipline. I chose mathematics specifically because research on this topic has increased dramatically in the past ten years (Byrnes, 2012).

I also incorporated a brief review of some of the intelligence/reasoning literature in the Discussion. As mentioned previously, the construct of intelligence continues to be an interest of both educational researchers and neuroscientific researchers. While there are certainly other cognitive skills that are both important to the learning process and being explored via neuroscientific methods, I chose intelligence/reasoning as representative of an increase in research into these domain-general topics and cognitive

skills in the field as it is today. I believe this body of literature is beginning to inform our understanding of students' individual differences as well as highlighting some of the interesting aspects of the relationship between academic ability and *disability*. With such a strong focus on understanding disability at this point in the field, I consider it valuable in shaping a landscape of the development of the discipline.

All of these reviews focused on communicating generally accepted knowledge in addition to the viability and potential for educational applications and recommendations for pedagogy. These reviews provide a glimpse at the progress made in expanding the knowledge base since 1995, adding background context for my analysis and for recommendations of new, fruitful directions for research in educational neuroscience (Webster & Watson, 2002).

Participants

The participants in this study included four of the ten (living) researchers (see Table 1) who participated in the Cognitive Neuroscience & Education Conference in 1995. This was a purposeful sample selection (Creswell, 2008) and the participants themselves were not the primary unit of study in this project. Instead, their interviews provided data that informed the development of educational neuroscience. The sample is also purposeful in that I chose the sample after initial data collection had started (i.e. I had already viewed the videotaped proceedings). I chose this sample because, as participants in the conference in 1995, they could provide insights from personal experience about the context and setting of educational neuroscience at that time, as well as interpretations of the development of the field from then to now.

I was not personally acquainted with any of the participants beforehand. That being said, I was familiar with the contributions of these researchers to varying degrees. Additionally, because I am a graduate student in the field, it is possible that participants associated me with my graduate advisor, Dr. Kalbfleisch, who is an established presence in the field and chair of this dissertation. I did not experience any explicit consequences of this relationship, though these issues and concerns are addressed under the Ethics and Validity headings, later in this section.

Data Analysis

Data analysis for this study was a recursive and continuous process throughout the project. I utilized a bricolage approach (Kvale & Brinkmann, 2009) to the analysis of video and interview data. Kvale and Brinkmann (2009) describe bricolage as an “eclectic form of generating meaning – through a multiplicity of ad hoc methods and conceptual approaches” (p. 233). This allowed me to move freely between different analytic techniques and concepts, such as those suggested by constructivist grounded theory (Charmaz, 2014) and data-driven meaning coding (Kvale & Brinkmann, 2009). Consequently, the analysis process involved multiple coding phases, as well as constant comparison between and within data sources. This cyclical and interactive process allowed me to constantly revisit and compare my analyses of individual presentations and interview to one another. Through this approach, I was able to develop categories and themes throughout and recursively use these to analyze other data.

In addition to the specific steps that follow, I wrote analytic memos (Charmaz, 2014; Maxwell, 2005) throughout the study in order to organize, reflect on, and develop

my ideas, insights, and theories on this topic. This helped me document and track important themes as they emerge and develop from the data. Reflective memoing about my role in the research process helped me develop and understand myself as the researcher (Maxwell, 2005). The activity of memoing was an essential part of my interpretations and construction of meanings. They allowed me to articulate and dissect the emergent ideas from the data and to explicitly deal with the influence of my preconceptions on the formation and development of these ideas. Examples of an initial analytic memo of a conference presentation and a reflective memo after an interview can be found in Appendix B and C, respectively.

Throughout the analysis of my data, I also used the Knowledge Menu (Renzulli, Leppien, & Hays, 2000), provided to me by Dr. Kalbfleisch and presented in Appendix D. Dr. Kalbfleisch first presented this Knowledge Menu document as a way to help conceptualize and organize my understanding of a discipline. I used the heuristic to guide a perspective paper I wrote as a degree requirement for my graduate studies. I found it useful then for organizing my thinking and, due to the nature of this project, I decided the same heuristic could be helpful in guiding my analyses and thought processes. This heuristic implicitly aided me in recognizing and organizing any patterns related to a conceptualization of the field of educational neuroscience, however, the heuristic only explicitly influenced my analysis as I made sense of the conference presentation data. An example of this can be found in Appendix E.

The first step in my data analysis was the transcription of the videotaped conference presentations. I manually transcribed each of the presentations using the

Transana software program, Standard Version 2.6 for Mac (Woods & Fassnacht, 2012). This helped me organize the many data sources and points. Further, the pause and rewind functions inherent in the software program were designed specifically for the transcription of qualitative data and streamlined the transcription process. After I transcribed each presentation, I performed a preliminary exploratory analysis through an analytic memo. This memo also served as my initial notes about the overall organization of the presentation and the main ideas and themes within each one (Creswell, 2008).

I then performed an initial, line-by-line open coding of these transcripts. During this coding phase, I kept my codes close to the data and tried to focus on coding with gerunds – a heuristic strategy suggested by Charmaz (2014) in order to emphasize action in the data. “This type of coding helps to define implicit meanings and actions, gives researchers directions to explore, spurs making comparisons between data, and suggests emergent links between processes in the data to pursue and check” (Charmaz, 2014, p. 121). I then wrote an analytic memo after coding each presentation to begin to shape my interpretations of the data and to make note of any implicit themes that began to emerge.

The next step in my data analysis was to perform this initial coding of the interview data. Exactly as with the presentations in step one, I manually transcribed the recorded interviews using the Transana software program (Woods & Fassnacht, 2012), primarily as an organizational tool. After transcribing each interview, I wrote a memo in order to articulate and reflect on anything that seemed important and emerged during transcription. I then performed line-by-line open coding of the interview transcripts with the same heuristic in mind as before, namely, “coding with gerunds” (Charmaz, 2014).

As mentioned previously, the interviews primarily explored the interviewees' interpretations of the 1995 conference, the development of their own research, as well as the field as a whole since that time, and the developments in their conceptualization of the discipline of educational neuroscience.

During the subsequent step in my data analysis, I performed a second line-by-line coding on the presentations and interviews, though this time I focused on meaning condensation, or condensing the long statements made by each teacher into shorter more concise, informative phrases (Kvale & Brinkmann, 2009). This allowed me to enrich my action-oriented codes and move toward constructing themes and categories. As key categories began to emerge from the data, I engaged in focused coding (Charmaz, 2014). During this phase, I critically examined my initial codes, comparing them to one another within and between the different presentations and interviews. I performed this focus coding of the presentations and interviews separately, but utilizing the same strategies to develop significant themes and categories. My goal was to establish larger, conceptual themes based on the interpreted significance of certain categories across presentations and interviews.

I then wrote analytic memos about some of the major themes that emerged. In these memos, I compared and connected the ideas that were present in both the presentation data and the interview data in order to start constructing interpretations about the development of educational neuroscience. As this process evolved, common categories began to emerge from the presentation data and shared themes emerged from the interview data. At this point, I used a separate document to organize and catalogue the

initial codes into the main categories and themes that emerged. This document was a way for me to organize specific quotes and examples in support of the categories and themes.

These themes were guided by my interview questions and research questions, however they were also grounded in ideas that emerged from the data. These themes were then mined for duplicate concepts and meanings, which were combined. Due to the nature of the conference presentations, the categories that emerged from that analysis were largely organizational (Maxwell, 2005), in that they could have been anticipated before analysis began. I address this development in the Discussion.

Of the categories that emerged from the interviews, four of them were also organizational categories and address the intentions of the study directly, thus I use these to organize this portion of the Results section. The remaining categories were closer to substantive categories, as defined by Maxwell (2005) as: “primarily descriptive, in a broad sense that includes description of participants’ concepts and beliefs” (p. 97). These emergent substantive categories provide context and insight for the findings and interpretations of this study and I address them as they arise.

Importantly, while I described the analysis process as stepwise and linear, in actuality the process was fundamentally recursive and simultaneous. In other words, at any time point, I was in various stages of analysis with various data sources. The cyclical and interactive nature of my analysis allowed me to explore the connections between each participant’s presentation and interview. Consequently, I was able to interpret the data from the perspective of the individual and construct a cohesive understanding of the development of educational neuroscience from each of these four perspectives. Most of

my connecting analyses (Maxwell, 2005) work took place in the analytic and reflective memos.

Ethical Concerns

I do not foresee any potential negative effects on the participants of this study. I obtained approval from the Institutional Review Board of George Mason University (IRB) for the Interview Protocol (Appendix A) and the Initial recruitment letter (Appendix F) before initiating contact with the participants. This initial contact was made via electronic mail sent to all 10 presenters from the conference videotapes, and included my intentions and goals for this study as well as the requirements of participation. After its approval by the IRB, I sent a second recruitment letter to those presenters whom had not responded to the first recruitment letter, which, as requested by the director of the Ph.D. program, is also included in Appendix F. The IRB approval letter can be found in Appendix G. The affirmative response to either recruitment letter served as an informed consent, a fact explicitly mentioned in the letter. I provided participants with the option of using a pseudonym, but all interviewees opted to allow the use of their real name. Nonetheless, during my analysis of the interviews, I recognized a handful of instances where the topic and opinion of the researcher could be seen as controversial. In these instances, I used my best judgment to avoid specific attribution of these potentially damaging ideas, though for the most part they did not develop into meaningful additions to my study.

In the initial contact letter, during the recruitment process, and at the beginning of the interview, participants were made aware of the fact that I recorded the interviews and,

each time, they were given the opportunity to utilize a pseudonym. After I transcribed the interviews and reached a meaningful level of interpretation, I sent each participant a copy of the full transcript of their interview along with a brief description of my key interpretations from the interview. This latter document served as a respondent validation (Maxwell, 2005), also called a member check (Creswell, 2008), whereas the transcript was sent primarily as a reminder of our conversation and context for my interpretations.

I asked each participant for their thoughts and comments on my interpretations of our conversation. I received responses from three of the four interview participants to whom I sent respondent verification messages. One of those responses included revisions to my interpretations, largely to supply a more measured tone in my interpretation of the participant's influence and impact on the discipline. The other two participants confirmed and approved the main interpretations of our conversations.

Issues of Validity

One potential threat to the validity of the interpretations of this study is the purposeful selection of participants. I intentionally chose the researchers that presented in the videotapes as potential participants. One reason for this decision was to obtain a level of consistency with regard to my data sources. In other words, their conference presentations and then the present-day interviews with those same presenters provided consistency and 'bookends' for the construction of a developmental trajectory of the field. A second reason for this decision was that these researchers made foundational contributions to our understanding of brain mechanisms, cognition, and how they interact with education. This purposeful sample developed into a validity threat in two ways.

First, four of the ten surviving speakers from the conference responded to invitation to participate, which presents the possibility that my data was not representative. However, I believe that I interviewed a representative sample from the group of conference speakers, and will describe how the four participants can be seen as a representative of the field.

Dr. Stigler is a cognitive psychologist interested in educational problems. His experience is in researching problems of math teaching and learning. While he purposefully remains a generalist in terms of research methods, he does not have experience with neuroimaging or investigating educational problems in terms of brain function.

Dr. Raichle is a trained neurologist, though – as he himself mentioned – his research is not aimed toward informing educational practices and contexts. Dr. Raichle’s extensive experience lies with the brain and neuroimaging research, though his questions and approaches do not focus on educationally oriented research questions.

Dr. Posner organized and hosted the conference in 1995, and has contributed to cognitive and neuroscientific research on educational processes throughout his career. Dr. Posner has long experience with neuroscientific research about attention in learning and is, admittedly, farther-than-average on the optimistic side of the scale in terms of the potential for neuroscience to inform educational practices.

Finally, Dr. Bruer is the President of the McDonnell Foundation (the Foundation that sponsored the conference in 1995) and has a broad perspective on the landscape of both educational research and cognitive neuroscience research. He is outspoken – in text as well as speech – about his hesitations and skepticism regarding the application of

neuroscience information to education. His position is that cognitive psychology and other behavioral sciences are more capable of informing the educational context.

This sample of participants is evenly distributed on the spectrum of optimism/skepticism about educational neuroscience. Dr. Posner and Dr. Bruer represent the poles; Dr. Raichle and Dr. Stigler represent the mean. I believe this distribution mitigates the low number of participants as a threat to the validity of the study.

The second way my purposeful sample presented a validity threat was by the fact that many of the conference speakers are not notably visible in the field at this time. I address this in the Discussion, as well. While many of the participants may not be currently active in the field of educational neuroscience, their foundational roles in its existence give their perspectives credence. Additionally, my interpretation of these perspectives informs a contemporary context of the discipline. Further, my ability to converse about methodological and research concepts models level of literacy needed in the field. My knowledge and experience helped me explore beyond the surface-level responses to my interview questions and dive deeper into the perspectives and opinions of the participants.

In addition to being an asset, my membership and, therefore, investment in the subject of my study introduced the potential for unrecognized researcher bias. To guard against this potential, I used reflective memos to monitor my role as researcher, identify my successes and failures achieving depth in the interviews and maintain the integrity of my interpretations (Maxwell, 2005). I also sought to identify counterexamples and

negative cases in my data that did not fit into the substantive picture of the field that I was constructing. In fact, one interviewee held the opinion that educational neuroscience has nothing to offer educational practice, providing a point of view that I might not have fully encountered otherwise. I was aware of this researcher's prior critiques and criticisms of the discipline of educational neuroscience, though I lacked the ability to adequately conceptualize or articulate the position.

Another potential validity threat was the interpretive validity of my findings. As mentioned above, I used respondent validation (Maxwell, 2005) to guard against this threat to the interpretations of the interview data. Again, I received responses from two participants confirming and approving my interpretations, while a third offered revisions to my interpretations. Based on the changes to certain verbs and attributions, it is my understanding that my initial articulation was too dogmatic.

Further, the identification and incorporation of discrepant evidence will also help address concerns about the validity of my interpretations. The framework of constructivist grounded theory is characterized by the recognition of the relativism inherent in the research endeavor. "The constructivist approach treats research as a construction but acknowledges that it occurs under specific conditions" (Charmaz, 2014, p. 13). Therefore, the emphasis is placed on reflexivity and awareness of these specific conditions that influence the construction of meaning, as opposed to eliminating this very subjectivity and uniqueness.

RESULTS

The results of this study are first organized according to the type of data from which they are drawn. In the first section, I describe the results of my analysis of the videotapes of the presentations at the 1995 Cognitive Neuroscience and Education conference held in Eugene, Oregon. I used the Knowledge Menu (Renzulli, et al., 2000) (Appendix D) to structure my report. In the second section, I present the results of the interviews with four of the ten participants who presented at the 1995 conference. I chose to organize the results this way in order to present these two snapshots in a developmental arc of the discipline of educational neuroscience as captured from the videotapes, interviews, and background literature.

Conference Presentations

The presentations were all largely content-oriented, and focused on three subject areas: plasticity of the brain, reading, and mathematics. These content domains were drawn from the presentation topics and were used, along with the Knowledge Menu (Renzulli, et al., 2000) (Appendix D) in order to present my analysis of the conference proceedings most clearly as a snapshot of the discipline at that time. As mentioned above, an example of how this heuristic aided my organization can be found in Appendix E.

Plasticity. The presentations that discussed plasticity were by Dr. Michael Merzenich and Dr. Helen Neville. Dr Merzenich presented results from some animal

studies to highlight the way training on motor and auditory tasks can reorganize the functional and structural representations of those stimuli in the brain. He then presented data of an intervention for children with language and reading deficits that showed similar results, namely, that the children improved in recognizing and distinguishing the sounds in words.

Dr. Neville presented ERP data comparing the different aspects of the visual systems and the verbal systems in subjects who were congenitally deaf to hearing control subjects. Her data suggested that while these systems are largely biologically biased, early sensory experiences could change their organization and representation in the brain.

Some of the key concepts and principles in these presentations were plasticity, variability, and representation. Dr. Merzenich presented the brain as “a learning machine” and provided many examples of the principle that ‘neurons that fire together, wire together’. Dr. Neville showed the results of naturally occurring abnormalities in development and subsequent experiences on the organization of certain sensory subsystems

Methods these researchers used included: electrophysiological techniques such as topographical mapping and using electroencephalography (EEG) to measure event related potentials (ERPs). Dr. Merzenich primarily studied animals to map representation areas in the brain, while Dr. Neville studied human differences. One main goal of this research was to identify and draw boundaries between different cognitive systems and subsystems, while exploring understand “the extent to which these strong biological biases can be modified and when can they be modified.” The stated goal with educational

implications was to understand the nature of the phenomenon of learning disabilities, therefore informing the design of interventions and curricula.

One key theory in these presentations was that the cortex *wants* temporally sharpened distinctions for successive inputs, which informs intervention design. It was also posited that the variable plasticity between subsystems is due to the “different rates of maturation, different degrees of anatomical divergence early on in development.” Specifically, Dr. Neville suggested that the peripheral visual system – and therefore dorsal pathway – is more modifiable than the full view visual system, and that in the “auditory cortex, which is strongly biased to process auditory information, may actually become organized to process visual information under certain conditions early on in human development” [i.e. congenital deafness].

Reading. The presentations that discussed reading were by: Dr. Marc Raichle, Dr. Michael Posner, and Dr. Tom Carr. Dr. Raichle presented the neuroanatomy involved with single word processing, a fundamental aspect of reading. Dr. Posner discussed the neural circuitry involved, or the time course of activation of the brain areas associated with this single word processing. Dr. Carr approached the task of reading as a “problem for the brain to solve” and discussed evidence for how the transformation from non-reading to reading takes place.

The key concepts present throughout these presentations obviously included reading, and also its subcomponents. Specifically, word recognition and single word processing were discussed at length and the latter used to characterize the whole progression from seeing a string of organized lines to recognizing that it has conceptual

meaning. One key idea from Dr. Carr's presentation was conceptualizing reading as a problem of integrating the visual system with the language system in the brain. Further, another concept discussed at various points in these presentations was the visual word form area (VWFA). This area is responsible for recognizing whole words and, according to Dr. Carr's primary gateway hypothesis, serves as the connection between the visual and language systems in the brain.

Dr. Raichle traced the development of neuroimaging techniques from computer tomography (CT) scans to PET, and he briefly mentioned the new method of FMRI. Dr. Raichle discussed the nuances of these methods and described the analysis techniques used to acquire activations associated with specific tasks. Dr. Posner's presentation focused on EEG data as he traced the time course of activity, and drew from Dr. Raichle's presentation of associated anatomical structures as well. Dr. Carr primarily used the data presented by Dr. Raichle and Dr. Posner, however he also corroborated his theories of an integration mechanism with evidence from lesion studies.

Dr. Raichle conveyed two goals for his presentation. The first was to understand how the brain organizes processes for word recognition and the second was to convey how to think about cognitive or educational problems in terms of neuroimaging methods. Dr. Posner wanted to examine the circuitry of the processes of reading through ERP data, thereby "attempting to look at the time dynamics of these anatomical areas and then seeing how they might change with practice." Dr. Carr's aims were to present reading as a problem for the brain to solve, and offer a theory about how this happened, namely, the integration of the visual and language systems through the VWFA.

Additionally, there were some key theories about single word processing that emerged from these presentations. First, Dr. Raichle presented evidence of learning effects during word recognition and verb generation tasks that suggested two separate systems involved with this task that he labeled the automatic and the non-automatic systems. He further posited a conceptualization of how brain function is organized and results in behavior: “[like] a symphony orchestra, in which there are a finite number of processing elements in there, that in various combinations contributing operations which may seem highly primitive relative to the behavior you're studying, contribute to these operations . . . you have a pool of functional neuronal ensembles. And it's the way in which they organize themselves that produces the behavior.”

Both Dr. Raichle and Dr. Posner hinted at the VWFA, but Dr. Posner’s main theoretical point was regarding the various levels of plasticity in the brain. The first level he mentioned was the plasticity that might occur in milliseconds as you try to think about information in different ways. The second level of plasticity was change in seconds to minutes, like shifting from the non-automatic pathway to the automatic pathway and back. A third level of plasticity was on the scale of days to weeks, such as learning new language items. Another level of plasticity was what can be seen in the VWFA, or up to 10 years to organize part of the brain. The final level of plasticity he mentioned, he described as: “The process of developing mechanisms, in infancy, which then become important in the processing of this kind of information in the rest of life.”

Dr. Carr suggested that the primary goal early in the development of reading is to learn to recognize words. He offered evidence from linguistic studies and eye tracking

studies that suggest that the word is the focus of the reader. The main theory he proposed, in connection with this previous idea, is the Primary Gateway Hypothesis. He presented it as the solution to how the brain resolves its reading problem. “The solution that the brain adopts - at least in alphabetic languages like English - appears to be to establish a gateway, a communication device, an interface, in occipitomedial cortex that mediates between visual system input and the language system.” This area was posited to process orthographic information, and Dr. Carr used lesion studies to suggest that this area (the VWFA) sends this information to both the object recognition areas *and* the phonological processing areas. This fact highlights the role of the VWFA and that it “lies between the two systems, it's in a position where it could communicate with both, and its processing capabilities seem to make it a candidate to produce the kind of code that - I've tried to establish earlier on - is the necessary code for establishing visual word recognition capabilities.”

Mathematics. Five of the eleven presentations were about issues regarding teaching and learning mathematics. They were given by: Dr. Jim Stigler, Dr. Stanislas Dehaene, Dr. Karen Wynn, Dr. Robbie Case, and Dr. Robert Siegler.

These presentations focused on concepts of mathematical representation, both psychologically and in the brain. Number processing, magnitude representation, and calculation are the main concepts in these presentations on mathematics. Further, Dr. Stigler discussed non-universal experiences, like instruction, whereas Dr. Wynn spoke about infant number representation and speculated on its relation to adult subitization abilities. Dr. Dehaene separated the visual processing of number from both the verbal

processing of number and the more general analog magnitude representation of number; and Dr. Case suggested that the integration of this magnitude representation system with counting schema was a crucial development in children's math understanding, that took place between the ages of 4 and 6.5. Dr. Siegler focused on the discovery and use of different problem solving strategies, as well as their variability and change due to certain types of arithmetic problems.

Four of these five presentations were of behavioral and psychological studies, so most of the methods used were behaviorally oriented. They included: experimental comparison of instructional differences, infant habituation studies, intervention studies, and strategy observation via videotape. Dr. Dehaene presented evidence from brain-lesion patients, as well as from EEG studies of typical adult brains. Dr. Siegler described a method he called, "microgenetic methods," which consisted of "providing an intense amount of an experience that you believe people are going to get in the real world anyway, and that you think is functionally related to their acquisition of a skill, but you do it a little bit before they would ordinarily get that experience." The goal of this method was to gain a fine-grained perspective on the process of change between and within the strategies children used.

The goals of these inquiries were, naturally, as numerous as the methods used. Dr. Stigler wanted to "compare what happened when we train children to associate different visual representations with different numbers understand," and then "how classroom experiences and the structure of classroom lessons can affect cognitive processing of events in classrooms." He found that both of these variables, how number is presented to

children and the structure of classroom lessons result in children forming significantly different mathematical representations and classroom expectations.

Dr. Siegler wanted to detect children's discovery of a new strategy and when it was used for the first time. This allowed for a retroactive, fine-grain look at the context surrounding this type of discovery. Not only did he find – similar to Dr. Stigler – that there was cultural variance in the frequency of specific strategy use, but that strategy use varied within the child. Dr. Siegler posited that “this variability is quite fundamental part of learning and . . . that it enables children to explore the space of possible ways of solving problems increasingly effectively.” Further, Dr. Siegler was able to increase the discovery rate of a target strategy by introducing “challenge problems,” or, problems that were very difficult to solve using any strategy besides the target strategy.

Dr. Dehaene aimed to determine what brain areas were involved in the different processes of the triple-code model and what is happening in your brain when you are doing mental arithmetic. He found verbal number processing and mental arithmetic to be almost exclusively left-lateralized in the language areas, whereas visual number processing and magnitude representations were bilateral processes in inferior and parietal occipitotemporal areas.

In connection with this magnitude representation system, Dr. Wynn aimed to demonstrate that human infants could represent number and reason from those representations. She found that “five-month olds are sensitive to the numerical relationships between small numbers of objects.” Further, she demonstrated that these

representations generalize to other types of entities, such as auditory- and action-based units.

Furthermore, in consideration of this magnitude representation system, Dr. Case posited that a critical development in children's mathematical understanding happened between the ages 4 and 6.5 when they integrated their ability to count with this general magnitude representation system. His goal was to determine if this integration could be facilitated with educational intervention. According to his presentation, this intervention was incredibly successful in facilitating the development of children's mathematical knowledge, though he suggested that the timing of the intervention was important to "level the playing field" before kids entered the classroom setting.

In addition to these presentations about specific content areas, Dr. Bruer's presentation closed the conference proceedings. He started by stating the goal of the conference: "to begin to discuss how cognitive neuroscience may contribute to improved educational practice in our classrooms," which indicated to me exactly where this conference took place in the timeline of the development of educational neuroscience, that is, at the very beginning. He emphasized the importance of research and development in the field of education, but warned of "a lot of bad neuroscience being pedaled in the educational marketplace." This is a specific reference to the Early Head Start policies being implemented at the time. He stated that in order to achieve the goal of neuroscientific contributions to education, researchers must figure out how to (1) differentiate the bad neuroscience from the good for practitioners, as well as figuring out (2) how and why to talk to teachers.

Dr. Bruer highlighted that teachers are interested in solving real, classroom level problems, so we need to be interested in that too. He stated: “there’s a natural allegiance and interest between the researchers and the teachers and, if at all possible, that’s the place to start with acknowledged classroom problems.” Dr. Bruer recommended some real, classroom level problems that are situated at the junction between cognitive psychology, neuroscience, and education; and throughout his presentation, he conveyed a guarded optimism about the convergence of these fields.

He ended his presentation – and the conference – by asking: “what can we do to encourage the congenial co-evolution of cognitive psychology and cognitive neuroscience; what can we do to encourage the mutual facilitation of their research programs to really see what it's going to take to link behavioral and neuropsychological, neuroscientific science; and then see how the deeper understanding that might emerge from that mutual facilitation can be translated into better understandings of learning and teaching and used in the schools.”

Interviews

I placed the ideas and statements expressed by the participants in the interviews into four main categories that emerged from my analysis: (1) Perspectives on the 1995 Conference; (2) Perceptions about Educational Neuroscience; (3) Socio-Political Concerns; and (4) Future Directions for Success. These categories are discussed in depth.

Perspectives on the 1995 Conference. Generally, all of the participants had similar views about the goals of the conference. Dr. Raichle saw his involvement in the conference from a different view, namely he saw it as a way to honor Dr. Posner’s career

in cognitive psychology and cognitive neuroscience. As the organizer of the conference, Dr. Posner was able to describe some of the background and context about the goals and outcomes of the meeting. He reported that the presenters were chosen due to their perceived potential contributions to education. As Dr. Posner simply put it, “I invited those who I thought would be the leaders in this field.” He explained that the two main goals he had for the conference were: (1) to expose the students and faculty in the relevant domains at the University of Oregon to the ideas of neuroscience that may be influential to education; and (2) to convince the presenting scientists themselves that their work had strong implications for education.

When I asked Dr. Stigler, he mentioned right away that he did not have a very good recollection of the conference. Even still, he summarized the goal as trying to “investigate the potential for neuroscience for addressing problems in education.” He noted that it seemed to him that, within the group of presenters, the neuroscientists knew little of educational research and the psychologists were not familiar with neuroscience. In this way, the purpose of the conference could be seen as sharing information across the boundaries of these disciplines.

Dr. Bruer also did not remember the conference clearly, though he did offer an interpretation of the goal of the conference: “I think it was an attempt by some people who were primarily basic scientists – with a few exceptions – to try to ask how their research might be relevant to educational practice.” As I mentioned before, this formulation is rather similar to Dr. Stigler’s. Dr. Posner’s goals were coming from a bit

more of a personal perspective, as the host of the conference; but even still, his second goal is on par with this understanding.

Dr. Bruer offered some political context for the conference, saying that the mid '90s saw neuroscience become a significant influence in terms of policy programs. He mentioned the trouble with how critical periods were conceptualized then, and expressed a deeper concern about these rationalizing policy initiatives. I address that more deeply in the category of Socio-Political Concerns.

Even with the influence of cognitive neuroscience at that time, Dr. Posner suggested the field is even more popular now. He remembered having a hard time attracting faculty from the school of Education back then, but was confident that a similar conference today could expect a higher attendance.

Dr. Raichle discussed, in detail, the type of experimental paradigms in cognitive neuroscience at that time. He described the “traditional neuroscience” paradigm as creating a behavioral situation and then comparing the brain activity in that situation to it *not* in that situation. He discussed the limitations of this subtraction method of data analysis, as well as the conceptual limitations of understanding the brain as only reflexive. He acknowledged that when he was working with Dr. Posner (slightly before the conference), a lot of the focus was just on figuring out and establishing the ‘how to’ of examining the neural correlates of complex stimuli. At one point he described this as combining the new imaging methods with cognitive psychology paradigms.

Perceptions about Educational Neuroscience. Through these interviews, I was able to learn about how these prominent scientists perceived educational neuroscience as

a discipline today. One important idea that Dr. Posner communicated to me about the current state of the field was that a deeper, fuller understanding of what is happening during a specific cognitive skill or task is critical to practical applications. The reasoning Dr. Posner gave for this position is that if you understand what it is happening during training (or intervention), as well as the likely outcome of the training, you can use these tools more effectively, and more accurately to remedy difficulties that individual students may have. In other words, that providing teachers with a deeper understanding of the processes allows them to use that information as a context in which to make better decisions about pedagogy – for which they are trained. This is certainly not the finish line for educational neuroscience, according to Dr. Posner, he said later, “then if you have some information about what brain systems are important in that form of expertise, then you have a chance to apply it.” While he was talking specifically about understanding expertise here, I think the larger point is that the application of neuroscience to education is a multi-phase process, and that each step of the process can inform educational practices as – at the very least – a context for better understanding learning.

Additionally, he states that educational neuroscience has made real contributions to the classroom context and instructional debates. He referenced the discovery of the visual word form area, to which he and Dr. Raichle made significant contributions. “It was always a controversy between look/say and phonology, but actually they’re both necessary, both play different roles and their time course is really rather different.” He spoke about these same studies as leading to the discovery of the attentional control system, which he says has blossomed into a “neuroscience of self-regulation.” Dr. Posner

also mentioned that there were many practical implications from that work they did, but some have not been explored further. Dr. Posner did admit that he probably falls pretty far on the optimistic side of the spectrum when it comes to assessing the progress of the field. Nonetheless, his opinion is clear: “I believe that the cognitive neuroscience approach is relevant – relevant, not the determining factor – but relevant to the study of high levels of, or any level of skill in any of these domains.” He expanded on this sentiment saying, “of course curricular development doesn’t start with cognitive neuroscience . . . not every question is a question about what the brain mechanism is, but if you understand the brain mechanisms then when you design a curriculum you have another way of thinking about it.” This emphasizes the benefits that a teacher may gain from having this knowledge as context and as a way of thinking about it. This quote also stresses the belief that neuroscience is not aiming to replace or overshadow another discipline of research, but quite the opposite – collaboration and cooperation are important for improving educational practices.

As for the issue of communication between researchers and practitioners, Dr. Posner mentioned many multimedia efforts from various researchers in the field, though admitted to not be able to assess the status or efficacy of these. He did, however, mention that much of the time when he goes to conferences where there are teachers, they are all very interested in the topic and can often think of various applications themselves. Dr. Posner acknowledged that while he feels like a lot of progress has been made, there are still skepticisms and controversies.

On the other hand, when I asked Dr. Bruer about the goals of educational neuroscience today, he said: “People working in that field claim to be doing research that has implications for education; those practical implications in the classroom are few and far between.” He asserted these few substantive results to be incommensurate with the hype surrounding the discipline. He stated, “what I see, in this emphasis on cognitive neuroscience, is studying issues that lend themselves to designing imaging experiments.” His focus is largely on tangible contributions, and to this end, educational neuroscience has simply not done enough to warrant the support. He detailed the main difficulties with the field as articulated by Stanovich (1998) and Mayer (1998), which are referenced in the Introduction. He reiterated these opinions as his own, adding, “the debate about the relationship between brain science and mind science persists, and it really hasn’t been resolved.” While Dr. Bruer did mention that he thinks “the closest link between education and neuroscience is through the study of the attentional system and frontal lobe function,” but ultimately he submitted that cognitive theories from psychology are all that matter in terms of educational interventions.

Dr. Stigler’s comments about educational neuroscience mainly emphasized his problem-motivated approach to research, which provides the ability to choose the methods and theories that are relevant to that particular problem. He said that it is critical, in order to maintain the problem-motivated orientation, to remain a generalist. With that said, he did allude to the possibility of contributions from neuroscience, stating “it’s also important to have people who specialize in those [any specific] fields, helping us unpack and understand what’s going on.” Generally, Dr. Stigler spoke of educational

neuroscience as fascinating, though not useful in solving the problems he is working on. His perspective on the discipline is summarized well in this quote: “that conference [in 1995] did not cause me to go out and start doing FMRI. I found it really fascinating, but I also realized that there were too many gaps from that to where I was trying to go – in terms of understanding why some people are so much better at math than others. I mean, that could be a part of it . . . but by it’s self it’s not going to solve the problems of mathematics teaching and learning.”

When Dr. Raichle spoke of the current state of educational neuroscience, he said, “These are highly subtle things. [If] you have a learning disability or something – these are going to be very, very subtle differences in a very complicated system; and the ability to move in that direction, particularly in the human brain, to me, is deeply interesting.” In other words, Dr. Raichle is quite optimistic about the potential of neuroscience with respect to educational applications, though he maintained an emphasis on patience as we find out more about the systems. He mentioned the potential for danger in over-using FMRI data. Not only because it is not an appropriate tool for all contexts, but because it has led to some push back from some disciplines. He characterized this push back situation as: “‘I don’t need that’; ‘all I need is to know the behavior’; and ‘you’re not telling me anything new here’ . And to some extent there’s truth to that.” One recommendation he had for overcoming this barrier is an open communication between scientists and researchers: “Even though it’s kind of premature in terms of the details, we ought to know what they’re [educators] worried about and they ought to know what we’re thinking about.” Dr. Raichle emphasized that despite these push backs from some,

“there are things that we’re learning about the brain and, say, the brain in development, where education surely ought to be concerned about this.”

Socio-Political Concerns. One theme that emerged from every interview – albeit in different ways – is what I labeled ‘Socio-Political Concerns’. Dr. Bruer was the most vocal about these issues. When I asked how his interest in educational neuroscience had developed since the mid-1990’s, he expressed deep concern “that if we’re going to use science to provide policy, that the science is accurate and not propaganda.” Many times during the interview, he expressed this kind of concern about the various aspects of what seems to be multi-faceted difficulties involved in the relationship between science and general socio-political influences.

Dr. Bruer referenced the increased attention in the mid-1990’s specifically surrounding the brain and early childhood, saying: “Essentially what that mid-1990’s brain science activity was was a public relations campaign to get early Head Start passed. The scientific basis to their policy argument was wanting, to say the least.” This idea is important in many ways, not all of which are historical. These are discussed more fully in the Discussion.

Dr. Raichle touched on a similar complexity, though not quite as firmly. We had started discussing brain development as a topic of interest for education, and, as a comparison, he referenced the significant amount of time spent studying aging in the brain, attributing this fact to the presence of a lobby. Even this slight attribution suggests a complex relationship between science and socio-political entities that underlie research

agendas. That being said, I only suggest that there is a concern in the field about these issues.

As a subcategory of socio-political concerns, a theme emerged that I labeled 'science and education as cultural activities'. This code is partially an in vivo code from my interviews with both Dr. Raichle and Dr. Stigler, though they each emphasized only one of the two. While discussing the benefits for the field of helping students and post-doctoral researchers, Dr. Raichle paraphrased a friend of his as saying, "science progresses one funeral at a time." He paraphrased from a book he read, expressing a similar sentiment, "it's futile to convince your colleagues, you have to wait for the next generation." These quotes were obviously both delivered in jest, though somewhat later in the conversation Dr. Raichle stated, "science is a cultural thing as well," implying a slowness of paradigm shifts within the field. Dr. Posner mentioned the difficulty attracting members from the school of Education to the meeting in 1995 and suggested there would be less problem doing so in the current climate, suggesting an attention to this socio-political relationship with research.

Dr. Stigler also spoke in these terms, but about education. When I asked him how well he thought we, as researchers, had responsibly influenced classroom practice, he said: "Almost not at all . . . that's not just because we're not good at it; it's because classroom practices are cultural activities . . . they have evolved over long periods of time . . . they're very difficult to change." He went on to describe the way teachers are able to integrate new material into their prior teaching strategies, but slowly over time. Further, when talking about the benefits of approaching educational contexts and problems as

systems, as opposed to a more traditional view of individual variables interacting, Dr. Stigler stated that he does not yet see this conceptual shift happening in the field of psychology. In this way, the participants framed all three domains that join to form educational neuroscience as “cultural activities”, in that they are slow to shift paradigms and adopt schema-breaking research results.

Future Directions for Success. Each participant placed a heavy emphasis on collaboration moving forward. Dr. Stigler was the most explicit about the role of collaboration moving forward as he said: “I do think that the field requires collaboration between at least three different groups of people.” He specified that they were: a researcher, a designer, and a practitioner. He discussed the respective skills that each of the members brings to the team, but reiterates the essential role of the teacher. “The idea is maybe 20%, but the implementation is 80%.” This articulation of collaborative efforts in educational research seems to me to be potentially very powerful. Dr. Stigler mentioned a couple obstacles to this approach, one being that many researchers might not be accustomed to not taking the lead on a research team, but thinks nonetheless, this is the way forward. The other obstacle he discussed is that often these collaborative projects are large and working to solve intricate problems, which results in less publications. At his stage of his career, this isn’t a concern for him, but he said he could see how it wouldn’t be prudent for, say, me to think this way.

Dr. Bruer asserted a very similar emphasis on teacher-driven collaborations. He said we should “identify classroom, educational problems and fund collaborations between teachers and basic scientists to develop research-based interventions to address

those programs.” He proposed that not only would this be good for the progress of research, but it would serve as important professional development for both teachers and researchers.

Dr. Posner’s statements agreed with Dr. Stigler’s and Dr. Bruer’s, but approached the idea from the other side. He stated that understanding the brain mechanisms involved with learning does not eliminate the need for other types of knowledge. As an example he said, “Curriculum development does not start with cognitive neuroscience.” And he further offers an analogy that conveys the same necessity for collaboration: “Even though you may be a physics expert, that doesn’t allow you to build a bridge . . . you have to have other skills, practical skills.” Further, Dr. Posner suggested a collaboration of a slightly different kind, as well. He stated that most people recognize that educational applications of neuroscience will need to come from the cognitive branch of the field, as opposed to finer-grained branches. However, he mentioned, cognitive neuroscience relies on those other branches, suggesting an important collaboration between neuroscientists at different levels.

Dr. Raichle also articulated a need for collaboration. He conceptualizes it in terms of thinking broadly about the brain. He described that in order to form deeper, more sophisticated understandings of the brain, and then scientists will need to figure out how to communicate findings and ideas across the scale of analysis boundaries. He said, “it is bringing together, in a common setting, the ability to talk about these kinds of things; and to share views about them.” Further, Dr. Raichle returned to the educational context at the end of our conversation saying, “Even though it’s kind of premature in terms of the

details, we ought to know what they're [teachers] worried about and they ought to know what we're thinking about." To summarize, all of the participants I spoke with emphasized collaboration in learning about real educational problems and then learning how to solve them.

The other major ideas that emerged during our discussions about future progress were specific research topics and frameworks to explore. Moving forward in research Dr. Raichle emphasized the importance of understanding the intrinsic activity in the brain, or the resting state activity. He presented this as more of a conceptual switch from conceiving of the brain as a reflexive, reactionary organ to understanding that it is processing and activating in an organized way before any scientist gets there to give it a task to do. He mentioned that "the other thing that strikes me about this [implications from resting state analyses] is that all of this is moving in a direction of increasing sophistication and subtlety that begins to approach the questions that emerge in understanding human behavior at a very sophisticated level." He did not suggest that it is happening now or soon, in fact he warned that it will take some serious deep thinking in order to get closer to this idea, but he is optimistic that these default mode investigations are moving in that direction. He suggested that brain development is a crucial aspect of neuroscience for the educational community to be aware of. He referenced things like nutrition to talk about the importance of being aware and being sensitive to what is happening in brain development.

Dr. Posner offered a few areas of interest for educational neuroscience research that might be pursued further. He sees possibility in understanding what brain systems are

important for expertise in various domains, as well as in furthering our understanding of brain connectivity – especially as it relates to reading deficits. He acknowledged that “we’re just at the beginning” of that line of work, but that it adds to our understanding of this cognitive system. Dr. Posner also suggested moving from the neuroscience of basic school subjects – i.e. reading and mathematics – to exploring the brain while it performs algebra problems. These all appeal to him as beneficial to the field of educational neuroscience and potentially applicable in the classroom.

Dr. Bruer similarly mentioned one fruitful research problem being “how [do] we move from knowledge that is quite easily and naturally acquired – like counting – to rational numbers, which for some reason people have great difficulty with.” He mentioned fractions in particular as this type of instructional problem. Dr. Bruer discussed the value in further investigating reading comprehension, because much of the work being done is on single word recognition, yet much of the reading deficits are comprehension related. He suggested investigating the nature of transfer of knowledge from one domain to another, as well.

Dr. Stigler’s answer to this question was concerned with new and beneficial paradigm shifts. Therefore, he started by reiterating his emphasis on problem-motivated research, that is, doing research to solve an educational problem as opposed to using a specific method or measuring a specific variable in different contexts. This approach to research is connected to the idea of thinking about the systems of things as well. So, he said, “Variables don’t add up to solutions.” He discussed some of his work using online learning to investigate math instruction strategies, and proposed that online learning

might provide educational researchers with a very powerful way to investigate educational problems in more systemic ways.

To summarize, the presentations during the conference in 1995 were content-oriented. The topics included plasticity, reading, and mathematics, the educational topics on which neuroscience research was focused at the time. Further, much of the synthesis explored the boundaries between the education, psychology, and neuroscience disciplines and how to address the concepts and ideas of one discipline in terms of the others. Much of the neuroscience research presented during the conference became foundational in our neuroscientific understanding of these areas of cognition.

The interviews provided the perspectives of some of the presenters both on the conference, in hindsight, as well as on the current state of educational neuroscience. Beyond these perspectives, another theme that emerged from these interviews was socio-political concern. These concerns ranged from the role of research in informing educational policy and practice, to the difficulty initiating significant paradigmatic change in both the disciplines of education and neuroscience. In addition, the interviews revealed that, according to these researchers, communication and collaboration between researchers and educators are essential for the future success of educational neuroscience. I discuss these findings in more detail, below, in the context of important developments within the field as well as with the research of each presenter.

DISCUSSION

I conducted a qualitative study in order to conceptualize educational neuroscience as a discipline from the perspectives of researchers instrumentally involved in pioneering its formation. I used video of an early conference concerned with integrating neuroscience and education research, in combination with the current perspectives of some of those presenters, to portray a developmental arc of the discipline. I used literature from important areas in the field as a backdrop for understanding these perspectives and to understand the progress of the field to this point. This study provides a new perspective on the definitions, motivations, boundaries, and challenges that have faced and continue to face the discipline of educational neuroscience, namely, that of some of the pioneering researchers involved in the formation of the field.

Since the *Cognitive Neuroscience and Education: Brain Mechanisms Underlying School Subjects* conference in 1995, the discipline of educational neuroscience has grown significantly, and the research careers of the speakers at that conference are no different. While these cognitive neuroscientists, cognitive psychologists, and educational researchers do not place themselves in the center of the field as it is today, the development and evolution of their research since that conference nonetheless provides insights about the field, as many of the topics are potentially influential to our understanding of human cognition and education. These brief reviews of some of their

published work circa 1995 and their most recent contributions to the literature provide a glimpse of how each researcher's career has evolved in order to understand their proximity to educational neuroscience in its current form.

At the conference in 1995, Dr. Merzenich presented evidence of the plasticity mechanisms in the brain. His primary data were from studies in which monkeys were trained for a motor task or an auditory recognition task. He presented the changes in the brain areas of the targeted sensory representations, as well as the synchronicity of neuronal firing after these training sessions. He went on to present data from an intervention he developed with Dr. Paula Tallal that utilized the principles of this plasticity research, specifically the brain's ability to re-organize given proper stimuli. This intervention aimed to improve children's language skills through temporal processing training and was quite successful. In fact, this intervention served as the foundation of the company they subsequently started, called Scientific Learning.

Since 1995, Dr. Merzenich's plasticity research has developed along with these commercial and therapeutic endeavors. One of his most recent articles reviewed and summarized the neuroscience of brain plasticity to illustrate how this knowledge has the potential to change the shape of therapy for brain-based disorders and diseases (Merzenich, Van Vleet, & Nahum, 2014). The authors suggested that because this reorganization capability of the brain is now known to continue throughout the lifespan, the principles of plasticity can be used to create training therapies for everything from schizophrenia to general age-related cognitive impairments (Merzenich, et al., 2014). The

authors admitted that these are future potentials, but reaffirm that brain plasticity-based therapeutics may be able to drive a “re-normalizing for distorted brain systems” (p. 12).

In another recent article, Dr. Merzenich and colleagues presented a new internet-based cognitive training intervention for children with Attention Deficit Hyperactivity Disorder (ADHD) (Mishra, Merzenich, & Sagar, 2013). While this intervention is still being evaluated, it is presented as a specifically targeted and personalized cognitive training program that may serve as an alternative to the stimulant medications currently being used to treat ADHD (Mishra, et al., 2013). The principles of brain plasticity in general, and this concept of remediation for ADHD in particular, are directly relevant to educational practice. If these computer-based interventions are successful in utilizing the brain’s natural re-organization ability in order to treat learning deficits, then student academic achievement would be greatly improved. It seems that in order for these therapies to be applicable for learning disabilities, it will be necessary to fully understand the neural organization and circuitry involved before designing and applying such specifically targeted remedies.

Dr. Raichle’s presentation at the 1995 conference was about the neuroanatomy involved with single word recognition. The studies he presented were in collaboration with Dr. Posner and Dr. Carr. The experiments were foundational in terms of our understanding of the brain areas involved in reading, as well as establishing a paradigm for investigating complex cognitive processes with neuroimaging techniques. Dr. Raichle was also involved with the discovery of blood oxygen level dependence (BOLD) in the brain, which forms the basic unit of measurement in FMRI. As he mentioned in his

interview, some of the interesting findings from his work with Dr. Posner sparked his interest in the default mode network, or the intrinsic, task-independent activity of the brain. He has continued to study this resting state connectivity at the metabolic level, as well as the level of neural circuitry.

For example, in one recent study, Burton, Snyder, and Raichle (2014) examined the resting state functional connectivity in early blind humans. They found significantly greater connectivity between the visual cortex and regions typically associated with memory and attentional control in this population than in typical, seeing populations. Further, they found that the visual cortex showed less-than-typical connectivity with other, non-deprived sensory cortices. The authors stated that these findings suggest a suppression of inter-sensory distracting activity and that the visual cortex becomes more incorporated into attention and recall systems of the brain (Burton, et al., 2014). These findings are not directly relatable to education, though Dr. Raichle suggested that a deep understanding of this intrinsic brain activity (default mode network) will lead to a more sophisticated understanding of human behavior (from interview).

Dr. Raichle studies the metabolic activity of the brain. Specifically, he and his colleagues recently investigated the role of aerobic glycolysis in the adult human brain (Goyal, Hawrylycz, Miller, Snyder, & Raichle, 2014). Aerobic glycolysis is defined as “nonoxidative metabolism of glucose despite the presence of abundant oxygen” (p. 49). This process accounts for 10-12% of glucose used in the adult human brain, but is increased significantly in children, when synaptogenesis rates are high. The authors concluded from their investigation that aerobic glycolysis supports developmental

processes in the brain and particularly those of synaptic growth and formation (Goyal, et al., 2014). Again, this metabolic level of analysis is quite distant from classroom applications. However, comprehensive knowledge of how the human brain functions will benefit every field in which humans are the objects of inquiry.

In 1995, Dr. Posner's presentation went hand-in-hand with Dr. Raichle's presentation, and was about the neural circuitry involved with single word recognition. He presented EEG data about the time course of activations involved with single word recognition. One of the main takeaways from this presentation was that the first ERP detected was in the frontal lobes along the midline of the brain. This implicated an attentional system that came online during non-automated tasks.

Following the conference, Dr. Posner became interested in the role of attention in high-level cognitive tasks. He was instrumental in the discovery and mapping of the development of the attentional control systems, a line of inquiry that has blossomed into a neuroscientific investigation of self-control and self-regulation. A recent article by Dr. Posner and colleagues presented evidence for a training program that improves students' self-regulation (M. I. Posner, Rothbart, & Tang, 2013). This paper essentially combined the knowledge of the attentional control networks and their development with the concepts of brain training, similar to Dr. Merzenich's research. This article differs though, in that it presented a meditative training program to train brain states as opposed to cognitive skills (M. I. Posner, et al., 2013). M. I. Posner and Rothbart (2014) expanded on their previous paper by suggesting the connection of attentional networks to memory areas as being important for the cataloguing of new information. The authors proposed

that “this network provides a mechanism for how attention influences learning” (p. 14), and that understanding attentional control systems related to knowledge acquisition can potentially contribute to content-domain-general educational applications (M. I. Posner & Rothbart, 2014). This potential is supported by the recognition that self-regulation is an important factor in academic achievement (Zimmerman & Kitsantas, 2005).

In another article, Dr. Posner and colleagues traced the development of these attentional systems through a longitudinal study from 7 months to 7 years old (M. I. Posner, Rothbart, Sheese, & Voelker, 2014). They found that temperamental measures during infancy related to self-regulation measures at 7-years old and while the brain areas involved were present during infancy, their connectivity develops and changes over time leading to improvements in self-control (M. I. Posner, et al., 2014). This study focused on an age range that is largely, pre-school age. Still, an understanding of the development of these attentional systems would likely contribute to decisions about school and classroom structures, as well as potential remedial interventions to improve these meta-cognitive abilities.

Dr. Posner has further contributed, directly, to the progress of educational neuroscience with his chapter tracing the evolution of the field in the context of neuroimaging techniques and tools (M. I. Posner, 2010), as well as providing the forward to a recent educational neuroscience textbook (M. I. Posner, 2013).

Dr. Carr’s presentation at the conference in 1995, again, was an extension of the single word recognition and reading data. He took a conceptual approach to reading and framed the skill as a problem that the brain has to solve. Through this inquiry, he

demonstrated the goal in the acquisition of reading was to integrate the visual processing system with the language processing system. He offered the VWFA as the connection between these two systems and used evidence from lesion patients to demonstrate that this area communicated to both the object recognition area (visual system) and the phonological awareness area (language system). The thrust of this presentation was that whole word recognition is the foundation of the reading process.

Since 1995, Dr. Carr has remained active in cognitive neuroscience, broadening his inquiries from reading processes to writing, mathematical computation, and problem solving. In one recent study, Dewey, Seiffert, and Carr (2010) studied how people determined when they were in control of objects. The authors used a virtual boat navigation task using a joystick to manipulate the participants' sense of control of the boat. They found that random discrepancies between motor action and boat behavior decreased judgments of control unless the boat was brought closer to the goal. In other words, even when discrepant from joystick inputs, increased success resulted in increased sense of control (Dewey, et al., 2010). The authors concluded that subjective control was influenced by consistency between motor action and their effects, but was also mediated by perceived success and goal achievement.

In a related study, Dewey and Carr (2013) studied the influences on the participants' sense of agency on a tone-producing task. The authors defined sense of agency as "the perception of willfully causing something to happen" (p. 155), and found contiguity, or the lack of delay in tone onset, to be the main determinant of the participants' sense of agency. These psychological findings are not directly relatable to

educational contexts, however the sense of agency and control could potentially influence self-efficacy, or other educationally pertinent constructs.

Dr. Neville's presentation in 1995 was about the environmental and experiential effects on the development of sensory systems in the brain. She presented evidence of the reorganization of the auditory cortex in congenitally deaf participants to enhance peripheral visual field recognition as compared to hearing participants. This suggested that the peripheral visual system was more malleable via early sensory experience than other aspects of the visual system. Further, she compared the organization of the language systems in these populations and determined that American Sign Language speakers recruited more bilateral areas for language processing when compared to English speakers.

Her research since 1995 has largely continued in this direction, as she has investigated across the lifespan in order to distinguish between the brain systems which are largely fixed and those that can be significantly modified by experiential intervention. In one recent article, Batterink and Neville (2013) used EEG recordings to examine how adults were able to process syntactic information during a novel distraction task. The findings of this study showed that syntactic violations that were not consciously detected produced a neural response pattern nonetheless (Batterink & Neville, 2013). This result suggests that even high-level cognitive processing such as recognizing syntactic errors can occur outside the conscious awareness of adult participants. This finding demonstrates the effortlessness with which humans can process language, though this is not directly applicable to educational contexts (Batterink & Neville, 2013).

In another study, Neville, et al. (2013) used the neuroplasticity research – specifically for selective attention – to develop a family-based training program for preschool children. They found positive results from electrophysiological measurements of brain functions supporting selective attention, as well as psychometric evaluations of the treatment group participants. This study is similar to the work by Dr. Merzenich and Dr. Posner, and if these kinds of cognitive training interventions, both for skills and mind states, are successful and the results are successfully replicated, they may be of significant value in improving these skills in at-risk or deficient students.

Dr. Stigler’s presentation in 1995 was about the role of non-universal representations on future numerical processing. He presented evidence that numerical conceptual knowledge, as taught, determined future conceptualization of number representations. Further, he discussed evidence that different mathematics instructional styles establish different expectations of students for future math processing.

Since the conference in 1995, Dr. Stigler continued his research into the teaching and learning of mathematics from a cognitive psychology perspective. He has focused largely on improving math instruction, which led him to investigating instructional delivery methods such as video lessons and online learning environments. While the majority of his research has been with K-12 populations, he is currently working on math instructional issues at the community college level.

In on recent article, Dr. Stigler and colleagues presented information about the level of conceptual mathematics knowledge of community college students. They suggested that these students prefer to use previously memorized procedures instead of

drawing inferences about the current problem or representations (Richland, Stigler, & Holyoak, 2012). The authors recommended refinement of K-12 classroom instruction is necessary to encourage this conceptual approach to math problem solving. Further, the authors pointed to literature that demonstrates other cultures teach mathematics more conceptually, which is correlated to high student performance. This paper is directly related to the classroom, though does not include a neuroscientific approach. As Dr. Stigler pointed out in his interview, he is an educational psychologist, not a neuroscientist, so this is not surprising. It is clear, however, that these findings are certainly informative for classroom practices.

At the conference in 1995, Dr. Dehaene presented neuroimaging evidence for his triple-code model of numerical processing and calculation. This theory, in an evolved form, still serves as the conceptual model for a majority of the neuroimaging investigations into arithmetic processing. Since that conference, Dr. Dehaene has investigated a number of topics including the neural correlates of numerical cognition, reading processes, and consciousness. His authorship of *The Number Sense* (1997) and *Reading in the Brain* (2009) mark significant treatment of the neuroscience information on those subjects for the average reader, though much of his recent is exploring conscious versus unconscious processing.

In one recent paper, Charles, King, and Dehaene (2014) set out to test a dual-route model of error detection in the brain before external feedback. The model suggested this error detection mechanism results from the confrontation of a quick, unconscious signal based on a direct sensory-motor pathway, and a second, slower, and conscious intention

code that computes the task-required response. The authors used multivariate decoding methods on magnetoencephalography (MEG) and EEG data from adult human participants. Their results corroborated the dual-route model of intrinsic error detection, and suggested that a distinct conscious representation of the desired task response is necessary for this error detection mechanism. While not yet applicable to educational contexts, a better understanding of the brain's intrinsic error detection mechanisms would potentially inform the self-efficacy literature in educational research. Obviously more research is needed, however the combination of these lines of inquiry may provide insight into a neural influence on self-efficacy to be remedied.

In another paper, Dehaene, Charles, King, and Marti (2014) reviewed the behavioral and neuroscientific data about the computations underlying conscious processing. This review demonstrated that much of the brain's computation can be performed un-consciously, and that an amplification, global propagation, and integration of brain signals characterize conscious perception. The authors concluded that it is important to carefully distinguish between conscious perception and selective attention and that one way to think about conscious perception is that it ignites a non-linear distributed network of brain areas. This discussion about consciousness is very far from mature in the literature and therefore not in the areas of educational applications or implications, at this time.

Dr. Wynn's presentation in 1995 was about the early numerical representation and reasoning abilities of infants. She presented evidence from infant habituation studies for the claim that infants have the ability to distinguish between small quantities and

accurately expect outcomes of simple +/- 1 calculation. Since then, her research has continued with this theme. Her current research aims to understand the inherent structure of the human mind before experiential influences are presented. Dr. Neville has extended her work with infant numerical cognition to investigate how infants categorize individuals in order to discover the social understanding of infants.

In one recent study, Dr. Neville and colleagues examined the development of attitudes toward similar and dissimilar others in infancy. Their findings suggested that infants as young as 9-months prefer individuals who treat similar others kindly and dissimilar others poorly. Further, this response was increased in 14-month-old infants, a developmental trend that suggests the ability to compare and contrast personal attributes increases in powerful ways during this time of life (Hamlin, Mahajan, Liberman, & Wynn, 2013). These findings do not have direct implications for education in part because of the age range of the participants. However, understanding how social judgment develops may lead to interesting changes to educational practice in the future.

In another study with 5- to 10-year-old children, Sheskin, Bloom, and Wynn (2014) examined the aversion of young children to receiving less than others, but not to others receiving less than themselves. This study replicated previous findings that children will take a measured loss to avoid being at a disadvantage, and further, that 5- and 6-year olds will spitefully take a loss to ensure that they remain better off than another. The authors drew connections to the concept of fairness as a learned response, and suggested that initially humans may prefer others to receive less than they receive (Sheskin, et al., 2014). These ideas are indirectly related to classroom considerations, as it

may benefit teachers to understand that this ‘fairness’ concept is learned just as school subjects are. How to implement these findings directly to educational practice, however, requires further research.

Dr. Case presented the development of one of the central conceptual structures in his neo-Piagetian theory of cognitive development. This conceptual structure was formed by the integration of the counting system and the magnitude representation system in children ages 4-6.5. One of his emphases during this presentation was the significant impact of socioeconomic status (SES) on children’s school readiness and academic performance. His research after the conference continued to parse the implications of his theory and use those implications to develop educational interventions for struggling and low-SES students. This research continued until his death in 2000. For this reason, it was difficult to locate a curriculum vita, or another list of publications by Dr. Case between the years 1995 and 2000. It appears his last co-authorship was a book chapter about the role of SES in children’s early cognitive development and school readiness (Case, Griffin, & Kelly, 2001). As you can see, these topics lack a neuroscientific perspective, though they are directly aimed at improving educational contexts.

Dr. Siegler’s presentation in 1995 was about children’s discovery of new problem solving strategies for arithmetic calculation. He presented the microgenetic experimental paradigm, as mentioned previously, in order to examine the process of discovery in fine-grain detail. The presentation of ‘challenge problems’, or problems designed to elicit the target strategy, did in fact encourage strategy discovery and future use.

Since the conference in 1995, Dr. Siegler's work has continued to explore the cognitive development of children, specifically their math and science reasoning. In one recent article, Laski and Siegler (2014) examined the relationship between number board games and learning from those games. The authors tested the hypothesis that encoding of numerical-spatial relations in number board games facilitated the encoding of these relations. The authors utilized the microgenetic design, as described in his presentation, in order to investigate the effects of the type of counting procedure on child learning. They found that having kindergarteners count-on from their current number promoted their encoding of numerical-spatial relations and improved their number line estimates, and numeral identification as well, as opposed to a count-from-one strategy (Laski & Siegler, 2014). This has obvious classroom implications, though does not include a neuroscientific perspective. Nevertheless, it may be interesting to examine the neural correlates of these findings to understand the underlying processes involved with this numerical-spatial encoding.

In another article, Bailey, Siegler, and Geary (2014) investigated the early mathematical knowledge that predicts fraction knowledge in middle school students. This longitudinal study used multiple psychometric assessments of numerical and cognitive abilities to predict future fraction knowledge. They found that whole number magnitude knowledge of first grade students predicted fraction magnitude knowledge in middle school and that whole number arithmetic ability in first grade predicted fraction arithmetic ability in middle school (Bailey, et al., 2014). This suggests a direct relationship between early whole number knowledge and later understanding of fractions,

which may aid in remedying the perennial classroom difficulty in teaching fractions to students. Again, this study lacks neuroscientific evidence, though is directly related to student and classroom outcomes.

Dr. Bruer's presentation at the conference in 1995 was a summative presentation at the end of the proceedings. He summarized some of the data that he found interesting and framed them in terms of real educational problems. His 1997 paper, *Education and the brain: A bridge too far*, remains a central piece in the meta-level discussion of educational neuroscience as a field.

Since 1995, Dr. Bruer has remained the President of the James S. McDonnell Foundation, which supports research in the areas of cognitive psychology and cognitive neuroscience. He has also remained skeptical of the role of neuroscience in improving educational practice and continued to question the convergence of these fields. In one recent article, he mapped the development of the field of cognitive neuroscience and discussed the impact of non-invasive neuroimaging on the development of our understanding of the biological foundations of human cognition (Bruer, 2009). This overview did not address educational applications of cognitive neuroscience, but provided an in-depth analysis of the development of cognitive neuroscience as its own field.

In another recent article, Bruer (2010) used co-citation analysis to provide a similar overview of the research, though in this case his focus was the emergence of attention as an important construct in human cognition from both the psychological and cognitive neuroscience literature. This link, while not directly related to education,

provides a blueprint of how evidence from both psychology and cognitive neuroscience are able to converge and inform an area of interest for the educational community.

Further, these attentional processes are certainly of interest in educational contexts, offering a potential connection of this research back to educational practice.

As the careers of these pioneering researchers have branched into many areas of cognitive, neuroscientific, and psychological research, the topics of inquiry within educational neuroscience, as well as the number of researchers pursuing them, have grown and progressed considerably. The knowledge base of educational neuroscience has increased, as has our understanding of the processes of learning and the specifics regarding experiential influences on these learning processes. Along with creating new knowledge and understanding, educational neuroscience has been able to corroborate and refine ideas and concepts previously established by cognitive and educational psychology. I briefly discuss two areas of research that offer interesting and insightful implications for how we view the learner as an individual, in terms of abilities and *disabilities*. Specifically, I review some of the recent developments in the mathematics literature, as well as the domain-general research into the topic of intelligence/reasoning. These reviews provide a glimpse of (a) the ways in which the literature has progressed and the knowledge base expanded, and (b) an example of a domain-general area of research that provides context about learning and educational contexts. As mentioned previously, this overview is not meant to be comprehensive, but only to provide a basic outline and understanding of a research area through which educational neuroscience may provide implications for educational practice.

Since 2004, neuroscientific investigations into arithmetic processes have increased dramatically (Byrnes, 2012). Arsalidou and Taylor (2011) performed a meta-analysis of 53 fMRI studies of number processing and calculation tasks, primarily in healthy adult subjects. The authors found a significant number of brain areas likely to be active during number processing and arithmetic, often overlapping, but also involving some process specific areas. They proposed that while these overlapping regions exist, the areas in which they differed were most noteworthy. Specifically, they discussed prefrontal areas associated with working memory (Arsalidou & Taylor, 2011). Their study found that calculation tasks elicited these prefrontal activations more so than number tasks, which suggested the need for more cognitive resources for calculations than for basic number processing. While this may seem intuitive, it is not incorporated in the triple-code model of arithmetic processing (Dehaene & Cohen, 1995; Dehaene, et al., 2003), the driving conceptual framework for much of the neuroscientific investigations of these arithmetic processes (Arsalidou & Taylor, 2011). Further inquiry into calculation processes showed that addition, subtraction, and multiplication differentially recruit prefrontal and parietal areas. In other words, these processes are distinguishable based on the patterns of brain activations they elicit. While all three processes involved both hemispheres, addition activity was left hemisphere dominant, subtraction was either bilateral or left hemisphere dominant, and multiplication was primarily right hemisphere dominant.

The authors concluded by recommending revision to the triple-code model of mental arithmetic to incorporate the cingulate gyri, the insula, cerebellum, as well as

prefrontal regions associated with working memory (i.e. dorsolateral and frontopolar areas) (Arsalidou & Taylor, 2011).

As in the reading literature, deficits in arithmetic skills receive as much, if not more, attention than typical arithmetic processing (Ashkenazi, Mark-Zigdon, & Henik, 2009; Askenazi, Black, Abrams, Hoefft, & Menon, 2013; Butterworth, Varma, & Laurillard, 2011; Landerl, Bevan, & Butterworth, 2004; Mussolin, Mejias, & Noel, 2010; Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007). Results from both behavioral and neuroimaging studies demonstrate that numerical magnitude processing deficits may be at the root of dyscalculia (Ansari, et al., 2012). Dyscalculia is defined in a myriad of ways, but all definitions revolve around the severe disability in learning arithmetic (Butterworth, et al., 2011). In their review of the dyscalculia literature, Butterworth, et al. (2011) highlighted that neuroimaging evidence shows reduced gray matter volume in relevant brain regions, reduced activity in those regions, *and* reduced connectivity between these number processing relevant brain areas. These three deficits represent different impairments that may manifest similarly in behavior. For this reason, individual differences in arithmetic and numerical processing is receiving significant attention in both psychological and neuroimaging research.

One example of the investigation of individual differences in math learning difficulties is a study by Bartelet, Ansari, Vaessen, and Blomert (2014) in which they used a factor analysis of 226 third to six grade students to distinguish six subtypes of learning difficulties in mathematics learning. The authors were able to classify the struggling students into the categories based on the specifics of their individual

difficulties with math. The categories included: “(a) a weak mental number line group, (b) weak ANS group, (c) spatial difficulties group, (d) access deficit group, (e) no numerical cognitive deficit group, and (f) a garden-variety group” (Bartelet, et al., 2014, p. 657). The heterogeneity of these groups suggested that different approaches to remediation are necessary depending on the students’ particular weaknesses.

Additionally, while this was a psychometric experiment utilizing behavioral data, there are implications for further investigation through neuroimaging methods (Bartelet, et al., 2014). Understanding which aspects of the numerical processing networks are affected for each subtype of difficulty may provide information about the underlying deficit and therefore informing intervention strategies.

Much of the studies of arithmetic processing focus on the role of numerical magnitude processing and its relation to arithmetic outcomes due to the convergence of results across species and experimental methods (i.e. neuroimaging, behavioral measures, neuropsychological patients) (Ansari et al., 2012). In fact, this approximate magnitude system is often considered foundational in the development of more advanced math abilities, in part due to its presence and apparent maturity in non-human primates, as well as human infants (Ansari, et al., 2012).

While many studies support the role of numerical magnitude processing in predicting future arithmetic achievement, Lyons, Price, Vaessen, Blomert, and Ansari (2014) illuminated some complexity within this issue. In this study, the authors collected psychometric data of eight basic numerical skills and three non-numerical skills from a sample of 1391 students in grades 1-6. They aimed to examine the relative importance of

these basic skills for early math education across a significant developmental age range. The comprehensive inclusion of numerical skills demonstrated in the literature to be relevant to arithmetic performance, along with the very large sample and age range, provided significant strength to the results of this study. Lyons et al. (2014) used backwards, stepwise elimination in order to establish the most parsimonious regression model to fit their data.

They found “basic symbolic number processing” (p. 723) to account for the majority of unique variance in arithmetic ability in their sample. Additionally, they found that dot comparison (i.e. approximate magnitude comparison) did not predict unique arithmetic variance, which contradicts many studies showing the predictive ability of this numerical skill (Lyons, et al., 2014). The authors stated, “Our results therefore provide a strong caution to claims about the importance of approximate number processing for more complex math skills” (p. 723). In other words, it is important to reevaluate the role of this approximate number system in the development of future math abilities. The authors did offer a caveat to this finding, namely that their data speak to the role of these skills after the onset of formal schooling, and not to the importance of the approximate magnitude system before this structure is in place.

Another interesting finding from this study was a developmental trend in predictive power of particular numeric abilities. Specifically, number line estimation was a strong predictor of arithmetic ability in grades 1 and 2, but this faded in older students. This suggests a nuance to the development of math ability in that students may utilize certain numerical skills differently at different ages (Lyons, et al., 2014). These dynamic

relationships are important for practical considerations such as instructional strategies and curriculum development for elementary mathematics education.

Additionally, educational neuroscience is providing new insights into domain-general cognitive abilities in order to better understand academic achievement. For example, Intelligence has very likely been studied more and for longer than any other human cognitive or psychological constructs, yet its essence remains elusive and its consequences, problematic. Further complicating the matter, researchers in education and psychology have not been able to establish a consensus definition of intelligence (Roberts & Lipnevich, 2012). Educational psychology has made great strides in disentangling the abundance of slightly variant definitions, proposing and investigating theoretical models of intelligence, and halting the over-interpretation of intelligence in order to diminish its high-stakes value in society. Although, accomplishing these goals has not come easily.

Educational neuroscience has recently begun contributing to the understanding of intelligence by examining the underlying neural circuitry associated with the construct. For 200 years, scientists have considered that the brain held the key to the accurate measurement of intelligence (Gould, 1996), however it was not until much more recently that neuroimaging methods provided the ability to search for the illustrious construct within the brain. As mentioned previously, there is not a consensus definition of intelligence within educational psychology, which provides an opportunity for contributions and understanding from the discipline of educational neuroscience. Neuroimaging studies initially aimed to discover the neural substrates associated with the general factor of intelligence, or 'g'. The concept of 'g' was asserted by Charles

Spearman in order to account for significant correlations between different aptitude tests (Spearman, 1904). This general factor of intelligence was defined as a mental energy that is utilized in order to complete cognitive tasks.

However, attempts by educational neuroscience to parse and verify the neural substrates of multiple psychological theories of intelligence, for the most part, have not panned out. Further, these theoretical discussions move the discussion farther away from - not closer to - influencing classroom contexts. With this in mind, educational neuroscience began positing theories of intelligence and giftedness of their own.

One prominent neuroscientific theory of intelligence is known as the Parieto-Frontal Integration Theory of intelligence (P-FIT) (Jung & Haier, 2007). This theory asserts a distributed network including areas in the frontal lobes and association areas in the parietal lobes. Specifically, the brain regions included in the P-FIT network are: the dorsolateral prefrontal cortex, the inferior and superior parietal lobule, the anterior cingulate, as well as regions in the temporal and occipital lobes (Jung & Haier, 2007). P-FIT theory was conceived through the analysis of 37 neuroimaging studies from which the relevant regions were extracted. Follow up studies have both verified and extended the original P-FIT theory of intelligence.

These theories are necessarily couched in the same constructs that were developed psychology, as the tasks used to measure reasoning aptitude are often used as the tasks for neuroimaging studies. One example of neuroscience using psychological theories to understand reasoning in the brain is the investigation into the neural networks associated with the theory of fluid and crystalized ability (Horn & Cattell, 1966). Crystalized ability

is ability reflecting the influences of formal learning, acculturation, and familiarity (Roberts & Lipnevich, 2012). Fluid ability, on the other hand, refers to reasoning and novel problem solving ability. Fluid ability, or fluid reasoning, is a domain-general skill, and has been implicated in contributing to individual differences in general intelligence. In support of this implication, fluid reasoning was shown to be positively correlated with the volume of gray matter in the lateral and medial prefrontal cortex (Gong, et al., 2005) and the volume of gray matter in this region of the prefrontal cortex has been shown to be related to tasks involving 'g'. This mediated correlation suggests a connection between fluid reasoning and 'g'. Additionally, fluid reasoning is interesting to educational neuroscientists in part because this general novel problem solving ability is the gold standard of assessing learning in any scholastic domain.

Despite this neuroscientific interest in fluid reasoning, Kalbfleisch, Van Meter, and Zeffiro (2007), suggested fMRI studies to date were not measuring true fluid reasoning. The claim is, in essence, one of ecological validity – a pervasive concern in educational neuroscience. Specifically, due to the nature of fMRI research, participants are traditionally required to practice extensively in order to become familiar with the task and with the response method (i.e. the button boxes a person uses to press or 'key' a response) and in order to increase accuracy and statistical power during scanning. Kalbfleisch et al. (2007) argued that this training period eliminates the 'novel problem solving' that is associated with fluid reasoning, a claim that is supported by the plasticity literature and observed practice effects (Ansari, et al., 2012).

Kalbfleisch et al. (2007) conducted an fMRI experiment without significant training pre-scanning and found a more distributed network of brain activations associated with novel problem solving, or fluid reasoning. They referred to this network as the cerebrocerebellar system, and it includes the left cerebellum (Lobule VI), the right middle frontal gyrus, the right superior parietal lobule, the left lingual gyrus, and the subcallosal gyrus. Kalbfleisch et al. (2007) assert that the subcallosal gyrus, in combination with this distributed cerebellar system, provides individuals with an internal system of detection aimed at managing uncertainty. As the authors stated in their conclusion, this finding illustrates that the brain has a system for monitoring accuracy even when a person receives no feedback about their performance. This study suggests that fluid reasoning is a more complex construct than previously granted. The paradigm of this experiment offers an example of an ecologically valid neuroimaging study of fluid reasoning as it pertains to novel and time dependent problem solving.

Another neuroscientific theory of the expression of intelligence, or giftedness, proposed by Kalbfleisch (2009) attempts to bridge the gap between the micro-level processes in the brain and the macro-level processes in educational contexts. This 'state of mind' theory is derived from findings from intelligence, creativity, and twice-exceptionality and proposes that the expression of giftedness is the result of a combination of environmental, psychological, and neural factors that lead to a gifted 'state of mind'. This theory, while difficult to test, attempts to articulate the importance of preserving the ecological validity of cognitive processing and introduces another

example of the level of complexity needed to better understand our conceptualization of expertise and what it takes to succeed in an educational setting.

Further, in an attempt to illuminate the complexity of this ‘state of mind’ theory of high cognitive performance, Kalbfleisch and Loughan (2011) explored the influence of IQ discrepancy (IQD) on executive function in children with high functioning autism. IQD is defined as the difference between the intelligence test’s subscales in an individual: verbal and performance intelligence. The authors found that when IQD remained within one standard deviation (15 points), the executive function profiles of children with high-functioning autism demonstrated deficits in many subscales of the executive function assessment. This included problems with behaviors such as inhibiting inappropriate behavior, shifting between tasks, initiating new activities (homework, chores, etc.), working memory, planning and organization, and monitoring their behavior and other things happening around them. These observed deficits were consistent with the previous literature that ascribes this pattern of deficits in children with high-functioning autism.

However, the surprising finding was that as this discrepancy increased above one standard deviation (favoring VIQ), deficits were no longer measured for skills related to working memory, planning and organization, and monitoring (Kalbfleisch & Loughan, 2011). In other words, the students still demonstrated certain executive function deficits in the areas of inhibit, shift, and initiate, but the increased discrepancy in favor of verbal intelligence was correlated with fewer deficits in the some of these other subscale areas of executive function. This result suggests the potential importance of high language ability to support and accommodate some executive function deficits. This study also

illustrates the level of complexity among the various cognitive functions so often associated with academic success. A deep understanding of these interactions and complexities will help discern how schools and educators may accommodate students with certain cognitive deficits in a way that enables success while simultaneously remediating specific weaknesses.

In this way, the neuroscientific study of reasoning provides insight into an important, domain-general ability, namely novel problem solving, that has a significant impact on student achievement and academic outcomes. Further, this line of inquiry demonstrates the intimate relationship between these learning abilities and learning disabilities, a fruitful perspective as the field attempts to translate our knowledge of disabilities like dyslexia and dyscalculia into an understanding of typical, and even above average educational processes. There is no doubt that our knowledge of reasoning is not as mature as that of mathematics or reading. However, current research suggests important implications for improving student achievement through improving problem solving ability, as the research continues to develop.

Interpretations

In the context of this investigation, the perspectives of these pioneering researchers have evolved and progressed over time since the conference in 1995. During the presentations at the conference, there was a sense of optimism despite unfamiliarity. Some researchers had begun mapping the neural systems involved with basic cognitive tasks, but at the time, the field of *cognitive* neuroscience was not established yet. fMRI was a new and somewhat opaque neuroimaging technique, though it would soon burst

onto the scene. There was an initial inquisitive enthusiasm in the presentations at the conference in 1995, because these researchers were investigating the potential of newly developing neuroimaging techniques to not only inform our understanding of cognition, but also to further contribute to educational practice.

This enthusiasm was present in the media and political spheres during this time, and that enthusiasm seems to have persisted through the 2000's until now. This enthusiasm and attention – that Dr. Bruer wearily referred to as “hype” – has definitely revealed itself to be a double-edged sword. For example, the neuroscientific conclusions on which the national policy program Early Head Start have been questioned in the book *The Myth of the First Three Years* (Bruer, 1999). Beyond this, the field itself revised their schema from these rigid, deterministic critical periods from age 0-3 being a ‘make-or-break’ time for the development of cognitive skills (OECD, 2007). Additionally, the plasticity literature is beginning to reframe the ‘aging brain’ in a more optimistic, malleable light (Alwis & Rajan, 2014; Gutches, 2014). While this is not directly relevant to education, it is relevant to concerns about determinism and reductionism within the field of educational neuroscience. Specifically, every bit of evidence from neuroimaging suggests the brain is designed as an efficient learning organ and remains that way throughout the lifespan. The brain certainly changes over time, however, and current undertakings in educational neuroscience are aimed at a full understanding of how the brain develops and changes, with an emphasis on the school age years for obvious reasons.

Some remain skeptical about the motives of the science in cases like the ‘age 0-3 critical period’ theory, though it is not clear at this point, if that was the result of a misrepresentation of the research findings or a misinterpretation of those findings. Further, a third option is likely, and that is the fact that the excitement and attention surrounding the potential of the field led to the hasty generalization and application of research findings.

Nevertheless, the fact remains that neuromyths have haunted the discipline of educational neuroscience from its conception to its present form. As researchers who care to make a difference in educational communities, this should cause us great alarm. These misconceptions not only undermine the responsible and accurate findings in the field, but most importantly and most urgently, they are the root of the implementation of inappropriate curricula, instructional strategies, and policy reforms. It is imperative for the success of the field that educational neuroscientists monitor and actively participate in the responsible, clear communication of their results, in order to ensure that they are not over-generalized in the market place for financial gain.

Each of the four senior researchers that I interviewed emphasized the importance of communication and collaboration as a partial solution to these issues. Dr. Stigler and Dr. Bruer suggested that incorporating teachers into the research process will help researchers ask and answer more educationally relevant research questions. Dr. Posner and Dr. Raichle suggested open, bi-directional communications between scientists and teachers. Dr. Raichle also recommended conducting studies with larger sample sizes, as this would both add to the generalizability of findings (lessening the chance or impact of

generalizations), as well as providing the opportunity to observe extremely subtle differences in brain function that possibly result in behavioral and cognitive abnormalities. If the high cost of neuroimaging tools is prohibitive of large sample sizes, then independent replication and verification becomes even more indispensable for our purposes.

Additionally, we need to encourage teachers to become more scientifically literate in order to be able to discern baseless claims of ‘brain-based’ programs from actual, responsible conclusions from neuroscience research. This requires not only providing opportunities for them to learn (i.e. teacher training programs and professional development), but also providing teachers with the time and space to pursue these opportunities. Teachers are often juggling new instructional policies and curricular implementations (i.e. Professional Learning Communities, teaching to academic benchmarks, etc.). Further, as Dr. Stigler pointed out in his interview, as well as in his book (co-authored with James Hiebert), The Teaching Gap (1999), teachers’ practices are ingrained in their cultural practices. Therefore, as researchers, we need to empower teachers to be active participants in sense making. Geake and Cooper (2003) suggested that “a return to the fundamentals of teaching and learning, [with which educational neuroscience is concerned] might even help reclaim the education agenda” (p. 11), thereby returning a sense of agency and autonomy to the teacher.

In our conversations, Dr. Raichle and Dr. Posner emphasized the importance of researcher-to-researcher communication. “The ability to, the willingness, the *enjoyment* of reaching out and talking to people at other levels of analysis, and

treating each other with mutual respect in terms of how we view these things, I think is just hugely important here,” said Dr. Raichle. In other words, respectful communication across levels of analysis is important for the progress of any discipline of research. What does this mean for educational neuroscience? The interdisciplinary aspect of the field complicates these lines of communication; though it is possible and important to be able to communicate between the fields of neuroscience, psychology, and education. Many prescriptive articles about the discipline support this idea from Dr. Raichle by introducing the idea of a “bilingualism,” (or in this case, perhaps, tri-lingualism) to allow neuroscientists, educators, and cognitive psychologists to understand each other on their respective levels of analysis.

For educational neuroscience in particular, the idea of a “translator” has been around for more than thirty years. The ‘neuroeducator’ (Cruickshank, 1981; Fuller & Glendening, 1985), as it was referred to fills this role as being versed in the cognitive theories of learning, the practical issues of classroom management and lesson planning, as well as the neural structures underpinning cognition. I believe it is becoming increasingly possible to obtain this type of multidisciplinary training. As Dr. Posner mentioned in his interview, in 1995 it was difficult to attract members of the school of education to attend the conference, however now there are focused educational neuroscience departments sprouting in higher education institutions around the country, such as Vanderbilt University, Harvard University, and Stanford University. Further, my graduate training may serve as a potential guide for establishing such an actor, capable of crossing the boundaries between education and neuroscience on a professional level,

perhaps paving the bridge. My experience leads me to believe that both researchers and educators would benefit from a comparable educational track. The exact prescription would necessarily need to be tailored to the specific end goal, just as my penchant for research has guided my training.

In my conversation with Dr. Stigler, he described to me an article he had read about the development of aircraft design. “The big break through in aircraft design came with the invention of the wind tunnel. Because suddenly you could, actually very quickly, make different versions of winds and see how they worked.” This description took place in the context of my question about his current research interests. Specifically, Dr. Stigler and his students had been developing and experimenting with different instructional modules in an online learning environment. He told me, “In some senses I think online learning could be like the wind tunnel for studying and approving educational processes.” I not only find this opinion insightful for educational research as a whole, I also interpreted this in the context of improving the discipline of educational neuroscience and our ability to contribute to education. In other words, I believe the use of virtual learning environments has the potential to introduce an avenue toward ecological validity within the neuroimaging experimental paradigm.

In other words, if participants are given an opportunity to become immersed in the virtual environment, the environmental influences may be equal, or approach being equal to the influences present solely within the virtual environment, all but negating the laboratory constraints. Obviously, as Dr. Stigler and his group are currently doing, any evidence gathered in online learning environments must first be verified in physical

classrooms before being applied. However, I believe this to be an opportunity for educational research in general, and educational neuroscience in particular to embrace the complexity of *in vivo* learning environments, and potentially to account for some of those characteristics in the research.

Further, utilizing virtual learning environments in neuroimaging would encourage equal and respectful communication between researchers, practitioners, and designers. Significant input from curriculum designers and designers of virtual environments would be necessary to construct a representative model learning space. Additionally, practitioners would be needed to provide input on the instructional decisions and structural decisions regarding the presentation of content. In addition, the researchers would provide the necessary paradigmatic considerations, ensuring an adequate number of data points, of a control state, etc. I believe this collaborative research paradigm is ready for implementation and ready to enable the investigation of complex, real world, educational problems in neuroscientific experiments.

Another outcome of my analysis of educational neuroscience from 1995 to now from the perspectives of senior researchers was the need for continued self-evaluation and self-reflection as a discipline. Dr. Posner suggested current neuroscientific developments such as the discovery of the VWFA and the identification of specific connectivity deficits in subjects with dyslexia contribute to improving educational practice. His position became clearer when he says, “then if you have some information about what brain systems are important in that form of expertise, then you have a chance to apply it.” In other words, knowledge is power, and a deeper, fuller understanding of

what is happening in the brain (or elsewhere) during a specific cognitive skill is critical to practical applications. On the other hand, Dr. Bruer focused more on tangible applications, such as the development of interventions or specific instructional strategies, as he declares contributions from educational neuroscience to educational practice “few and far between.”

Meanwhile, Dr. Raichle expressed true optimism and interest in the potential neuroscience has for understanding complex human behaviors and the slightest, subtle cognitive variations potentially underlying learning disabilities. He emphasized patience stating: “you know, we are not quite there yet, but we certainly have some things . . . that suggest to me that that [understanding the default mode network] is going to be very fruitful [for a more sophisticated look at things like learning disabilities].”

It is clear from my interviewees’ perspectives that there is great cause for both optimism and restraint in educational neuroscience. For this reason, I think it is important to monitor the viability of neuroscience to inform education, and continue the discussions about the conceptual and pragmatic obstacles we face. There have been mistakes in applying neuroscientific information to educational practice and policy, and the discipline will benefit to take that fact and potential recurrence seriously. Continuing to self-monitor and self-reflect as a discipline, acknowledging the limitations of our methods and findings, and maintaining focus on the ultimate goal of improving educational contexts provides a recipe for success and perseverance.

Lastly, we are not there yet. The brain is a complex and sophisticated organ, and it is important that educational neuroscience continue to pursue knowledge and

understanding. The knowledge base of the discipline is definitely larger now than in was in 1995, and the researchers involved with the conference (for the most part) have acknowledged that. At that time, when the wheels were just getting into motion, the field was somewhat compartmentalized by research domain. In the presentations, it is evident that at the time, even the psychologists and neuroscientists who studied the same content area (e.g. math, reading) were unsure about how to cross the boundaries and incorporate one another. The discipline has traveled a long way since the mid 1990's, both in terms of crystallizing as a research field and in terms of our capabilities to measure brain activity with increasing accuracy. That being said, the silo effect can still be felt today, there is more work to be done. As Ansari, et al. (2012) stated, "The groundwork is most certainly laid; now it is time to [continue to] do the hard work in an effort to find new, creative and scientifically-based ways to improve education" (p. 115).

To reiterate, cognitive neuroscience continues to develop in the heat of the national and international spotlight. Its influence on the social sciences in general, and education in particular, is active and consequential. While brain research does have the potential to help educational researchers, teachers, parents, and students as we strive to improve our educational practices, neuroimaging information is still relatively new and therefore, much of the progress being made is foundational knowledge building; which makes direct, responsible, and scientifically supported applications to educational practices complex. Further, there have been, and continue to be serious obstacles and concerns with regard to this end goal.

The increase and extension of our neuroscientific understanding of learning mechanisms and the influences on them is in no small part due to the cognitive frameworks established previously by psychology and educational research. The new knowledge that educational neuroscience has added to understanding education is often grounded upon psychological foundations, either in theory, in construct, or evidenced-based conclusions. The ability of educational neuroscience to utilize such a deep knowledge base is a significant contributor to the rapid development of the discipline. It is clear that the best practice toward the goal of improving educational contexts is for educational psychology and educational neuroscience to work in partnership to produce optimally effective, highly contextualized, and easily implemented educational practices, curricula, and environments.

APPENDIX A: INTERVIEW PROTOCOL

Questions about the Conference

1. How did you become involved in the Cognitive Neuroscience and Education Conference in 1995?
2. What goals did you have, personally, for that conference presentation?

Questions about Subjects' Current Research

1. How did you become interested in studying the neuroscience of learning school subjects, or [educational neuroscience]. (Probe: What were the topics or questions that originally attracted you to the field?)
2. How have those original interests developed throughout your career?
3. What purposes, or goals do you have for your current research?
4. What topics [domains, or areas of research] are you currently interested in/focused on?
5. Can you tell me some of the key ideas, or important concepts in this line of research?
6. Tell me about the methods that you use to conduct your research.

Questions about the Current Discipline of Educational Neuroscience

1. How would you describe the mission or goals of the field as a whole, as you see it?
2. In your opinion, what are the important areas of research in the field that will help us achieve those goals?
3. Do you see any areas of study that would be beneficial to the field, but that are not currently being investigated?
4. Can you describe some instances of generally accepted knowledge in educational neuroscience? (Meaning: What have we learned thus far that is helpful?)
5. Where do you think the field stands in terms of our ability/efficacy to responsibly influence and inform classroom practices?

Wrap-up, Concluding Questions

1. Your presentation at the conference 1995 was about [X topic]. How has your thinking and understanding of that changed and developed since then?
2. If you could go back in time to that conference, what would you change about it? What would you keep the same?

APPENDIX B: ANALYTIC MEMO EXAMPLE

01 Dr. Merzenich Presentation - Plasticity Mechanisms & The Effects of Training in Monkeys + Implications for Human Language Deficits

As I've thought most of the way through, the presentation(s) is largely information oriented. By that I mean, only small parts of the presentations will be able to address my more meta-level research questions about the state of the field.

Merzenich introduces his presentation as being about "**the plasticity of the brain, or the self-organization of the brain that occurs with learning.**" This is a concise way to define and talk about plasticity - a concept that is often used, but its meaning rarely understood.

He distinguishes in the introduction between the learning of perceptual and cognitive skills on one hand, and issues in education in the other. I think this highlights an important perspective of these scientists - namely, their schema of the relationship between these topics. Cognitive science, and now brain science study cognitive processes in the brain. Separate from that are the issues in education, and perhaps even educational subject domains (reading, math, etc.). Perceptual and cognitive skills are things like distinguishing different auditory tones, recognizing & distinguishing consonant sounds, how the brain represents motor activity, abstract meanings, etc. Issues in education are reading, arithmetic, curriculum, teaching, learning disabilities, etc. Maybe.

Dr. Merzenich consistently refers to the brain as a machine, as a learning machine. This mechanistic view often leads to a deterministic perspective re: students and learning. Terms like "**operational capacities.**" His first point is at birth, the brain cannot do much, but it soon develops these operational capacities. "**Before long it will have control of thousands of symbols that represent the things, the actions, and the relationships between things and actions that it has to deal with. . . it will have created an incredible knowledge base, a store of information, based upon its interactions with the environment.**" This plasticity, or self-organization might be a way to conceptualize the development of the field as a whole. Maybe the field of educational neuroscience has developed like our understanding of the brain has?

As with the style of conference presentations, much of the discussion is about specific experiments: their procedures, paradigms, etc. This can be helpful to my articulation of what experiments were like then. Dr. Merzenich used electrophysiological techniques - not really mentioned in his talk, though.

Most of this presentation is about animal studies. Brain research started here. Tasks were motor or sensory based. But this produced results that we take for granted now: i.e. practice makes perfect, the potential variability in problem-solving strategies, and once the optimal strategy is learned, it becomes constant and highly stereotyped.

One idea present in the presentation that is still important is the idea that training changes the brain physically (spatial size of areas representing stimuli) as well as changing the selectivity and connectivity aspects. **“Now the monkey is representing the skin over a larger territory and it’s representing it at approximately finer grain.” And this happens, with training, in a short amount of time. “It means that the specific selective responses of hundreds of thousands, or millions, or tens of millions of neurons are changing as a consequence of engaging this adult monkey in this simple task for this limited period of time.” (p. 5)** I think the fact that plasticity exists in more than one “dimension” in the brain is fundamental to understanding and talking in terms of brain plasticity. A quote from the auditory results: **“There’s also a change in the selectivity with which neurons respond to sound frequency across this region. So, if we looked that the tuned responses of neurons across this region, we’d see that they’re significantly sharper than normal or before.” (p. 6)** He goes on to mention that this increased neuron-level selectivity does not correlate strongly with performance improvement, but that is probably because distinguishing sound frequencies is based upon population (of neurons) coding, not upon selective responses.

Plasticity is also described as domain general - at least in terms of sensory domains. Dr. Merzenich presents results with motor tasks, with sensation tasks, and with auditory tasks. This may be the only domain-general area of research in 1995.

Another thing that Dr. Merzenich emphasizes multiple times is explaining the direct relationship between neural changes and behavioral changes. This happens in both directions: from behavior (training) to cortical changes, see above quote; from cortical changes to behavioral improvements: **“those changes relate specifically to the behavioral gains of the monkey, to what the monkey is learning to do, about acquisition of his new perceptual or motor abilities.” (p. 5-6);** across domains: **“Now the region in the neighborhood of 2.5 kilohertz is expanded in representation in the cortex and. . . that expansion in representation is highly correlated with the improvement of the performance of the monkey” (p. 6)**. I’m not sure the significance of this repeated emphasis, but it may be to convince audience members that this neuronal-level, electrophysiological method can and does report on behavioral changes (learning, performance gains, etc.). Perhaps this was (or still isn’t) widely accepted outside of the field of neuroscience.

Another interesting concept he presents is the difference between differentiation and integration in the brain. The brain has different physical regions of cortex that represent different inputs that are strongly and sharply separated from each other in location. **“The cortex is integrating things [inputs] that co-concur in time and it’s separating things that are delivered non-simultaneously.”** (p. 8). He then manipulates this phenomenon to show that these differentiations and integrations can be re-organized by purposefully presenting inputs simultaneously, which integrates their cortical representations. I don’t think this influences educational contexts much beyond a behaviorist-type of co-occurrence phenomenon, but it is interesting nonetheless. And the nuances of the relationship between differentiation and integration are discussed as well.

Another constant theme in the animal portion of the presentation is that **“in the period of behavioral training. . .is a change of neurons respond to this stimuli applied in time. Initially, that response is relatively temporally dispersed, but, very rapidly, stimuli come to respond very, very strongly coincidentally to each of these successive stimuli. . .So again, you see very high correlation strengths to stimulus-driven discharge [selectivity], but also you see very high distributed synchronicity in a response to these successive impulses. . .and, again, this is partly attributed, or substantially attributed to the fact that these neurons are now very strongly, or powerfully, positively interconnected.”** (p. 9-10). This is simply the Hebbian concept that “neurons that fire together, wire together”. While this idea has been around a long time, understanding how and when this interconnection happens can be influential for education, I think.

He mentions the negative effects of over-training the monkeys (emergent focal dystonia) that is also observed in humans, such as musicians holding their instruments under tension while vibration is introduced. This is important because, while it may not be ethical, or a justification FOR animal studies, it is certainly a justification for not doing these motor-training experiments on human subjects, or in other words, part of the reason for why animal studies were deemed beneficial. A second reason this is important is that it bridges the research with animals into the domain of the human brain. First, it is true that “practice makes perfect” and “fire together, wire together”, but these plastic properties of the brain have negative consequences if over-applied. Second, we are able to talk about the human instances of focal dystonia in a much more informed way because we understand, from monkey studies in which this condition was induced, exactly what happened on the cortical level and how. This understanding provides possible treatment. For example, re-distinguishing different physical inputs to the hand by presenting various sensations non-synchronously. In other words, we know how this condition arose in the monkey, and because of this plasticity, we have information that may help reverse the condition. This idea of treating deficiencies or disabilities comes back specifically later.

This discussion of negative aspects of brain plasticity, or re-organization, reintroduces the concept of the brain as a machine - changing without moral judgment. **“We think of the self-organizing processes of the brain as - when we apply the word learning - as positive, differentiating, elaborating. But, of course, they don’t know they’re that. They are time-input, or coincident dependent processes, which can easily be, or relatively easily by driven to create negative, as well as positive changes in behavior.”** (p. 11). This quote implies the significance of what and how we teach students. The brain is a learning machine, differentiating and integrating representations based on frequency and temporal relations. It is up to us as teachers - in what content we present and how that content is presented - to ensure the brain learns in a way that is positive, not 'dystonic'.

He then goes on to explain that this “fire together, wire together” concept applies to complex stimuli as well as simple, motor stimuli. His example is vocalizations of the marmoset. These calls are both temporally (multiple phrases in each call with varying lengths) and spectrally complex (tonally, essentially). Their study finds that there is a population of neurons tuned to both the spectral and temporal characteristics of individual vocalizations (specific to each monkey). About 1/3 of the neurons that respond in the auditory cortex are selective (tuned to the specific call) and excited nearly simultaneously in time (fire together) for the specific characteristics (both temporal and spectral) of the mate’s vocalization. This is an important bridge from simple monkey brains wiring and firing together during simple sensory tasks to monkey brains accurately and specifically representing complex stimuli. And they also found that this can be taught. **“What is seen is just those features that represent - that different specifics, spectral and temporal aspects of a new learned stimulus - come to engage neurons across the cortical network with increasing positive coupling strength, and respond more and more nearly synchronously in time. And this is the creation, or the formation of a reliable, of a robust representation of a learned stimulus - it is a main event in learning.”** (p. 14). This is a huge statement about the main event of learning. I’m not sure how to parse it, or even include it in my paper, but the claim seems to make sense: the main event of learning is when robust (large space in the brain & large responses) and reliable (selective and almost synchronous) representations are formed about complex inputs.

Spectral-temporal complexity is a long way from semantics and calculation — or is it? An important part is that the sensory inputs associated with a single vocalization have been integrated, thereby abstracting the sensory inputs into a thing in itself, a representation of an identifying vocalization. The physical/sensory input pieces being integrated into a complex representation of “mate’s voice.” Cognition emerging from experience. ? **“The learning mechanisms of the cortex are input coincident dependent, they operate on the basis - considered at the simplest level - they operate on the basis of headlight synaptic change. That is to say, inputs that arrive at neurons nearly simultaneously in time are mutually strengthened in their connectivity, under the right enabling cognitive conditions.”** (p. 15). This is just another iteration and emphasis on the idea that neurons that fire together, wire together.

Seems to be an important point in Dr. Merzenich's argument - if neurons fire together to wire together (which there's tons of research showing), then we have a way to understand training (& teaching?) as a deliberate re-organization of brain connectivity through specific experiences and tasks.

The end of this presentation is directly relevant and directly about educational considerations. One explicit goal - seemingly attainable goal - for application of neuroscience information is understanding the nature of the phenomenon of learning disabilities. Educational research had described a major facet of speech & language-based learning disabilities as a problem in processing of rapid temporal successive events (p. 15), which is exactly what Dr. Merzenich was able to train monkeys to improve with. The goal was to **“try to apply some of the principles adopted from cortical plasticity experiments in the manipulation of representations of temporal — ah, successive temporal stimuli, to these [speech and language-based learning disabled] children.”** (p. 15). It is clear from this part of the talk: the way Dr. Merzenich talks about collaborating with Dr. Paula Tallal, the ways he describes the goals of the projects, etc. that neuroscience is not seen as a possible replacement for understanding educational contexts. Quite the opposite, the collaboration is important (as seen throughout the presentation), and it is the **combination** of principles and concepts from the plasticity literature **with** the concepts and descriptions from the educational (speech/language-based learning disability) literature that is the aim, that will provide the most efficacious and practical results.

Based on this similarities between Dr. Tallal's description of the learning disabilities and Merzenich's experience successfully training monkeys to make distinctions about complex stimuli, they created an intervention, 2 training 'games' focused on training time-order judgments of pieces of sound. The total amount of time the children played the games ranged from 20, 20-minute sessions to 40, 40-minute sessions over a 4-weeks. That's between 400 minutes (6 hours, 40 min.) and 1600 minutes (26 hours, 40 min.) of total training time over the 4 weeks (excluding weekends - which I'm not sure they actually did - that averages to between 20min. and 80min. per day for 20 days. Not a ton of training time). Improvement was seen in every child and the improvement held for stimuli not delivered in the behavioral training: **“looking at generalization with tonal stimuli, we saw improvement in all children in the average of fivefold improvement in being able to make these [time-order] distinctions.”** (p. 16). This is another bridge from the monkey research to human research, as the same type of training resulted in the same type of improvements/learning. **“From a clearly, initially defective performance ability, every child could be driven to a virtually normal performance ability over over this one-month-long training period.”** (p. 17). This quote speaks to the potential power of a neuroscientific contribution to education and, specifically, student learning.

Further, Dr. Merzenich's plasticity work shed light on a current intervention for speech & language-based deficits that had been deemed effective and validated “several times in the literature.” The intervention was to simply prolong the speech sounds in order to help

students recognize them. BUT **“merely prolonging speech is probably not a good idea. Because prolong speech and delivering heavy schedules of slow transitions is negative from the point of view of brain plasticity mechanisms. In fact, we know in monkeys that we can give monkeys heavy schedules of relatively sluggish stimuli and degrade their representations of fast stimuli.”** (p. 17). In other words, monkey studies show, and the perspective of plasticity suggests, that how you train the brain is how the brain will organize and operate. 'You play how you practice.' So they developed a more nuanced way to teach these children to differentiate speech sounds. Their first iteration was successful, though they continued to experiment and develop their intervention and **“we have a much more beautiful version now, after further years of experimentation, and we think we can probably create speed in virtual real time that will be very highly intelligible to these children from the outset.”** (p. 17). Plasticity experiments showed that the cortex WANTS (differentiation is optimized with) temporally sharpened distinctions for successive inputs, so the intervention exaggerated that for fast elements.

“We were shocked to see that at the end of this training - a combination of training these children to make fast temporal distinctions and to recognize speech elements delivered in faster and faster forms combined with this language and speech training - we were shocked to see that it generalized from the presentation of speech in this artificial and synthetic form to natural speech.” (p. 18). This is the panacea - training with synthetic tasks, in a contrived, laboratory environment results in performance improvements that generalize to naturalistic stimuli and environments.

We must understand the nature of the deficit, i.e. speech/language-based learning disabilities are characterized as (1) time order judgment deficits and (2) fast-speech-element recognition deficits. THEN we must understand the nature of how the brain learns/organizes these skills and what tasks promote that particular learning/organization. FURTHER, we must understand the potential negative effects of over-training the particular skill so that we do not accidentally elicit dystonic-type consequences. Only then can neuroscience adequately and responsibly offer interventions or task training exercises to target specific learning difficulties.

One thing I'm noticing is that there are many popular idioms implicit in this presentation. 'You play (or perform) how you practice'; 'practice makes perfect'; fire together, wire together. That last one is neuro-specific, but the other two are often said in sports or any skill development. I don't know if that matters. Or if there will be more.

Some key vocabulary that seems rather discipline specific: plasticity, inputs, and representations.

“Carrying information into the practical realm”

“it’s time now to extend what we understand about brain plasticity mechanisms, what we understand about the processes by which the brain is remodeling its representations of learned stimuli in detail, day-by-day and week-by-week, as a function of its ongoing experiences - it’s time to carry that information into the practical realm.” (p. 18)

“delivering inputs that drive change, by using a model that’s based on brain plasticity mechanisms, based upon a little better understanding of what the brain really wants to drive change, can potentially have a great impact on the creation of more valid representational constructs in the brains of learning children.” (p. 19)

“My guess is that this represents a tip of an iceberg and that that iceberg can be played into many areas of rehabilitation and which we introduce the concept that human brains don’t operate flawlessly in their self-creation, that the other side of creating the tremendous range of abilities, the variety of human performance capacities, is that occasionally everything doesn’t go perfectly to generate the perfect student. But we have we have a much greater capacity to affect that, impact that, and the vista to that is just opening.” (p. 19-20).

APPENDIX C: REFLECTIVE MEMO EXAMPLE

Interview with Dr. Jim Stigler

I was nervous. First one!

The interview went rather smoothly. Dr. Stigler said at the very beginning that he is very much not a neuroscientist, so we really didn't get specific about any neuroscience kinds of things. That being said, we did talk generally and broadly about the field and I was able to glean important information. He's a psychologist interested in non-universal experiences.

I found my familiarity with the educational literature and research topics to be of great value during this interview. Because Dr. Stigler explicitly distanced himself from anything brain-related, I relied on a knowledge of educational research in general to continue to interview in positive directions. Nonetheless, he was very accommodating during the interview, as my nerves did affect me somewhat. He was forthcoming and comfortable which helped me settle down as the interviewer.

Some of my research questions were too general, as they were asked. Things about the goals of the field as a whole and important areas of research did not result in specific answers. That being said, I do believe his opinion and thoughts on those questions came through in his answers, so not all was lost from them.

I was able to ask most of my questions in terms that were general enough to not be limited to neuroscientists, which I again attribute to my familiarity with educational psychology as a field. Dr. Stigler may have been slightly more positive about neuroimaging methods because he knew that was my approach, but much of the conversation was about issues and questions that were outside of specific methodological decisions.

Overall, I think I was able to restrain my opinions in a way that allowed Dr. Stigler's ideas and thoughts to drive. I was able to ask most of my questions in the flow of the interview, while still listening and responding to his cues. I was quite nervous, and for that reason think I can still improve as a listener, but for the most part I feel that this interview went well and will provide interesting avenues for discussion.

Other participants will be coming to the interviews with different backgrounds, so I foresee my role to be somewhat different in the next interview, as far as the specific training and knowledge that I use to meet the participants half-way.

APPENDIX D: KNOWLEDGE MENU

Knowledge Menu Directions

A note about terminology:

***Discipline** means a *field of study* such as **HISTORY** or **MATHEMATICS**.

***Subdivision** means a *branch of the field of study* such as **U.S. HISTORY** or **GEOMETRY**.

***Topic** means the *specific subject of a unit* such as the **AMERICAN CIVIL WAR** or **ANGLES**.

Part 1: Knowledge Tree

Create a knowledge tree.

1. Identify the discipline in which your topic resides.
2. Determine how your discipline is related to the other disciplines within the realm of all knowledge.
3. Identify the subdivisions into which your discipline is divided.
4. Determine how the subdivision in which your topic resides is related to the other subdivisions in the discipline.
5. Represent these relationships visually using a concept map, tree, or other graphic.

If you decide to draw your tree by hand, keep in mind it is likely you will revise your knowledge tree multiple times before the final deadline.

Part 2: Discipline Overview

Provide an overview of the discipline in which your topic resides using the following questions as lenses:

1. How is the discipline defined?
2. What is the general purpose or mission of the discipline?
3. How is knowledge organized and classified in the discipline?
4. What are the major subdivisions of the discipline? (should align w/ knowledge tree)
5. What are the key areas of concentration of each subdivision of the discipline?
6. What are some examples of questions that are asked in each subdivision?
(At some point in Part 2, identify which subdivision will be your area of focus.)

7. *What are key basic reference books in the discipline or subdivision?
8. *What are key major professional journals in the discipline or subdivision?
9. *What are key major databases in the discipline or subdivision?
**(Provide both names and brief annotations of the resources you find for #7-9 so that the nature of the resources is evident.)*
10. If there is a history or chronology of events that will lead to a better understanding of the discipline or subdivision, what is it? **(2 pages max)**
11. What are the major events, people, places, or beliefs that are the predominant concerns of the discipline or subdivision and that reveal what the field is all about? **(3 pages max)**
12. What are some selected examples of discipline-specific (or subdivision-specific) "insiders' knowledge"? This includes but is not limited to: humor, trivia, abbreviations and acronyms, "meccas," scandals, hidden realities, or unspoken beliefs within the discipline. **(4 pages max)**

Part 3: Discipline Key Concepts and Principles

Provide a list of the key concepts of your discipline (not your topic).

Provide a list of the principles of your discipline. Bold the concepts embedded in the principles.

1. Key concepts are the intellectual instruments with which a subject area specialist works. They serve as the vocabulary of the field and help experts communicate precisely with one another. They organize knowledge in the discipline.
2. Principles are generally agreed-upon truths within the field that have been arrived at through rigorous study and research. They illustrate the relationships between/among concepts and apply to a variety of situations. They are statements that reflect the meaning or core truth of one or more concepts.

Example from the discipline of sociology:

***Key concepts:** society, system, taboo, role, acculturation, assimilation, norm, sanction, value*

***Principle:** Every society develops a system of roles, norms, values and sanctions that guides the behavior of individuals within that society.*

You may choose to have 1) all of your concepts and principles come from your discipline or 2) some concepts and principles come from both your discipline and your subdivision.

Part 4: Methodologies

Identify and explain the general and specific methodologies of practicing professionals in the discipline or subdivision.

1. What are practitioners in this discipline or subdivision called?
2. What do practitioners need to know how to do in their day-to-day work?
3. What skills do practitioners routinely use to make new contributions to their field (e.g., to identify problems, solve problems, move the work of the field forward)?

In almost every discipline, practitioners seek to answer the questions of the discipline and make contributions to the field by following investigative procedures. How do the ten questions below about general methodologies apply to your discipline or subdivision?

How do practitioners in your discipline or subdivision...

1. Identify an area of contention/concern/need for investigation within the field?
2. Find and focus on a specific problem to investigate within that area?
3. State hypotheses or research questions?
4. Identify sources of data?
5. Locate and construct appropriate data gathering instruments?
6. Classify and categorize data?
7. Analyze and summarize data?
8. Draw conclusions and form generalizations?
9. Report or communicate findings?
10. Develop products?

The methodology used in your field may also have some field-specific attributes that should be addressed.

What other questions might you ask and answer about the procedures in your discipline or subdivision?

Field-specific examples:

How do historians obtain data through interviews?

How does an ecologist find the rate of water evaporation?

How does a philatelist interpret stamp authenticity and value?

How does a biologist prepare a microscope slide?

How does a statistician use statistical analysis software?

How does an artist find a gallery to display her artwork?

How does an actor prepare for an audition?

How does a creative writer get her work published?

Part 5: Representative Topic

Identify and explain the specifics of your representative topic.

NOTE: This is the first point at which you will focus on your topic rather than the discipline or subdivision as a whole.

Representative topic: A topic the teacher will use to help students apply the concepts, the principles, and the methodologies used by practicing professionals. (Representative topics also help students see connections to other topics in the discipline. For example, if the Salem Witch trials are the representative topic, related topics might include the Holocaust and McCarthyism.) If a student understands the representative topic well, he is equipped to think about, understand, and act on other topics with the same conceptual framework in related fields. Your PCM unit will be focused on the representative topic.

This section will reflect but not duplicate the previous sections. You will overlay the framework of the larger discipline or subdivision onto the representative topic for your PCM unit.

Identify the following specifics **related to your representative topic**.

1. Key concepts and principles
2. Key facts
3. Key skills/methodologies
4. Key questions/dilemmas/issues within the field
5. Conventions within the field (codes, etiquette, ethics, do's and don'ts)
Which conventions in the field that apply to the study of the topic might your students need to observe/be aware of?
6. Classifications and categories of knowledge
How is the topic connected to classifications of knowledge in the discipline/subdivision?
7. Databases, references, resources (3 pages max)
8. Criteria for evaluating quality of work in the field
When practitioners produce work related to this topic, how is its quality evaluated?
9. Theories
What theories of the discipline/subdivision apply to the study of this topic?

Part 6: References

Keep a list of the references you consult.

APPENDIX E: KNOWLEDGE MENU EXAMPLE

Representative topic: Plasticity: Dr. Merzenich & Dr. Neville

1. Key concepts and principles

- a. Cognition
- b. Plasticity
- c. Variability
- d. The brain as a learning machine
- e. Representation
- f. Differentiation and integration in the brain
- g. the direct relationship between neural changes and behavioral changes
- h. Plasticity is also described as domain general
- i. “neurons that fire together, wire together”
- j. stimuli as inputs
- k. effects of experience - inputs from the environment

2. Key facts

- a. at birth, the brain cannot do much, but it soon develops these operational capacities
- b. training changes the brain physically (spatial size of areas representing stimuli) as well as changing the selectivity and connectivity aspects – and this can cause negative effects
- c. “neurons that fire together, wire together”
- d. a very prevalent view that still persists (in 1995, but probably now too) is that most aspects of this development are biologically determined – only true in some cases
- e. the levels of mutability (also plasticity, modifiable) are highly variable between different brain regions, different cognitive systems, and even within cognitive systems
- f. these (biological) biases are highly mutable
- g. different subsystems in vision and language vary in their plasticity due to experience
- h. the visual system is reorganized after “auditory deprivation.”
- i. Non-identical brain systems are involved with different aspects of language processing
- j. There are also many similarities in the organization of language systems of English speakers and ASL speakers

- k. There are biological constraints on the organization of language-relevant processing in the left hemisphere, though ASL leads to more R hemisphere activations than English
- l. “not just chronological age that determines the organization of the language-relevant brain systems during this time period, but the degree of language knowledge that a child has, independently of chronological age, is a very strong predictor of the degree to which these systems are specialized in infants” (H.N., p. 16)

3. Key skills/methodologies

- a. Electrophysiological techniques (seconded by H.N.)
- b. Animal studies
- c. Human training w/auditory stimuli
- d. Started using fMRI – ROI analysis
- e. Corroboration from other domains of study (dyslexia) and behavioral results
- f. Developmental studies of sensory systems in children

4. Key questions/dilemmas/issues within the field

- a. Merzenich’s plasticity work shed light on a current intervention for speech & language-based deficits that had been deemed effective and validated “several times in the literature.”
- b. Very infrequent that they get input from educators/educational researchers
- c. “The extent to which these strong biological biases can be modified and when can they be modified.” (H.N., p. 2)
- d. “what would the absence of auditory input, what impact might this have on the development of classical auditory brain areas?” (H.N., p.4)
 - i. what impact might this experience (acquiring visuospatial language) have on the organization of the language systems in the brain?
 - ii. Are there strong biases about how these are organized, so that there are no organizational differences or does the different experience result in different organization?
- e. “Are there different subsystems within language that can be more or less modified by different early experience?” (p. 7)
- f. Can we use this information to predict future language impairments in infants?

5. Conventions within the field (codes, etiquette, ethics, do's and don'ts)
 - a. "We take two general approaches to this issue: one is to look at development sort of backwards by comparing brain organization in normal adults with adults who've had different early experience. Like people who are born deaf and have different early sensory experience and different language experience, and bilinguals. So this is sort of a retrospective look at development. And then in addition, we look at development prospectively, so we look at children of different ages and different stages of cognitive development." (H.N., p. 3)

6. Classifications and categories of knowledge
 - a. We must understand the nature of the deficit, i.e. speech/language-based learning disabilities are characterized as (1) time order judgment deficits and (2) fast speech element recognition deficits. THEN we must understand the nature of how the brain learns/organizes these skills and what tasks promote that particular learning/organization. FURTHER, we must understand the potential negative effects of over-training the particular skill so that we do not accidentally elicit dystonic-type consequences. Only then can neuroscience adequately and responsibly offer interventions or task training exercises to target specific learning difficulties.
 - b. The subsystems of each sensory system: peripheral vs. full visual field; semantic, grammatical, syntactical language systems)
 - c. 1st step: Are these systems different in typical adults? 2nd step: How do they compare based on atypical early experiences?

7. Goals
 - a. understanding the nature of the phenomenon of learning disabilities.
 - b. To understand "The extent to which these strong biological biases can be modified and when can they be modified." (H.N., p. 2)
 - c. Identify and draw boundaries between different cognitive systems and subsystems.
 - d. Identify which systems are most modifiable and when incoming input might be most effective in changing them.
 - e. Informing the design of educational programs for typically developing students, as well as the design of interventions for developmentally disabled students.

8. Theories
 - a. ***"the creation, or the formation of a reliable, of a robust representation of a learned stimulus - it is a main event in learning."*** (M.M., p. 14)

- b. Plasticity experiments showed that the cortex WANTS (differentiation is optimized with) temporally sharpened distinctions for successive inputs, so the intervention exaggerated that for fast elements
- c. Variable mutability between subsystems is probably due to brain development, or, “the mechanisms include different rates of maturation, different degrees of anatomical divergence early on in development.” (H.N., p. 3)
- d. The peripheral visual system is more modifiable following altered early sensory experience than the full view visual system. Peripheral system is associated with dorsal pathway, suggesting a more modifiable dorsal pathway than ventral
- e. The “auditory cortex, which is strongly biased to process auditory information, may actually become organized to process visual information under certain conditions early on in human development.” (H.N., p. 6)
- f. “it may be over the first 3 or 4 years of life in humans that sensory experience can have its greatest impact on the organization of sensory systems.” (p.7) “sensory systems may be less differentiated than they are later on.” (p. 7)
- g. semantic & syntactic processing systems are not vulnerable to atypical language experience (ASL vs. English), but grammatical systems are.
- h. Child studies suggest: “there appear to be different subgroups of children: some do show auditory processing deficits, but these are not the same kids that have low scores on tests of grammar and actually show very marked anomalies in brain organization in response to grammatical information. And other children show deficits in visual sensory processing, but these are not the same ones who show auditory sensory processing deficits” (H.N., p.15-16)

APPENDIX F: RECRUITMENT EMAILS

Initial Recruitment Email Approved by the IRB:

Greetings!

My name is Charlie Gillmarten and I am a Ph.D. candidate at George Mason University in Education with a focus on Educational Neuroscience. I am currently working on my dissertation and my advisor, Layne Kalbfleisch, has offered me the use of the videotape of the 1995 Cognitive Neuroscience and Education conference in Eugene, Oregon hosted by the McDonnell Foundation. With this unique opportunity, I plan to do a qualitative study of the development and growth of the discipline of Educational Neuroscience and I would like to invite you – as a presenter at that early conference – to participate in my study.

As you are well aware, the complexity of how and when to apply neuroscience information to educational contexts is still relevant and increasingly important as interest from the general public and media increases and more and more ‘brain-based’ educational programs hit the market. Further, the breakdown in communication of relevant and accurate information from research to practice has been well documented, resulting in many misconceptions, misunderstandings, and misapplications (e.i. neuromyths) of neuroscience to the understanding of the educational process. With my project, I plan to formulate a developmental arc of Educational Neuroscience as a field, using the tapes of this early conference, a current review of the literature of relevant academic domains, and – I hope – your perspectives about the field as it is currently and has developed since your presentation at that foundational conference. This study will include research. I will first be coding and analyzing the videotapes of the conference in order to get a sense of the field at that point in time. I will also be conducting literature reviews of many relevant topics in educational neuroscience (i.e. reading, mathematics, reasoning, memory, attention, etc.). These reviews will take place throughout the project. Following my preliminary analysis of the videotapes, I would like to conduct interviews with you (and the other presenters at the 1995 conference). I would then transcribe and analyze the interviews in order to gain your perspectives on the field as it currently is shaped and situated.

As I briefly mentioned above, participation in this study will involve being interviewed via VoIP (i.e. Skype or some other internet video chat program) for approximately 45-90 minutes. The conversation will briefly address your reflections on the conference, but

will focus primarily on your perspectives, opinions, and ideas about the discipline of Educational Neuroscience as it is shaped today. I will record the interviews and transcribe them in order to ensure accuracy as well as aid in the data analysis process. During data analysis, copies of some initial interpretations and coding of your interview will be emailed to you for review and/or approval. I will also be willing to share the results and finished project with you when it is complete.

I do not foresee any risk or discomfort to you, the participant, due to your participation. I would prefer to use your real name as I write up the results because I think this will highlight your essential contributions to the field as it is now, while also providing the study and my conclusions more credibility and validity. That being said, if you are uncomfortable with the use of your real name, I will use a pseudonym in its place, which will eliminate all identifying information about you (with the exception of the fact that you participated in the conference in 1995).

As I mentioned, your participation would benefit the field by articulating a developmental arc of the field of educational neuroscience, and would benefit you by highlighting your contributions to the early formation of the discipline. The interviews will be recorded so that I may conduct a proper analysis of them, however these records will be password protected at all times and will only be accessible by me. As I mentioned, I would prefer to use your real name, though in the event that you prefer to use a pseudonym, all identifying information will be maintained on the password-protected computer and absent from the process after the recorded interview is transcribed. I will maintain confidentiality of all interview data, though, your participation in the 1995 Cognitive Neuroscience and Education Conference is a matter of public record, so I cannot guarantee full anonymity.

Please contact me (cgillmar@masonlive.gmu.edu) if you have any questions, comments, or concerns about your participation or about the study as a whole. Also, if you would like to contact my advisor and principal investigator on this project, you can email Dr. Layne Kalbfleisch (mkalbfle@gmu.edu). An affirmative response to participate in the study will be used in lieu of signing a consent form, so please do not hesitate to ask for clarification and please do respond indicating whether or not you are willing to participate. Additionally, because this email will serve as the informed consent I want to mention again that I plan to record our interview together. If this is a problem, or you do not consent to this aspect of the study, please indicate this and we can work together to ensure you are still able to participate.

Again, I must reiterate participation is 100 percent voluntary and refusal to participate will not result in any penalty or loss of benefits to which you are otherwise entitled. Further, you may discontinue participation at any time during the study without penalty or loss of the aforementioned benefits.

I understand that many folks travel and/or unplug this time of year. I am sending this email now so that we may coordinate schedules to find time for the interviews. I plan to conduct the interviews in September and October. I appreciate your reply as soon as possible so that we may begin the process of coordinating times and addressing any potential questions or concerns.

Thank you very much and I look forward to talking with you soon!

Kind Regards,

Charlie Gillmarten

Second Recruitment Email Approved by the IRB:

Hello again!

My name is Charlie Gillmarten and I contacted you last month regarding participation in my dissertation project.

To remind you, I am working on a qualitative study of the development and growth of the discipline of Educational Neuroscience using videotape of the 1995 Cognitive Neuroscience and Education conference in Eugene, Oregon hosted by the McDonnell Foundation as a beginning point.

I haven't heard from you, so I wanted to contact you one more time as I would very much value your input as a instrumental voice in the establishment and development of the field of Educational Neuroscience.

With my project, I plan to formulate a developmental arc of Educational Neuroscience as a field, using the tapes of this early conference, a current review of the literature of relevant academic domains, and – I hope – your perspectives about the field as it is currently and has developed since your presentation at that foundational conference. This study will include research. I will first be coding and analyzing the videotapes of the conference in order to get a sense of the field at that point in time. I will also be conducting literature reviews of many relevant topics in educational neuroscience (i.e. reading, mathematics, reasoning, memory, attention, etc.). These reviews will take place throughout the project. Following my preliminary analysis of the videotapes, I would like to conduct interviews with you (and the other presenters at the 1995 conference). I will

then transcribe and analyze the interviews in order to gain your perspectives on the field as it currently is shaped and situated.

Participation in this study will involve being interviewed via telephone for approximately 45-90 minutes. The conversation will briefly address your reflections on the conference, but will focus primarily on your perspectives, opinions, and ideas about the discipline of Educational Neuroscience as it is shaped today. I will record the interviews and transcribe them in order to ensure accuracy as well as aid in the data analysis process. During data analysis, copies of some initial interpretations and coding of your interview will be emailed to you for review and/or approval. I will also be willing to share the results and finished project with you when it is complete.

I do not foresee any risk or discomfort to you, the participant, due to your participation. I would prefer to use your real name as I write up the results because I think this will highlight your essential contributions to the field as it is now, while also providing the study and my conclusions more credibility and validity. That being said, if you are uncomfortable with the use of your real name, I will use a pseudonym in its place, which will eliminate all identifying information about you (with the exception of the fact that you participated in the conference in 1995).

As I mentioned, your participation would benefit the field by articulating a developmental arc of the field of educational neuroscience, and would benefit you by highlighting your contributions to the early formation of the discipline.

The interviews will be recorded so that I may conduct a proper analysis of them, however these records will be password protected at all times and will only be accessible by me.

As I mentioned, I would prefer to use your real name, though in the event that you prefer to use a pseudonym, all identifying information will be maintained on the password-protected computer and absent from the process after the recorded interview is transcribed. I will maintain confidentiality of all interview data, though, your participation in the 1995 Cognitive Neuroscience and Education Conference is a matter of public record, so I cannot guarantee full anonymity.

Please contact me (cgillmar@masonlive.gmu.edu) if you have any questions, comments, or concerns about your participation or about the study as a whole. Also, if you would like to contact my advisor and principal investigator on this project, you can email Dr. Layne Kalbfleisch (mkalbfle@gmu.edu). An affirmative response to participate in the study will be used in lieu of signing a consent form, so please do not hesitate to ask for clarification and please do respond indicating whether or not you are willing to participate. Additionally, because this email will serve as the informed consent I want to mention again that I plan to record our interview together. If this is a problem, or you do not consent to this aspect of the study, please indicate this and we can work together to ensure you are still able to participate.

I understand that we are in the heart of the fall semester and your schedule is likely busy. That being said, your input on this project is incredibly valuable to me, and will go a long

way towards my goal of articulating a developmental trajectory of our field. I appreciate your reply as soon as possible so that we may begin the process of coordinating times and addressing any potential questions or concerns.

Again, I must reiterate participation is 100 percent voluntary and refusal to participate will not result in any penalty or loss of benefits to which you are otherwise entitled. Further, you may discontinue participation at any time during the study without penalty or loss of the aforementioned benefits.

Thank you very much and I look forward to talking with you soon!

Kind Regards,

Charlie Gillmarten

APPENDIX G: IRB APPROVAL LETTER



Office of Research Integrity and Assurance

Research Hall, 4400 Univeristy Drive, MS 6D5, Fairfax, Virginia 22030
Phone: 703-993-5445; Fax: 703-993-9590

DATE: October 23, 2014

TO: Layne Kalbfleisch
FROM: George Mason University IRB

Project Title: [617801-4] An Historical and Developmental Examination of the Discipline of Educational Neuroscience Grounded in Voices from the Field

SUBMISSION TYPE: Amendment/Modification

ACTION: DETERMINATION OF EXEMPT STATUS
DECISION DATE: October 23, 2014

REVIEW CATEGORY: Exemption category #2

Thank you for your submission of Amendment/Modification materials for this project. The Office of Research Integrity & Assurance (ORIA) has determined this project is EXEMPT FROM IRB REVIEW according to federal regulations.

Please remember that all research must be conducted as described in the submitted materials.

Please note that any revision to previously approved materials must be submitted to the ORIA prior to initiation. Please use the appropriate revision forms for this procedure.

If you have any questions, please contact Bess Dieffenbach at 703-993-4121 or edieffen@gmu.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within George Mason University IRB's records.

REFERENCES

- Alwis, D. S., & Rajan, R. (2014). Environmental enrichment and the sensory brain: The role of enrichment in remediating brain injury. *Frontiers in Systems Neuroscience*, *8*, 1-20. doi: 10.3389/fnsys.2014.00156
- Ansari, D., & Coch, D. (2006). Bridges over troubled waters: Education and cognitive neuroscience. *TRENDS in Cognitive Sciences*, *10*(4), 146-151. doi: 10.1016/j.tics.2006.02.007
- Ansari, D., Coch, D., & De Smedt, B. (2011). Connecting education and cognitive neuroscience: Where will the journey take us? *Educational Philosophy and Theory*, *43*(1), 37-42. doi: 10.1111/j.1469-5812.2010.00705.x
- Ansari, D., De Smedt, B., & Grabner, R. H. (2012). Neuroeducation – A critical overview of an emerging field. *Neuroethics*, *5*, 105-117. doi: 10.1007/s12152-011-9119-3
- Ansari, D., & Dhital, B. (2006). Age-related changes in the activation of the intraparietal sulcus during nonsymbolic magnitude processing: An event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience*, *18*(11), 1820-1828. doi: 10.1162/jocn.2006.18.11.1820
- Arsalidou, M., & Taylor, M. J. (2011). Is $2+2=4$? Meta-analyses of brain areas needed for numbers and calculations. *NeuroImage*, *54*, 2382-2393. doi: 10.1016/j.neuroimage.2010.10.009
- Ashkenazi, S., Black, J. M., Abrams, D. A., Hoefft, F., & Menon, V. (2013). Neurobiological underpinnings of math and reading learning disabilities. *Journal of Learning Disabilities*, *46*, 549-569. doi: 10.1177/0022219413483174
- Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2009). Numerical distance effect in developmental dyscalculia. *Cognitive Development*, *24*(4), 387-400. doi: 10.1016/j.cogdev.2009.09.006
- Atherton, M. (2005, April). *Applying the neurosciences to educational research: Can cognitive neuroscience bridge the gap? Part I*. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada. Retrieved from:

<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.78.4727&rep=rep1&type=pdf>

- Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory. A proposed system and its control processes. In K. Spence & J. Spence (Eds.), *The Psychology of Learning and Motivation* (Vol. 2). New York: Academic Press.
- Bailey, D. H., Siegler, R. S., & Geary, D. C. (2014). Early predictors of middle school fraction knowledge. *Developmental Science*, *17*(5), 775-785. doi: 10.1111/desc.12155
- Bartelet, D., Ansari, D., Vaessen, A., & Blomert, L. (2014). Cognitive subtypes of mathematics learning difficulties in primary education. *Research in Developmental Disabilities*, *35*, 657-670. doi: 10.1016/j.ridd.2013.12.010
- Batterink, L., & Neville, H. J. (2013). The human brain processes syntax in the absence of conscious awareness. *Journal of Neuroscience*, *33*, 8528-8533. doi: 10.1523/JNEUROSCI.0618-13.2013
- Boschloo, A., Krabbendam, L., Dekker, S., Lee, N., de Groot, R., & Jolles, J. (2013). Subjective sleepiness and sleep quality in adolescents are related to objective and subjective measures of school performance. *Frontiers in Psychology*, *4*, 1-5. doi: 10.3389/fpsyg.2013.00038
- Bower, G. H., & Hilgard, E. R. (1981). *Theories of learning* (5th ed.). Englewood Cliffs, NJ: Prentice-Hall.
- Brindal, E., Baird, D., Danthiir, V., Wilson, C., Bowen, J., Slater, A., & Noakes, M. (2012). Ingesting breakfast meals of different glycaemic load does not alter cognition and satiety in children. *European Journal of Clinical Nutrition*, *66*, 1166-1171. doi: 10.1038/ejcn.2012.99
- Bruer, J. T. (1997). Education and the brain: A bridge too far. *Educational Researcher*, *26*(8), 4-16. doi: 10.3102/0013189X026008004
- Bruer, J. T. (1999). *The myth of the first three years: A new understanding of early brain development and lifelong learning*. New York: The Free Press.
- Bruer, J. T. (2009). Mapping cognitive neuroscience: Two-dimensional perspectives on twenty years of cognitive neuroscience research. In M.S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (4th ed.) (pp. 1221-1234). Cambridge, MA: The MIT Press.

- Bruer, J. T. (2010). Can we talk? How the cognitive neuroscience of attention emerged from neurobiology and psychology, 1980-2005. *Scientometrics*, 83(3), 751-764.
- Bruner, J. (1960). *The process of education*. New York, NY: Vintage Books.
- Bruner, J. (1990). *Acts of meaning*. Cambridge, MA: Harvard University Press.
- Burton, H., Snyder, A. Z., & Raichle, M. E. (2014). Resting state functional connectivity in early blind humans. *Frontiers in Systems Neuroscience*, 8, 1-13. doi: 10.3389/fnsys.2014.00051
- Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science*, 332, 1049-1053. doi: 10.1126/science.1201536
- Byrnes, J. P. (2012). How neuroscience contributes to our understanding of learning and development in typically developing and special-needs students. In K. R. Harris, S. Graham, T. Urdan, C. B. McCormick, G. Sinatra, & J. Sweller (Eds.), *APA Educational Psychology Handbook (Vol. 1): Theories, Constructs, and Critical Issues* (pp. 561-595). Washington, DC: American Psychological Association.
- Byrnes, J. P., & Fox, N. A. (1998). The educational relevance of research in cognitive neuroscience. *Educational Psychology Review*, 10(3), 297-342. doi: 10.1023/A:1022145812276
- Cameron, W., & Chudler, E. (2003). A role for neuroscientists in engaging young minds. *Nature Reviews Neuroscience*, 4, 763-768. doi: 10.1038/nrn1200
- Campbell, S. R. (2011). Educational neuroscience: Motivations, methodology, and implications. *Educational Philosophy and Theory*, 43(1), 7-16. doi: 10.1111/j.1469-5812.2010.00701.x
- Caplan, D. (2009). The neural basis of syntactic processing. In M. S. Gazzaniga (Ed.), *The Cognitive Neurosciences (4th ed.)* (pp. 805-817). Cambridge, MA: The MIT Press.
- Case, R., Griffin, S., & Kelly, W. M. (2001). Socioeconomic differences in children's early cognitive development and their readiness for schooling. In S. L. Golbeck (Ed.), *Psychological Perspectives on Early Childhood Education: Reframing Dilemmas in Research and Practice* (pp. 37-63). Mahwah, NJ: Erlbaum.
- Cerruti, C. (2013). Building a functional multiple intelligences theory to advance educational neuroscience. *Frontiers in Psychology*, 4, 1-4. doi: 10.3389/fpsyg.2013.00950

- Charles, L., King, J. R., & Dehaene, S. (2014). Decoding the dynamics of action, intention, and error detection for conscious and subliminal stimuli. *Journal of Neuroscience*, *34*(4), 1158-1170. doi: 10.1523/JNEUROSCI.2465-13.2014
- Charmaz, K. (2000). Grounded theory: Objectivist and constructivist methods. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of Qualitative Research* (2nd ed., pp. 509-535). Thousand Oaks, CA: Sage.
- Charmaz, K. (2002). Qualitative interviewing and grounded theory analysis. In J. F. Gubrium and J. A. Holstein (Eds.), *Handbook of Interview Research: Context and Method* (pp. 675-694). Thousand Oaks, CA: Sage.
- Charmaz, K. (2014). *Constructing grounded theory*. London: Sage.
- Christodoulou, J. A., & Gaab, N. (2009). Using and misusing neuroscience in education-related research. *Cortex*, *45*, 555-557. doi: 10.1016/j.cortex.2008.06.004
- Cooper, S. B., Bandelow, S., Nute, M. L., Morris, J. G., & Nevill, M. E. (2012). Breakfast glycaemic index and cognitive function in adolescent school children. *British Journal of Nutrition*, *107*(12), 1823-1832. doi: 10.1017/S000711451005022
- Creswell, J. W. (2008). *Qualitative inquiry and research design*. Los Angeles, CA: Sage.
- Cruikshank, W. M. (1981). A new perspective in teacher education: The neuroeducator. *Journal of Learning Disabilities*, *14*(6), 337-341. doi: 10.1177/002221948101400613
- Dehaene, S. (2009). *Reading in the brain: The science and evolution of a human invention*. New York, NY: Penguin Group.
- Dehaene, S., Charles, L., King, J. R., & Marti, S. (2014). Toward a computational theory of conscious processing. *Current Opinions in Neurobiology*, *25*, 76-84. doi: 10.1016/j.conb.2013.12.005
- Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing, *Mathematical Cognition*, *1*, 83-120.
- Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing, *Cognitive Neuropsychology*, *20*, 487-506. doi: 10.1080/02643290244000239

- Dekker, S., Lee, N. C., Howard-Jones, P., & Jolles, J. (2012). Neuromyths in education: Prevalence and predictors of misconceptions among teachers. *Frontiers in Psychology, 3*, 1-8. doi: 10.3389/fpsyg.2012.00429
- Delazer, M., Ischebeck, A., Domahs, F., Zamarian, L., Koppelstaetter, F., Siedentopf, C. M., . . . Felber, S. (2005). Learning by strategies and learning by drill – evidence from an fMRI study. *NeuroImage, 25*(3), 838-849. doi: 10.1016/j.neuroimage.2004.12.009
- Devonshire, I. M., & Dommett, E. J. (2010). Neuroscience: Viable applications in education? *The Neuroscientist, 16*(4), 349-356. doi: 10.1177/1073858410370900
- Dewey, J. A., & Carr, T. H. (2013). When dyads act in parallel, a sense of agency for the auditory consequences depends on the order of the actions. *Consciousness and Cognition, 22*(1), 155-166. doi: 10.1016/j.concog.2012.12.004
- Dewey, J. A., Seiffert, A. E., & Carr, T. H. (2010). Taking credit for success: The phenomenology of control in a goal-directed task. *Consciousness and Cognition, 19*(1), 48-62. doi: 10.1016/j.concog.2009.09.007
- Dommett, E. J., Devonshire, I. M., Plateau, C. R., Westwell, M. S., & Greenfield, S. A. (2011). From scientific theory to classroom practice. *The Neuroscientist, 17*(4), 382-388. doi: 10.1177/1073858409356111
- Driscoll, M. P. (2005). *Psychology of learning for instruction* (3rd ed.). Boston, MA: Pearson.
- Edefonti, V., Rosato, V., Parpinel, M., Nebbia, G., Fiorica, L., Fossali, E., . . . Agostoni, C. (2014). The effect of breakfast composition and energy contribution on cognitive and academic performance: A systematic review. *The American Journal of Clinical Nutrition, 100*(2), 626-656. doi: 10.3945/ajcn.114.083683
- Elliot, A. J., & Dweck, C. S. (2005). *Handbook of competence and motivation*. New York, NY: Guilford Press.
- Ferigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Neuroscience, 8*(7), 838-849.
- Ferrari, M. (2011). What can neuroscience bring to education? *Educational Philosophy and Theory, 43*(1), 31-36. doi: 10.1111/j.1469-5812.2010.00704.x
- Fischer, K. W. (2009). Mind, brain, and education: Building a scientific groundwork for learning and teaching. *Mind, Brain, and Education, 3*(1), 3-16. doi: 10.1111/j.1751-228X.2008.01048.x

- Fischer, K. W., Daniel, D. B., Immordino-Yang, M. H., Stern, E., Battro, A., & Koizumi, H. (2007). Why mind, brain, and education? Why now? *Mind, Brain, and Education*, 1(1), 1-2. doi: 10.1111/j.1751-228X.2007.00006.x
- Fuller, J. K. & Glendening, J. G. (1985). The neuroeducator: Professional of the future. *Theory into Practice*, 24(2), 135-137. doi: 10.1080/00405848509543161
- Gabrieli, J. D. E. (2009). Dyslexia: A new synergy between education and cognitive neuroscience. *Science*, 325(5938), 280-283. doi: 10.1126/science.1171999
- Gazzaniga, M. S. (1992). *Nature's mind: The biological roots of thinking, emotions, sexuality, language, and intelligence*. London: Penguin.
- Geake, J. (2004). Cognitive neuroscience and education: Two-way traffic or one-way street? *Westminster Studies in Education*, 27(1), 87-98. doi: 10.1080/0140672040270107
- Geake, J. (2008). Neuromythologies in education. *Educational Research*, 50(2), 123-133. doi: 10.1080/00131880802082518
- Geake, J., & Cooper, P. (2003). Cognitive neuroscience: Implications for education? *Westminster Studies in Education*, 26(1), 7-20. doi: 10.1080/0140672032000070710
- Glaser, B., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Chicago, IL: Aldine.
- Glesne, C. (2011). *Becoming qualitative researchers: An introduction*. Boston: Pearson Education.
- Goldberg, E. (2009). *The New Executive Brain: Frontal Lobes in a Complex World*. New York, NY: Oxford University Press.
- Gong, Q. Y., Sluming, V., Mayes, A., Keller, S., Barrick, T., Cezayirli, E., & Roberts, N. (2005). Voxel-based morphometry and stereology provide convergent evidence of the importance of medial prefrontal cortex for fluid intelligence in healthy adults. *NeuroImage*, 25, 1175-1186. doi: 10.1016/j.neuroimage.2004.12.044
- Gori, S., & Facoetti, A. (2013). Perceptual learning as a possible new approach for remediation and prevention of developmental dyslexia. *Vision Research*. Advance online publications. doi: 10.1016/j.visres.2013.11.011

- Goswami, U. (2004). Neuroscience and education. *British Journal of Educational Psychology*, 74, 1-14. doi: 10.1348/000709904322848798
- Goswami, U. (2005). The brain in the classroom? The state of the art. *Developmental Science*, 8, 467-469. doi: 10.1111/j.1467-7687.2005.00436.x
- Goswami, U. (2006). Neuroscience and education: From research to practice? *Nature Reviews Neuroscience*, 7, 406-413. doi: 10.1038/nrn1907
- Gould, S. J. (1996). *The mismeasure of man*. New York, NY: W.W. Norton & Company.
- Goyal, M. S., Hawrylycz, M., Miller, J. A., Snyder, A. Z., & Raichle, M. E. (2014). Aerobic glycolysis in the human brain is associated with development of neonatal gene expression. *Cell Metabolism*, 19(1), 49-57. doi: 10.1016/j.cmet.2013.11.020
- Grabner, R. H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., & Neuper, C. (2009). To retrieve or calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. *Neuropsychologia*, 47(2), 604-608. doi: 10.1016/j.neuropsychologia.2008.10.013
- Gutchess, A. (2014). Plasticity of the aging brain: new directions in cognitive neuroscience. *Science*, 346(6209), 579-582. doi: 10.1126/science.1254604
- Hamlin, J. K., Mahajan, N., Liberman, Z., & Wynn, K. (2013). Not like me=bad: Infants prefer those who harm dissimilar others. *Psychological Science*, 24(4), 589-594. doi: 10.1177/0956797612457785
- Hebb, D. O. (1949). *The Organization of Behavior*. New York: Wiley.
- Herrnstein, R. J., & Boring, E. G. (1965). *A sourcebook in the history of psychology*. Cambridge, MA: Harvard University Press.
- Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized intelligence. *Journal of Educational Psychology*, 57, 253-270. doi: 10.1037%2Fh0023816
- Hook, C., & Farah, M. (2012). Neuroscience for educators: What are they seeking, and what are they finding? *Neuroethics*, 331-341. doi: 10.1007/s12152-012-9159-3
- Howard-Jones, P. (2005). An invaluable foundation for better bridges. *Developmental Science*, 8, 469-471. doi: 10.1111/j.1467-7687.2005.00437.x

- Howard-Jones, P. (2011). A multiperspective approach to neuroeducational research. *Educational Philosophy and Theory*, 43(1), 24-30. doi: 10.1111/j.1469-5812.2010.00703.x
- Howard-Jones, P., Washbrook, & Meadows, S. (2012). The timing of educational investment: A neuroscientific perspective. *Developmental Cognitive Neuroscience*, 25, 18-29. doi: 10.1016/j.dcn.2011.11.002
- Hyatt, K. J. (2007). Brain gym: Building stronger brains or wishful thinking? *Remedial and Special Education*, 28(2), 117-124. doi: 10.1177/07419325070280020201
- Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelsätter, F., Benke, T., Felber, S., & Delzer, M. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction, *NeuroImage*, 30, 1365-1375. doi: 10.1016/j.neuroimage.2005.11.016
- Jobard, G., Crivello, F., & Tzourio-Mazoyer, N. (2003). Evaluation of the dual route theory of reading: A metaanalysis of 35 neuroimaging studies. *NeuroImage*, 20, 693-712. doi: 10.1016/S1053-8119(03)00343-4
- Johnson, J. M. (2001). In-depth interviewing. In J. Gubrium & J. Holstein (Eds.), *Handbook of Interview Research: Context and Method* (pp. 103-119). Thousand Oaks, CA: Sage.
- Jones, E. G., & Mendell, L. M. (1999). Assessing the decade of the brain. *Science*, 284, 739. doi: 10.1126/science.284.5415.739
- Jung, R. E., & Haier, R. J. (2007). The parieto-frontal integration theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behavioral and Brain Sciences*, 30, 135-187. doi: 10.1017/S0140525X07001185
- Kalbfleisch, M. L. (2008). Getting to the heart of the brain: Using cognitive neuroscience to explore the nature of human ability and performance. *Roeper Review*, 30, 162-170. doi: 10.1007/s11571-006-9007-4
- Kalbfleisch, M. L. (2009). The neural plasticity of giftedness. In L. Shavinina (Ed.), *International Handbook on Giftedness* (pp. 275-293). Springer Science. doi: 10.1007/978-1-4020-6162-2_12
- Kalbfleisch, M. L., deBettencourt, M. T., Kopperman, R., Banasiak, M., Roberts, J. M., & Halavi, M. (2013). Environmental influences on neural systems of relational complexity. *Frontiers in Psychology*, 4, 1-15. doi: 10.3389/fpsyg.2013.00631

- Kalbfleisch, M. L., & Gillmarten, C. (2011). The neuroscience of giftedness. In T.L. Cross & J.L. Cross (Eds.), *Handbook for counselors serving students with gifts and talents: Development, relationships, school issues, and counseling needs/interventions* (pp. 89-104). Waco, TX: Prufrock Press.
- Kalbfleisch, M. L., & Gillmarten, C. (2013). Left brain vs. right brain: Findings on visual spatial capacities and the functional neurology of giftedness. *Roeper Review*, 35(4), 265-275. doi: 10.1080/02783193.2013.829549
- Kalbfleisch, M. L., & Loughan, A. R. (2011). Impact of IQ discrepancy on executive function in high-functioning autism: Insight into twice exceptionality. *Journal of Autism and Developmental Disorders*, 42(3), 390-400. doi: 10.1007/s10803-011-1257-2
- Kalbfleisch, M. L., Van Meter, J. W., & Zeffiro, T. A. (2007). The influences of task difficulty and response correctness on neural systems supporting fluid reasoning. *Cognitive Neurodynamics*, 1(1), 71-84. doi: 10.1007/s11571-006-9007-4
- Kandel, E. R., Markram, H., Matthews, P. M., Yuste, R., & Koch, C. (2013). Neuroscience thinks big (and collaboratively). *Nature Reviews Neuroscience*, 14, 659-664. doi: 10.1038/nrn3578
- Kelley, P., Lockley, S. W., Foster, R. G., & Kelley, J. (2014). Synchronizing education to adolescent biology: 'Let teens sleep, start school later'. *Learning, Media, and Technology*, 39, 1-17. doi: 10.1080/17439884.2014.942666
- Kim, S. (2013). Neuroscientific model of motivational process. *Frontiers in Psychology*, 4, 1-12. doi: 10.3389/fpsyg.2013.00098
- Kral, T. V., Heo, M., Whiteford, L. M., & Faith, M. S. (2012). Effects on cognitive performance of eating compared with omitting breakfast in elementary schoolchildren. *Journal of Developmental & Behavioral Pediatrics*, 33(1), 9-16. doi: 10.1097/DBP.0b013e31823f2f35
- Kvale, S., & Brinkmann, S. (2009). *Interviews: Learning the craft of Qualitative research interviewing* (2nd ed.). Thousand Oaks, California: SAGE Publications, Inc.
- Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8-9-year-old students. *Cognition*, 93(2), 99-125. doi: 10.1016/j.cognition.2003.11.004
- Landi, N., Frost, S. J., Mencl, W. E., Sandak, R., & Pugh, K. R. (2013). Neurobiological bases of reading comprehension: Insights from neuroimaging studies of word

- level and text level processing in skilled and impaired readers. *Reading and Writing Quarterly*, 29(2), 145-167. doi: 10.1080%2F10573569.2013.758566
- Laski, E. V., & Siegler, R. S. (2014). Learning from number board games: You learn what you encode. *Developmental Psychology*, 50(3), 853-864).
- Leahey, T. H., & Harris, R. J. (1997). *Learning and cognition* (4th ed.). Upper Saddle River, NJ: Prentice-Hall.
- Lindell, A. K., & Kidd, E. (2011). Why right-brain teaching is half-witted: A critique of the misapplication of neuroscience to education. *Mind, Brain, and Education*, 5(3), 121-127. doi: 10.1111/j.1751-228X.2011.01120.x
- Liu, J., Hwang, W. T., Dickerman, B., & Compher, C. (2013). Regular breakfast consumption is associated with increased IQ in kindergarten children. *Early Human Development*, 89(4), 257-262. doi: 10.1016/j.earlhumdev.2013.01.006
- Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1-6. *Developmental Science*, 17(5), 714-726. doi: 10.1111/desc.12152
- Mason, L. (2009). Bridging neuroscience and education: A two way path is possible. *Cortex*, 45, 548-549. doi: 10.1016/j.cortex.2008.06.003
- Maxwell, J. A. (2005). *Qualitative research design: An interactive approach*. Thousand Oaks, CA: Sage.
- Mayer, R. E. (1998). Does the brain have a place in educational psychology? *Educational Psychology Review*, 10, 389-396. doi: 10.1023/A:1022837300988
- McCrink, K., & Wynn, K. (2004). Large number addition and subtraction by 9-month-old infants. *Psychological Science*, 15(11), 776-781. doi: 10.1111%2Fj.0956-7976.2004.00755.x
- Merzenich, M. M., Van Vleet, T. M., & Nahum, M. (2014). Brain plasticity-based therapeutics. *Frontiers in Human Neuroscience*, 8, 1-12. doi: 10.3389/fnhum.2014.00385
- Micha, R., Rogers, P. J., & Nelson, M. (2011). Glycaemic index and glycaemic load of breakfast predict cognitive function and mood in school children: A randomised controlled trial. *British Journal of Nutrition*, 106(10), 1552-1561. doi: 10.1017/S0007114511002303

- Mishra, J., Merzenich, M. M., & Sagar, R. (2013). Accessible online neuroplasticity-targeted training for children with ADHD. *Child & Adolescent Psychiatry & Mental Health, 7*, 38-41. doi: 10.1186/1753-2000-7-38
- Mussolin, C., Mejias, S., & Noel, M. P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition, 115*(1), 10-25. doi: 10.1016/j.cognition.2009.10.006
- Neville, H. J., Stevens, C., Pakulak, E., Bell, T. A., Fanning, J., Klein, S., & Isbell, E. (2013). Family-based training program improves brain function, cognition, and behavior in lower socioeconomic status preschoolers. *Proceedings from the National Academy of Sciences USA, 110*(29), 12138-12143. doi: 10.1073/pnas.1304437110
- Organization for Economic Co-operation and Development (OECD). (2002). *Understanding the brain: Towards a new learning science*. Paris, France: OECD.
- Organization for Economic Co-operation and Development (OECD). (2007). *Understanding the brain: The birth of a learning science*. Paris, France: OECD.
- Pasquinelli, E. (2012). Neuromyths: Why do they exist and persist? *Mind, Brain, and Education, 6*(2), 89-96. doi: 10.1111/j.1751-228X.2012.01141.x
- Piaget, J. (1964). Part I: Cognitive development in children: Piaget development and learning. *Journal of Research in Science Teaching, 2*(3), 176-186. doi: 10.1002/tea.3660020306
- Piaget, J. (1970). *Genetic epistemology*. New York, NY: Columbia Press.
- Pickering, S. J., & Howard-Jones, P. (2007). Educators' views on the role of neuroscience in education: Findings from a study of UK and international perspectives. *Mind, Brain, and Education, 1*(3), 109-113. doi: 10.1111/j.1751-228X.2007.00011.x
- Plato. (trans. 1997). Meno. In J. M. Cooper (Ed.), *Plato: Complete Works* (pp. 870-897). Indianapolis, IN: Hackett Publishing Company.
- Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York: Scientific American Books.
- Posner, M. I. (2010). Neuroimaging tools and the evolution of educational neuroscience. In D. A. Sousa (Ed.), *Mind, Brain, & Education: Neuroscience Implications* (pp. 27-43). Bloomington, IN: Solution Tree Press.

- Posner, M. I. (2013). Forward: Imaging the future. In D. Mareschal, B. Butterworth, & A. Tolmie (Eds.), *Educational Neuroscience* (pp. xii-xv). West Sussex, UK: Wiley Blackwell.
- Posner, M. I., Rothbart, M. K., Sheese, B. E., & Voelker, P. (2014). Developing attention: Behavioral and brain mechanisms. *Advances in Neuroscience (Hindawi)*, 2014, 405094-. doi: 10.1155/2014/405094
- Posner, M. I., Rothbart, M. K., & Tang, Y. (2013). Developing self-regulation in early childhood. *Trends in Neuroscience and Education*, 2(3-4), 107-110. doi: 10.1016/j.tine.2013.09.001
- Posner, S. (Producer). (1995). *Cognitive neuroscience and education: Brain mechanisms underlying school subjects* [motion picture]. (Available privately from Dr. Layne Kalbfleisch).
- Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language, and reading. *NeuroImage*, 62, 816-847. doi: 10.1016/j.neuroimage.2012.04.062
- Price, G. R., Holloway, I., Rasanen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*, 17(24), R1042-R1043. doi: 10.1016/j.cub.2007.10.013
- Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., . . . Shaywitz, B. A. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews*, 6(3), 207-213. doi: 10.1002%2F1098-2779%282000%296%3A3%3C207%3A%3AAID-MRDD8%3E3.0.CO%3B2-P
- Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., . . . Shaywitz, B. A. (2001). Neurobiological studies of reading and reading disability. *Journal of Communication Disorders*, 34(6), 479-492. doi: 10.1016%2FS0021-9924%2801%2900060-0
- Purdy, N. (2008). Neuroscience and education: How best to filter out the neurononsense from our classrooms? *Irish Educational Studies*, 27(3), 197-208. doi: 10.1080/03323310802242120
- Raskind, W. H., Peter, B., Richards, T., Eckert, M. M., & Berninger, V. W. (2013). The genetics of reading disabilities: From phenotypes to candidate genes. *Frontiers in Psychology*, 4, 1-20. doi: 10.3389/fpsyg.2012.00601

- Renzulli, J. S., Leppien, J. H., & Hays, T. S. (2000). *The Multiple Menu Model: A Practical Guide for Developing Differentiated Curriculum*. Mansfield Center, CT: Creative Learning Press.
- Richland, L. E., Stigler, J. W., & Holyoak, K.J. (2012). Teaching the conceptual structure of mathematics. *Educational Psychologist, 47*(3), 189-203. doi: 10.1080/00461520.2012.667065
- Rivera, S. M., Reiss, A. L., Eckert, M. A., & Menon, V. (2005). Developmental changes in mental arithmetic: Evidence for increased functional specialization in the left inferior parietal cortex. *Cerebral Cortex, 15*, 1779-1790. doi: 10.1093/cercor/bhi055
- Roberts, R. D., & Lipnevich, A. A. (2012). From general intelligence to multiple intelligences: Meanings, models, and measures. In K.R. Harris, S. Graham, T. Urdan, S. Graham, J.M. Royer, & M. Zeidner (Eds.), *APA Educational Psychology Handbook (Vol. 2): Individual Differences and Cultural and Contextual Factors* (pp. 33-57). Washington, DC, US: American Psychological Association.
- Samuels, B. M. (2009). Can the differences between education and neuroscience be overcome by mind, brain, and education? *Mind, Brain, and Education, 3*(1), 45-55. doi: 10.1111/j.1751-228X.2008.01052.x
- Schwartz, M., & Gerlach, J. (2011). The birth of a field and the rebirth of the laboratory school. *Educational Philosophy and Theory, 43*, 67-74. doi: 10.1111/j.1469-5812.2010.00709.x
- Shaywitz, B. A., Shaywitz, S. E., Blachman, B. A., Pugh, K. R., Fulbright, R. K., Skudlarski, P., . . . Gore, J. C. (2004). Development of left occipitotemporal systems for skilled reading in children after a phonologically-based intervention. *Biological Psychiatry, 55*, 926-933. doi: 10.1016/j.biopsych.2003.12.019.
- Shaywitz, S. E., Shaywitz, B. A., Pugh, K. R., Fulbright, R. K., Constable, R. T., Mencl, W. E., . . . Gore, J. C. (1998). Functional disruption in the organization of the brain for reading in dyslexia. *Proceedings of the National Academy of Sciences USA, 95*(5), 2636-2641. doi: 10.1073%2Fpnas.95.5.2636
- Sheskin, M., Bloom, P., & Wynn, K. (2014). Anti-equality: Social comparison in young children. *Cognition, 130*(2), 152-156. doi: 10.1016/j.cognition.2013.10.008
- Sigman, M., Peña, M., Goldin, A. P., & Ribeiro, S. (2014). Neuroscience and education: Prime time to build the bridge. *Nature Neuroscience, 17*(4), 497-502. doi: 10.1038/nn.3672

- Skinner, B. F. (1938). *The behavior of organisms: An experimental analysis*. Englewood Cliffs, NJ: Prentice-Hall.
- Skinner, B. F. (1974). *About behaviorism*. New York: Knopf.
- Spearman, C. (1904). 'General intelligence' objectively determined and measured. *American Journal of Psychology*, *15*, 201-293. doi: 10.2307/1412107
- Stanovich, K. E. (1998). Cognitive neuroscience and educational psychology: What season is it? *Educational Psychology Review*, *10*, 419-426. doi: 10.1023/A:1022893418735
- Stephenson, J. (2009). Best practice? Advice provided to teachers about the use of brain gym in Australian schools. *Australian Journal of Education*, *53*(2), 109-124. doi: 10.1177/000494410905300202
- Stern, E. (2005). Pedagogy meets neuroscience. *Science*, *310*, 745. doi: 10.1126/science.1121139
- Stigler, J. W., & Hiebert, J. (1999). *The teaching gap: Best ideas from the world's of teachers for improving education in the classroom*. New York: The Free Press.
- Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Thousand Oaks, CA: Sage.
- Szűcs, D., & Goswami, U. (2007). Educational neuroscience: Defining a new discipline for the study of mental representations. *Mind, Brain, and Education*, *1*(3), 114-127. doi: 10.1111/j.1751-228X.2007.00012.x
- Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., & Gabrieli, J. D. E. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from functional MRI. *Proceedings of the National Academy of Sciences*, *100*, 2860-2865. doi: 10.1073/pnas.0030098100
- Tommerdahl, J. (2010). A model for bridging the gap between neuroscience and education. *Oxford Review of Education*, *36*(1), 97-109. doi: 10.1080/03054980903518936
- Van Herwegen, J. V., Ansari, D., Xu, F., & Karmiloff-Smith, A. (2008). Small and large number processing in infants and toddlers with Williams syndrome. *Developmental Science*, *11*(5), 637-643. doi: 10.1111/j.1467-7687.2008.00711.x

- Varma, S., McCandliss, B. D., & Schwartz, D. L. (2008). Scientific and pragmatic challenges for bridging education and neuroscience. *Educational Researcher*, 37(3), 140-152. doi: 10.3102/0013189X08317687
- Vygotsky, L. (1928). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.
- Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: Writing a literature review. *MIS Quarterly*, 26(2), xiii-xxiii. Retrieved from: <http://www.jstor.org/stable/4132319>
- Willingham, D. T., & Lloyd, J. W. (2007). How educational theories can use neuroscientific data. *Mind, Brain, and Education*, 1, 140-149. doi: 10.1111/j.1751-228X.2007.00014.x
- Woods, D. K., & Fassnacht, C. (2012). Transana (Version 2.6) [Computer Software]. Madison, WI: The Board of Regents of the University of Wisconsin System. Retrieved from <http://www.transana.org>
- Woolfolk, A. (2010). *Educational psychology* (11th ed.). Saddle River, NJ: Pearson.
- Xu, F. (2003). Numerosity discrimination in infants: Evidence for two systems of representations. *Cognition*, 89(1), 15-25. doi: 10.1016/S0010-0277(03)290005-7
- Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, 74(1), B1-B11. doi: 10.1016/S0010-0277(99)2900066-9
- Zimmerman, B. J., & Kitsantas, A. (2005). The hidden dimension of personal competence: Self-regulated learning and practice. In A.J. Elliot & C.S. Dweck (Eds.), *Handbook of Competence and Motivation* (pp. 509-526). New York: The Guilford Press.
- Zwingmann, C., Inhelder, B., & Chipman, H. H. (Eds.) (1976). *Piaget and his school: A reader in developmental psychology*. New York, NY: Springer.

BIOGRAPHY

Charles Gillmarten graduated high school from GW Community School, Fairfax, Virginia, in 2004. He received his Bachelor of Arts from St. John's College, Annapolis, MD in 2008. He was employed as a croquet club professional for one year at the National Croquet Center in West Palm Beach, Florida. He received his Master of Science in Educational Psychology from George Mason University in 2011.