RESEARCH IN MIND, BRAIN, AND EDUCATION

Edited by Marc S. Schwartz
and E. Juliana Paré-Blagoev

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4

READING FROM A MIND, BRAIN, AND EDUCATION PERSPECTIVE

Donna Coch

> [T]o completely analyze what we do when we read . . . would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilization has learned in all its history.
>
> Huey, E. B

When you come to the period at the end of this sentence, pause for a few moments to think about what you were doing while you were getting there and generate a list of relevant verbs. Certainly you were *reading*, but what does it mean to read? You were *looking* at the lines and curves of the print and punctuation on the page, which involves visual perceptual processing. You were *recognizing* certain patterns of lines and curves as letters, and certain strings of letters as words, which involves orthographic processing. You might have been *hearing* a voice in your head, sounding out the words, which involves phonological processing. You could have implicitly *noticed* meaningful sequences of letters, like the *-ing* in *getting* marking the present tense, which involves morphological processing. You most likely *knew* and *remembered* the meaning of each of the words in the sentence, which involves semantic processing. And you probably *combined* the meanings of each of the words in the sentence into an understandable concept, which involves syntax and comprehension and allowed you to actually engage with the text and perform the tasks of pausing and generating verbs. And it is likely that you *coordinated* all of these processes automatically and flawlessly to successfully complete those tasks. In addition to these more specifically reading-related processes, you may have used more domain-general processes (i.e., not necessarily specific to reading only) like attention and motivation. If your attention flagged and your mind started wandering mid-sentence, or if you were really not motivated to begin reading this chapter, it is unlikely that you completed the tasks.

This example serves as an illustration of the complexity of reading. Reading is an inherently complex concept and skill that needs to be unpacked in both research and education. If a teacher believes that one of his second graders is a poor reader, what does that mean? That the child does not recognize letters or letter patterns? Is not able to sound out words? Does not have a large vocabulary and therefore does not know the meanings of many of the words in a text? Has not been given a text at an appropriate level? Does not use comprehension strategies? Is not motivated to read? This level of specificity *matters*: By unpacking the concept of reading, instruction and intervention can be focused and differentiated, targeting the component skills that each child needs to develop as a reader. In a similar way, studying reading in the lab requires researchers to think about what aspect of reading to focus on, isolate, and manipulate. For MBE researchers, this comes with the opportunity – and challenge – of thinking across different fields.

Reading Research in MBE: A Personal Perspective

An Interdisciplinary Mindset

As a teacher and reading researcher in MBE, one of my greatest challenges is to facilitate an interdisciplinary mindset. This involves helping learners to both recognize connections and begin building connections for themselves across relevant fields. The relevant fields differ according to the area of interest, but the basic contributing fields are psychology, neuroscience, and education; for reading research, linguistics is often also a contributor. For me, it is not a burden to work across these multiple fields, but rather a bonus – for me, questions and issues take on added depth and richness when considered from multiple perspectives, and the world becomes a more interesting place. Indeed, education seems the perfect "terrain for taking multiple perspectives" (Gardner, 2009, p. 69). Instances in which information about the same topic in different fields is contradictory or incompatible, or in which information is extensive in one field but sparse or simply missing in another, are leverage points to begin asking important questions. The cost, of course, is that it is difficult, especially in the beginning, to analyze and synthesize across multiple perspectives. However, like other skill sets, thinking and working across fields becomes easier the more practice you have with it. So where to begin? How would you actually go about conducting MBE reading research?

The Literature Search

It is easy to become overwhelmed by the plethora of scientific articles reporting on reading: An ERIC search for *reading* yields over 137,000 hits; a PsycINFO search over 126,000; and a MEDLINE search over 163,000. No one could master that entire literature, either within or across the education, psychology, and medical domains. So it is important to unpack complex concepts, and begin your search, not with a more general term like *reading*, but with a more specific (yet still broad) term like *orthographic processing* instead. Even then, the process of delineating your topic is generally an iterative one with many cycles of narrowing your search terms, following leads that seem promising but end up in a part of the literature that is irrelevant or uninteresting to you, and backtracking to pick up a previously abandoned thread, only to start all over again. This literature search to narrow down to a specific topic is a crucial, foundational process (e.g., Boote and Beile, 2005), but one with which many students struggle.

One of the reasons for that struggling may be that, while experimental science is supposed to be precise, the literature search at the beginning is often relatively ill defined, with fuzzy boundaries. But, eventually, after many iterations, you will develop a sense of the borders of your topic of interest and the research most relevant to your topic. Clearly defining the limits of your literature review affords the opportunity for scholarly, critical synthesis of ideas and methodologies (e.g., Boote and Beile, 2005). In MBE, those limits cross typical disciplinary boundaries, so your search terms may be different within different literatures and you will need to critically analyze and synthesize information across fields. The goal of this general approach is, within some area of interest to you, to find the edge of the literature: to have a deep understanding of what research has been done on a specific topic across relevant fields, how it has been done, what questions have been answered, and what questions remain to be answered. In recognizing what the next logical step is to take in your research topic area, you can begin to construct your research question and experimental design.

An example may help to illustrate an interdisciplinary literature search. The notion of the fourth grade slump has been discussed in the reading literature for decades (e.g., Adams, 1990; Chall, Jacobs, and Baldwin, 1990; Stanovich, 1986), and has also been considered in the education literature (e.g., Goodwin, 2011) and popular press (e.g., Tyre and Springen, 2007). It characterizes students who appear to have mastered the basics of reading in the primary grades, but struggle with the shift from "learning to read" to "reading to learn" that typifies the requirements of the traditional fourth grade curriculum (e.g., Chall, 1983). Although a marked shift at fourth grade is sometimes called a myth (e.g., Houck and Ross, 2012), that the relative balance between *learning* and *using* reading is expected to alter around the fourth grade was even instantiated in US federal education law: One goal of No Child Left Behind was to "ensur[e] that every child can read by the end of third grade" (Executive summary of the *No Child Left Behind Act of 2001*, 2004). Despite this goal, in 2013, only about one-third of a nationwide sample of fourth-graders was reading at or above a proficient level (National Center for Education Statistics, 2013). Why does this matter? Children who do not read proficiently by the end of third grade are more likely to drop out of high school (Hernandez, 2011), with all the concomitant negative economic, health, and societal consequences (e.g., Tyler and Lofstrom, 2009).

Curiously, although the fourth grade has been discussed as a crucial juncture in reading development from many perspectives, the neuroscience literature has contributed virtually nothing to this discussion. In my interdisciplinary review spanning the behavioral reading, educational practice and policy, and neuroscience literatures, I did not come across any neuroscience articles on the fourth grade shift or slump in reading. This is particularly important because one hypothesis in the behavioral literature is that the fourth grade slump may be due to a lack of automatic and accurate word recognition, which the more unfamiliar and difficult vocabulary used in fourth grade texts reveals (e.g., Chall and Jacobs, 2003). It is possible that a neuroscientific approach could directly test the hypothesis of a shift toward automaticity in word processing around the fourth grade, but no studies that I could find had directly addressed this.

This is a real example from my own research. It all started when I kept coming across references to the fourth grade slump or the fourth grade shift in books and articles that I was reading for other purposes. Then I began thinking about what I actually knew about this phenomenon, whether I believed that it was real, what evidence there might be to support the notion, and what evidence there was regarding various hypotheses about its cause. And then I began a literature search across disciplines, which confirmed that this topic had been or could be studied from the perspectives of the psychology of reading development, education, and neuroscience; yet there was no nexus. So I discovered a leverage point, an entry into making meaningful connections across fields and, potentially, producing useable knowledge.

Tools and Technologies

But wondering what is going on in the brains of 9- and 10-year-olds as they read is not a research question. A good experimental research question includes operationalized, measurable variables. What exactly would I be measuring? What precisely was I asking? Before I could develop a decent research question, I had to consider possible tools and methods in the context of my literature review.

Choosing a Tool

In my review, it was the neuroscience piece of the story that was missing. There were plenty of behavioral data from developmental psychology studies and educational discussion, but I could find no published neural data specifically relevant to the fourth grade shift. I would need to generate neural data of my own.

For non-invasive developmental neuroscience work, only a few basic tools are available: If you want to find out what is going on inside the brain of a child, you can use electrophysiological measures (electroencephalogram, EEG, or event-related potentials, ERPs), magnetoencephalography (MEG), near infrared spectroscopy (NIRS), or functional magnetic resonance imaging (fMRI). NIRS and fMRI are dependent on blood flow, and so provide better spatial resolution; these technologies are good for answering questions about *where* in the brain information is processed. EEG, ERPs, and MEG are dependent on the real-time electrical and magnetic fields that neurons create when they are active, and so provide better temporal resolution; these technologies are good for answering questions about *when* information is processed in the brain. There are certainly practical issues in choosing which tool to use, such as which are available to you, how much funding you have for your project, and which tools you have been trained on, but there are also conceptual issues. Your choice of technology should dovetail with your question.

At this point, you may notice a certain lack of logical consistency in my approach to designing a study. There is no specific research question yet, and there is no choice of neuroscience technology yet, and yet each of these depends on the other. The interplay between pieces that are not quite in place is often part of the process of design. In this case, one way to break the impasse is to reconsider the literature. You may recall that one hypothesis in the literature about the fourth grade slump is that it is due to a lack of automaticity in word processing (e.g., Chall and Jacobs, 2003). Automaticity means that, over developmental time and with reading practice, word recognition should become increasingly fast, obligatory, and autonomous, and require only limited use of cognitive resources (e.g., LaBerge and Samuels, 1974; West and Stanovich, 1979; Wolf, 1991). If automatic word recognition is critical to the fourth grade shift, it would make sense to choose a method with good temporal resolution in order to study the shift, since one of the key characteristics of automaticity is timing (i.e., fast). Thus, EEG, ERPs, and MEG would seem like good choices to study automaticity in word recognition around the fourth grade. Luckily, I have access to an ERP lab and have conducted many ERP studies with college students and children.

ERPs

ERPs are recorded non-invasively at the scalp, and reflect the stimulus-locked information processing activities of large assemblies of neurons in different areas of the brain, providing a real-time neural recording (e.g., Coles and Rugg, 1995; Luck, 2005). The ERP is a derivative of the EEG. Whereas the EEG is a more general measure of the ongoing electrical activity in the brain, the ERP is more specific because it reflects electrical activity related to the presentation of some kind of stimulus (an electrical potential specifically related to some kind of event: event-related potential, ERP). Thus, the incoming data in an ERP experiment are the EEG waveforms, marked or tagged by the data acquisition software whenever a stimulus was presented to a participant.

More About ERPs: There are many resources available for you to learn more about ERPs. For example, Steve Luck's books (e.g., http://cognet.mit.edu/book/introduction-to-event-related-potential-technique or https://mitpress.mit.edu/books/introduction-event-related-potential-technique-0, retrieved 31 Jan, 2017) and Wikipedia (https://en.wikipedia.org/wiki/Event-related_potential, retrieved 31 Jan, 2017) provide accessible introductions to the technique and ERP waveforms. For a more detailed consideration of ERP components, consider *The Oxford Handbook of Event-Related Potential Components* (Luck and Kappenman, 2012; http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780195374148.001.0001/oxfordhb-9780195374148, retrieved 31 Jan, 2017)

Serendipity: Note that there are multiple examples of serendipity in conducting MBE research here. First, I just happened to notice that the idea of the fourth grade shift kept coming up in materials that I was reading for other purposes. This recurring pattern prompted me to start thinking about what evidence there really was for such a thing. Second, all of the extant hypotheses about the fourth grade shift could have involved variables or concepts that are better studied with fMRI or behavioral measures. It just so happened that one of the main hypotheses involved timing, which is a strength of the ERP method in which I was trained. Third, in searching for neuroscientific evidence in support of a fourth grade shift, it appeared that no one had used ERPs to specifically investigate this phenomenon before.

In data analyses after the participant leaves the lab, all of the sections of the EEG tagged as coinciding with a presentation of stimulus type A are averaged together to create the ERP to stimulus type A. All of the EEG sections tagged as coinciding with another stimulus type, for example type B presentations, are averaged together to create the ERP to stimulus type B, and so on. The resulting ERPs are characterized by components, peaks and valleys in the waveform that have been related to specific types of perceptual and cognitive processing (for reviews, see Coch and Gullick, 2012; Luck and Kappenman, 2012). Not all processes are indexed by the ERP method, and not all regions of the brain can be recorded from with electrodes placed on the scalp. That means that you have to have some knowledge of ERP components before designing an ERP study, to ground your study in the existing ERP literature. Luckily, I was already familiar with the N400 component of the ERP waveform.

The N400 Component

The N400 is a negative-going (the "N") deflection in the ERP waveform that peaks on average at about 400 milliseconds (the "400") after presentation of a stimulus. One millisecond is one one-thousandth of one second. Because this component peaks so soon after stimulus presentation, it likely at least in part reflects automatic processing (Holcomb, 1988); that is, you are not conscious of the processing indexed by the N400. Like other ERP components, the N400 can be measured in terms of its latency (the time at which it peaks, or achieves maximum amplitude) and its amplitude. A shorter latency (an earlier peak) is indicative of faster processing. A larger amplitude is indicative of more resources marshaled for processing. But what kind of resources and what kind of processing? Across many studies, the N400 has been associated with language processing; in particular, with semantic, or meaning, processing (e.g., for reviews, see Kutas and Federmeier, 2011; Kutas and Van Petten, 1994; Lau, Phillips, and Poeppel, 2008).

The results of studies in which adults have been asked to read different kinds of word-like stimuli, presented one by one while EEG is recorded, illustrate how the N400 indexes semantic processing. Three categories of word-like stimuli often compose the stimulus lists used in such studies. The first is real words (e.g., *bring*), which follow both the phonological (they are pronounceable) and orthographic (the letter combinations are legal and familiar in the language) rules of a language and have meaning. The second is pseudowords (e.g., *fring*), which are pronounceable strings of letters that follow orthographic rules, but happen to have no current meaning in the language. The third is often letter strings, sometimes called nonwords (e.g., *nrfgi*), which are unpronounceable strings of letters that break combinatory orthographic rules (i.e., although they are created from legal letters, the letter sequences are not permitted or familiar in the language) and have no meaning. If N400 amplitude indexes semantic processing, which of these stimulus types should elicit the largest and smallest N400s?

In studies with adults, the amplitude of the N400 elicited by pseudowords is often similar to or larger than the N400 elicited by real words, while letter strings elicit comparatively reduced or no N400 activity (e.g., Bentin, 1987; Bentin, McCarthy, and Wood, 1985; Bentin, Mouchetant-Rostaing, Giard, Echallier, and Pernier, 1999; Carreiras, Vergara, and Perea, 2007; Deacon, Dynowska, Ritter, and Grose-Fifer, 2004; Holcomb, Grainger, and O'Rourke, 2002; Laszlo and Federmeier, 2007; Nobre and McCarthy, 1994; Rugg and Nagy, 1987; Smith and Halgren, 1987; Swick and Knight, 1997). That might not have been your prediction; you might have quite sensibly predicted that, because real words have meaning, they would elicit the largest N400 and, because letter strings have no meaning, they would elicit the smallest N400. Researchers explain the potentially surprisingly large N400 elicited by pseudowords in terms of partial activation of semantic representations of multiple similar real words (e.g., Holcomb, Grainger, and O'Rourke, 2002). For a real word that you understand, you efficiently access the meaning, as indexed by an N400. For a pseudoword that you have not seen before, there is no specific meaning to access, but you might access a number of meanings of similar real words – is *fring* like *bring* or *ring* or *frying*? Now you have partially (partially because there is no exact match) activated the meanings of multiple other real words, and the partial activations of all of those semantic representations can add up to a marked N400 to pseudowords.

Such studies with adults suggest that only orthographically and phonologically legal letter strings that activate meaning representations in the lexical system elicit an N400 (e.g., Rugg and Nagy, 1987). Developmental N400 work introduces an interesting twist to this theory. For example, in a study designed to compare picture and word processing, we found that real words, pseudowords, letter strings, and strings of letter-like symbols all elicited an N400 in 11-year-olds, although the N400s to words and pseudowords were larger than the N400s to letter and symbol strings (Coch, Maron, Wolf, and Holcomb, 2002). And in a study with first graders, the amplitude of the N400s elicited by known words, unknown words, difficult words, and letter strings were statistically indistinguishable (Coch and Holcomb, 2003). These developmental data seem to be in direct contrast to the contention that only orthographically and phonologically legal strings that activate meaning representations in the lexical system elicit an N400 (e.g., Rugg and Nagy, 1987): By definition, letter strings and strings of symbols are orthographically and phonologically illegal, and should elicit no word-meaning-related activation – and yet they did.

These findings suggest that the processing that the N400 indexes develops across the elementary school years. In the beginning, the word processing system seems inefficient, affording all sorts of letter strings attempted semantic processing – as indexed by the N400 – indiscriminately. This makes some sense, as every string is essentially a potential word that you have not seen before in beginning reading (e.g., Henderson and Chard, 1980). But by the later elementary years, phonologically and orthographically legal strings elicit larger N400s than strings that could not have meaning (although the latter still elicit N400s, unlike the pattern observed in adults). The early, less selective or less restrictive processing of all strings as potential word candidates, as indexed by an N400 to all sorts of letter strings, may reflect a learning mechanism (e.g., Seidenberg and McClelland, 1989); increasing experience with reading words may lead to more efficient and automatic word processing over time. Could it be that there is a marked shift in this automaticity around the fourth grade, reflected in a shift in relative N400 amplitude to more (real words, pseudowords) and less (letter strings, strings of symbols) word-like stimuli? I found no studies in my literature searches that addressed this possibility.

Research Question and Design

Piecing together what we learned from the topic literature search and the literature search regarding the N400 component is like following a trail of breadcrumbs.

Especially in interdisciplinary work, you may be the only person who recognizes that there even is a trail; you may be the only one who has read that specific combination of articles and realized the potential for connections to be made. Pause for a moment and see if you can follow back our trail of breadcrumbs. If there is such a thing as the fourth grade shift, and it is related to the automaticity of single word processing, and if the N400 serves as an index of automatic, meaningful processing of words and potential words, then we should be able to use the N400 to investigate the fourth grade shift neuroscientifically. But just how might we go about doing that?

The Paradigm

Here is what we did in my lab. We asked third, fourth, and fifth graders to look at real words, pseudowords, letter strings, and strings of symbols presented one by one on a monitor while their EEG was being recorded. We also included an additional category of stimuli, animal names, in order to give the children something to do: We asked them to press a button whenever an animal name appeared on the screen. This made the paradigm a semantic categorization task, and ensured that each stimulus was processed meaningfully (you cannot decide whether a stimulus is the name of an animal or not without attempting to access word meaning). It also let us know whether the children were paying attention, because we could calculate an accuracy score reflecting how many of the animal names they found during the task. Plus, it made a pretty boring task more interesting; children went on a safari of sorts.

The Question

Our question was whether legal word stimuli (real words and pseudowords) would be processed differently, in terms of N400 amplitude, than illegal stimuli (letter strings and symbol strings) across the late elementary years. What would neuroscientific evidence for the fourth grade shift look like in this paradigm? If the N400 to all stimulus types was of similar amplitude in third graders (the first-grade pattern in our previous study), and the N400 was larger to legal word stimuli than to illegal stimuli in fifth graders (the adult pattern in previous studies), that would be clear evidence of a shift in automatic single word processing, as indexed by the N400, across the fourth grade. What about the fourth graders? The ones who had successfully navigated the shift would hypothetically show a more adult-like pattern, while the ones who had not yet made the shift would show a more undifferentiated, first-grade-like pattern. Recall that we began this section wondering what was going on in fourth graders' brains as they were reading. In essence, we are still investigating that question, but we have now included a quantifiable variable, the amplitude of the N400 component elicited by different types of stimuli, as an exact measure that allows us to ask a more precise question.

Brain and *Behavior*

Many people who work in the field of MBE are interested in connections between brain and behavior. The study that I described so far includes one behavioral measure: accuracy on the animal name semantic categorization task. That measure tells us very little about a child's reading behavior. In order to measure reading behavior more directly, each participant took a battery of standardized tests that assessed reading-related skills, including orthographic and phonological skills, vocabulary, and comprehension. We wanted to explore whether and how scores on these normed tests were correlated with the amplitude of the N400, providing a brain-behavior link. Having these two kinds of measures can help to constrain interpretation of the data, as any story that you want to tell as an explanation of the brain data must also be consistent with the behavioral data, and vice versa.

We also included one more behavioral measure. Once the children had completed the ERP task, we gave them a printed list of the stimuli and asked them to circle all of the items that were real words in English. Why? Because this confirmed for us which stimuli children recognized as real words – it was possible that they consciously knew very well which stimuli were real words and which were not, but that their brains were still automatically (and somewhat inefficiently, in terms of resource costs) shuttling all sorts of types of stimuli into the word processing system at 400 milliseconds, as indexed by N400 amplitude. Thus, this measure provided another avenue into exploring brain-behavior relations.

This approach highlights the fact that an ERP waveform (or fMRI picture) in and of itself has little meaning; the image must be interpreted, ideally in terms of relevant models and theories and findings from the peer-reviewed literature, and not idiosyncratically. This is yet another reason to conduct a careful, critical, and thorough literature review in order to inform the design of your study. Neuroscience data in MBE are most meaningful when considered in the context of behavioral and educational data and theory, with each level of analysis constraining interpretation of the other (e.g., Ansari and Coch, 2006; Willingham, 2009). A study in which the best predictor of early reading ability was neither a behavioral measure nor a neuroimaging measure, but a combination of the two types of measures (Hoeft et al., 2007), illustrates how simultaneous consideration of multiple levels of analysis can be educationally significant.

The Methods Section

What I have shared above about the design of our study is the type of information that is typically included in the methods section of a scientific article. The methods section is like a recipe for what the experimenter did and how she did it; it is really the heart of the study. A good methods section is written at a level of detail such that you could actually re-run the study yourself and see if you got the same results, or you could systematically manipulate one variable and see how that affected the results.

The Methods Section as a Must-Read: A few years ago, I made a shocking (to me, but maybe not to you) discovery: Most students in my classes simply skimmed or altogether skipped the methods sections of the empirical articles that I assigned. They read or scanned the introductions and the discussions, and got some of the general ideas, but had foggy notions about how the authors actually went about conducting the research or why. The methods section is the beginning of your how-to; if you are thinking about becoming an MBE researcher, methods sections are a must-read – the key to *how* to address a question with research.

But be aware that the kind of reading required by an empirical article is quite different than the kind of reading required by, for example, a novel read for pleasure. It takes time and practice to develop the deep, as opposed to surface, reading skills that scientific articles demand and to become familiar with academic language (e.g., Bean, 2011; Nagy and Townsend, 2012; Snow, 2010; van den Broek, 2010). However, it is well worth the time – indeed, a necessity – if you want to contribute to the field.

Students Can *and* Do *Contribute to MBE*

Above, I have outlined some of my research processes for one study. When undergraduate students in my lab conduct their own thesis research, the process is very similar. It is up to the student to choose a topic of personal interest; thoroughly search the relevant literatures; narrow the topic to a manageable size; critically review, analyze, and synthesize information across disciplines; develop a research question; and decide on an appropriate method and paradigm to address that question. Of course we have many extensive discussions along the way, but both the deep knowledge of that literature and the motivation for the study – the passionate commitment to wanting to know something – need to come from the primary investigator, who is the student for thesis projects. Thus, developing a research project necessarily involves the abilities to pay attention to details, organize and synthesize, work with uncertainty, and take intellectual risks independently.

I trust that students who have worked as research assistants in my lab for multiple years and have taken classes in my department have developed the practical, critical, and analytical skills necessary to develop meaningful ideas, craft useful questions, and make important and real contributions to the literature. Do I have evidence to support the trust that I put in my students? Undergraduate ERP thesis projects from students in my lab have been published in the peer-reviewed literature, on topics ranging from the neural correlates of single letter processing (Mitra and Coch, 2009) to homonym processing (Dholakia, Meade, and Coch, 2016; Meade and Coch, 2017) to arithmetic processing (Jasinski and Coch, 2012) to the relationship between music training and working memory (George and

Coch, 2011). Each of these articles represents a contribution to ongoing conversations in the field. Students, especially those versed in interdisciplinary thinking and methods, are integral to the continued development of MBE.

A Brief Journey into Reading

I opened this chapter with an illustration of the complexity of reading, a process that must be unpacked into its constituent skills in order to be investigated and taught. Reading involves many components, all developing at once. Teaching reading and learning to read involve facilitating the development of each of the component systems and integrating them to work together, automatically and fluently. Reading components begin to develop before children start formal schooling and continue to develop across years, well beyond elementary school and into college (e.g., Adams, 1990; Bean, 2011; Biancarosa and Snow, 2004; Lonigan, 2003; Nagy and Townsend, 2012; National Institute for Literacy, 2007; Snow, Burns, and Griffin, 1998; Treiman, 2000) – which means that, in some respect, all teachers are teachers of reading.

From a neuroscience perspective, given the many components involved in reading, it is not surprising that there is no one part of the brain that "does" reading. Indeed, there is really no "reading brain" at all: The brain is not designed for reading. Instead, there is a brain that learns, over time, to read; a child, teachers, parents, texts, and contexts that work together to actively build a brain that can read. As part of that learning and building process, the brain reuses and recycles neural systems that are specialized to process other sorts of information (e.g., Dehaene, 2009), conscripting them into the service of reading. For example, our ability to process print (orthography) builds on the specialties of our visual system, and our ability to sound out words (phonology) builds on our spoken language processing systems. This perspective is important because it suggests that if there are weaknesses in the contributing systems – for example, an uncorrected visual acuity problem or a specific language impairment – then a child may face greater challenges in learning to read. This perspective is also important because it contradicts the educational theory that learning to read is "natural" (e.g., Goodman and Goodman, 1979).

While I have not explored all of the component processes and skills involved in reading in my research, I have conducted studies on a number of different aspects of reading. For the most part, I have dabbled in aspects of reading that I have found not only interesting and relevant from a developmental or educational perspective, but also amenable to a combined neural and behavioral approach as afforded by an ERP lab. The following subsections represent a brief, selective journey into reading, as reflected in some of the studies conducted in my lab.

Orthographic Processing

Essentially, the main task of the reader is to make meaning of marks on a page. Those marks are the orthography of the language. Unless you are reading this in

Braille, the only input that you are receiving as you read is orthographic information that is processed through the visual system. The lines, curves, junctions, angles, and terminals that characterize the letters of the Roman alphabet are processed in the visual cortex, in the occipital lobe (e.g.,Van Essen and Gallant, 1994). However, those basic elements need to be combined into letters and the letters need to be combined into meaningful groups that compose words. In order to accomplish this, the reading system capitalizes on the properties of the ventral visual processing stream (e.g., Szwed, Cohen, Qiao, and Dehaene, 2009), which travels from the occipital lobe through the temporal lobe (e.g., Ungerleider and Mishkin, 1982). Neurons along the ventral visual pathway are specialized for processing color, form, texture, pattern, and fine detail (e.g., Livingstone and Hubel, 1988); form, pattern, and fine detail are all essential characteristics of orthography.

In adults, the features of letters are processed within about 150 milliseconds of presentation (e.g., Cole and Haber, 1980; Petit, Midgley, Holcomb, and Grainger, 2006; Polk and Farah, 1998). Letters appear to be processed as letters, with their own abstract identities, about 100 milliseconds later, in a subregion of an area along the ventral visual stream pathway called the fusiform gyrus (e.g., Flowers et al., 2004; Jacobs and Grainger, 1991; James, James, Jobard, Wong, and Gauthier, 2005; Mitra and Coch, 2009; Petit, Midgley, Holcomb, and Grainger, 2006). How and when such specialization for letter processing develops is an open, and educationally relevant, question. Our ERP work has shown, though, that basic form processing is not yet adult-like even by the age of 8 (Coch, Skendzel, Grossi, and Neville, 2005).

Specialization for word processing also occurs along the ventral visual stream, in another subregion of the fusiform gyrus. This area was first identified in a PET study using a set of stimuli with which you are now familiar: real words, pseudowords, letter strings, and symbol strings. The researchers dubbed the region within the left fusiform gyrus that was activated only to stimuli that took the form of a word (real words and pseudowords) the visual word form area (Petersen, Fox, Posner, Mintun, and Raichle, 1988). Other studies have since replicated the finding of specialized processing for orthographically word-like stimuli in the visual word form area (e.g., Braet, Wagemans, and Op de Beeck, 2012; Cohen and Dehaene, 2004; Cohen et al., 2002; Dehaene and Cohen, 2011; Gaillard et al., 2006; Grossi and Coch, 2005; McCandliss, Cohen, and Dehaene, 2003). Despite this, there is some controversy about the exact nature of processing in this region (e.g., Devlin, Jamison, Gonnerman, and Matthews, 2006; Polk and Farah, 2002). However, it does seem to be the case that, as children repeatedly encounter specific letter strings, those strings begin to assume an orthographic identity beyond basic visual percepts and begin to be processed automatically as words (e.g., Grainger, 2008; LaBerge and Samuels, 1974). Thus, learning to read involves adapting and specializing the ventral visual system through practice with printed words (e.g., McCandliss, Cohen, and Dehaene, 2003; Polk et al., 2002): Remarkably, learning to read – practice with a culturally defined stimulus category – actually changes and shapes the visual brain (e.g., Dehaene et al., 2010).

The behavioral word superiority effect, first reported in adults, illustrates that words have a special orthographic status in fluent readers (Reicher, 1969; Wheeler, 1970). In the classic Reicher-Wheeler paradigm, a string of letters is presented briefly and then masked (quickly covered by a pattern), and participants are asked to decide which of two letters occurred at a given position in the string (Reicher, 1969; Wheeler, 1970). The brevity of the presentation and the masking essentially make perception of the letter string subliminal – most participants report having seen either something, but they were not sure what, or nothing at all just before the mask. Thus, they often feel that their choice of letter is arbitrary. Nevertheless, participants identify the correct letter more often if the briefly presented string was a word (e.g., DARK) than if it was a nonword (e.g., RDKA, Estes and Brunn, 1987; Ferraro and Chastain, 1993; Johnston and McClelland, 1974; Prinzmetal, 1992); this is the word superiority effect. The same pattern is seen with pseudowords (e.g., DARL) as compared to nonwords, likely due to the word-likeness of pseudowords (e.g., Estes and Brunn, 1987; Grainger and Jacobs, 1994; Massol, Midgley, Holcomb, and Grainger, 2011; Ozubko and Joordens, 2011); this is the pseudoword superiority effect.

Although the Reicher-Wheeler paradigm provides a way to investigate the development of orthographic automaticity, few studies have used it developmentally. One behavioral study reported that 7-year-olds, 11-year-olds, and adults showed both word and pseudoword superiority effects (Grainger, Bouttevin, Truc, Bastien, and Ziegler, 2003). Another reported that 7-year-olds, 11-year-olds, and adults all showed word superiority effects, but that the pseudoword superiority effect was larger for adults than children (Chase and Tallal, 1990). To our knowledge, no ERP studies had used this paradigm to explore the neural development of automatic orthographic processing.

In order to investigate both the behavioral and neural development of orthographic automaticity, we borrowed the stimuli from one of the previous behavioral developmental studies (Chase and Tallal, 1990) and adapted the Reicher-Wheeler paradigm for use with ERPs (Coch and Mitra, 2010; Coch, Mitra, and George, 2012). In our study with children, both 7-year-olds and 11-year-olds showed behavioral word and pseudoword superiority effects, choosing which letter had been in a given position in the masked string more accurately when the string had been a real word or pseudoword than when it had been a nonword. This replicated the previous behavioral findings. In terms of ERPs, superiority effects were evident in the amplitude of both the P150 (a positive deflection in the waveform peaking at about 150 milliseconds after stimulus presentation) and N400 components for 11-year-olds, but only in the amplitude of the N400 for 7-year-olds. Thus, although the age groups appeared similar behaviorally, the contributing underlying processing was quite different between groups: Both early (P150, sublexical) and late (N400, lexical) processing supported the superiority effects in 11-year-olds, but only late processing supported the effects in 7-year-olds. This pattern indicates a long developmental time course, extending at least to age

11, for automatic sublexical orthographic specialization. It also provides another example of the power of working at multiple levels of analysis: Without the neural evidence, the behavioral evidence alone might have suggested that automatic orthographic specialization, as measured in the Reicher-Wheeler paradigm, was adult-like by age 7.

Phonological Processing

Phonological processing has been a recent focus in reading, in part because the report of the National Reading Panel emphasized that "teaching that makes the rules of phonics clear will ultimately be more successful than teaching that does not" (National Institute of Child Health and Human Development, 2000; Rayner, Foorman, Perfetti, Pesetsky, and Seidenberg, 2002, p. 89). Phonics, at its core, involves learning the mappings between letters and sounds, or the links between orthography and phonology. For typically developing readers, phonics instruction can be limited to the primary grades (e.g., Stahl, 1992; Stahl, Duffy-Hester, and Stahl, 1998), as just one part of a literacy program (e.g., Pressley, 2006; Templeton and Gehsmann, 2014). Explicit, systematic teaching of phonics during the early grades facilitates the recognition that spoken words break down into smaller parts (i.e., phonological awareness), and that these parts correspond to print (i.e., the alphabetic principle, e.g., Adams, 1990; Moats, 2000).

Alphabetical languages such as English, in which the mappings between print and sound are not one-to-one, are said to have a "deep" orthography. For example, the letter *c* corresponds with multiple sounds, as in *cat*, *city*, *chute*, or *chair*. Not surprisingly, learning to read is slower in languages with deep as compared to shallow orthographies (e.g., Caravolas, Lervåg, Defior, Málková, and Hulme, 2013). In order to teach or study these foundational mappings during learning to read, teachers and researchers need to have some linguistic knowledge. However, most adults have never "analyzed language at the level required for explaining and teaching it" (Moats, 2000, p. 7), and many teachers have poor phonological awareness themselves (e.g., Bos, Mather, Dickson, Podhajski, and Chard, 2001; Stainthorp, 2003).

My own work on phonological processing has focused on the rime unit, which is defined as the vowel sound and any consonant sounds that come after it. For example, the rime in the word *gate* is *-ate*. You will recognize that it is the phonological rime unit that allows for rhyming, as in tr*ain* and c*ane*. Rhyming is one of the easier forms of phonological awareness; it does not require phonemic awareness (recognizing each individual sound in a word), but does require awareness that words can be segmented into smaller parts. There is strong behavioral evidence that awareness of rhyme contributes causally to reading skill development, most likely by helping children to form word families and, later, spelling categories (e.g., Adams, 1990; Bryant, MacLean, and Bradley, 1990; Wagner and Torgesen, 1987).

Early in my career, I was involved in a handful of developmental ERP studies of word rhyming. In two of these studies, while ERPs were being recorded, children aged 7 to college students were presented with pairs of words, like *moose-juice* and *moose-chair*, and were asked to judge whether the words in the pairs rhymed or not. The second word of the pair elicited a larger N400/N450 component when it did not rhyme with the first word of the pair than when it did, in both the auditory (Coch, Grossi, Coffey-Corina, Holcomb, and Neville, 2002) and visual (Grossi, Coch, Coffey-Corina, Holcomb, and Neville, 2001) modalities. We observed this ERP rhyming effect at all ages, suggesting that phonological processing systems for rhyme are well-established by the school-age years (Coch, Grossi, Coffey-Corina, Holcomb, and Neville, 2002; Grossi, Coch, Coffey-Corina, Holcomb, and Neville, 2001).

In these studies, we used stimuli with semantic content (real words). This made us question the specificity of the ERP rhyming effect – was it really specific to phonological (rhyme) processing, or did it reflect semantic processing as well? How might we control for the potential influence of semantics? In a subsequent study with 6-, 7-, and 8-year-olds and college students, we chose to control for semantics by using pseudoword stimuli (Coch, Grossi, Skendzel, and Neville, 2005). Participants listened to pairs of made-up words (e.g., *nin-rin, ked-voo*) and judged whether the pseudowords in each pair rhymed or not. We found the ERP rhyming effect in all age groups, suggesting that the effect does primarily reflect phonological processing and confirming that rhyme processing systems are established by the early school years. We also administered a standardized measure of phonological awareness in this study. In analyses in which we divided the children into two groups based on scores on this measure (called a median split), we found a direct brain-behavior connection: The ERP rhyming effect onset 80 milliseconds later in the group with poorer, as compared to better, phonological awareness (although all children scored within normal limits, Coch, Grossi, Skendzel, and Neville, 2005).

Serendipity Again: I had thought that this would be the extent of my ERP work on phonological processing. However, I was discussing some of these findings one day with a local teacher, and our discussion changed my thinking. A veteran primary teacher, she commented that she could learn more about the reading needs of her students from a simple, quick, self-designed rhyme task than from all of the standardized testing that her school conducted. If a teacher who had been in the classroom for more than two decades thought that rhyme was that powerful a tool, a leverage point in reading (which reflected the behavioral research literature), perhaps it was worth some further investigation with ERPs. Thus, I decided to continue my research on rhyme processing.

In a subsequent series of ERP studies, my goal was to determine if there was an orthographic stimulus set simpler than words or pseudowords that could be used in a visual rhyme paradigm. My concern was that, particularly for struggling and beginning readers, there was a potential critical confound in using visual words or pseudowords in a rhyme paradigm: A lack of a rhyming effect could be due to an inability to rhyme, but it could also be due to an inability to read the stimuli, and not really be a measure of rhyming ability at all. Are there stimuli that require orthographic-to-phonological mapping similar to word and pseudoword reading, but do not present this potential confound? In my lab, we investigated the possibility that single letters could play this role. Single letters used in a rhyming task are an attractive option because they allow for simultaneous consideration of the two best predictors of learning to read: phonological awareness and letter name knowledge (e.g., Adams, 1990; Treiman, 2000).

In the first study in this series, we used word, pseudoword, and single letter (e.g., *a-j*, *b-i*) pairs in a rhyme judgment task with college students (Coch, Hart, and Mitra, 2008). We found a similar ERP rhyming effect in each of the three conditions, suggesting that single letter pairs were processed (phonologically) like word and pseudoword pairs. In the second study with college students, we compared lowercase and uppercase letter pairs in the rhyming paradigm (Coch, George, and Berger, 2008). Previous developmental, behavioral work had suggested a preference for uppercase letters preceding use of lowercase letters in children (Treiman, Cohen, Mulqueeny, Kessler, and Schechtman, 2007; Worden and Boettcher, 1990), and the frequencies of lowercase and uppercase letters in print are not equivalent (Jones and Mewhort, 2004), suggesting that there might be processing differences for these stimuli. We found that both stimulus types elicited an N450 rhyming effect, and that the effect was similar in each condition (Coch, George, and Berger, 2008). In the third study, we (finally!) investigated the uppercase letter rhyming effect in 6- to 8-year-old children as compared to college students, and found a typical N400/N450 rhyming effect in each group (Coch, Mitra, George, and Berger, 2011). Thus, this series of studies confirmed the viability of using single letter stimulus pairs in a rhyming paradigm in order to investigate on-line phonological processing during learning to read.

Morphological Processing

A morpheme is the smallest pronounceable unit of a word that carries meaning (e.g., Nida, 1976). A morpheme can be a whole word (e.g., *cat*) or a part of a word, like a prefix (e.g., *pre-*, meaning before), suffix (e.g., *-ed*, meaning past tense), or root (e.g., *-chrono-*, meaning time). A morpheme that can stand alone as a complete and meaningful word is called a free morpheme, while a morpheme that cannot be used in isolation, but must be combined with other morphemes to form a word, is called a bound morpheme. There is both behavioral (e.g., McCormick, Rastle, and Davis, 2008; McQueen and Cutler, 1998) and neuroimaging (e.g., Lavric, Clapp, and Rastle, 2007; Morris, Grainger, and Holcomb, 2008) evidence indicating that adult fluent readers automatically decompose morphologically complex words (e.g., *unhappiness*) into their constituent morphemes (e.g., *un-, happy, -ness*).

From a developmental and educational perspective, there is ample behavioral evidence for an important role of both morphological awareness in reading and instruction in morphology in literacy development (e.g., Adams, 1990; Anglin, Miller, and Wakefield, 1993; Carlisle, 2010; Goodwin and Ahn, 2010; Kuo and Anderson, 2006). For example, Carlisle (2000) asked third and fifth graders to break down morphologically complex words into the smallest pieces possible and then explain the meaning of each piece; performance on this task was related to scores on standardized tests of word reading and comprehension. Others have reported similar positive correlations between morphological awareness and reading comprehension, vocabulary, decoding rate and accuracy, and spelling in students in grades four through nine (e.g., Nagy, Berninger, and Abbott, 2006). Overall, better, but not poorer, readers tend to be aware of the function of morphemes (e.g., Adams, 1990; Moats, 2000). Further, explicit instruction in morphology contributes to phonological skill, orthographic skill, and word meaning knowledge (e.g., Carlisle, 2010). These sorts of findings suggest that morphological awareness is a key component to literacy learning that should be addressed in reading instruction (e.g., Berninger, Abbott, Nagy, and Carlisle, 2010).

Given this abbreviated and selective review of the morphology literature, you can see that there are relevant psycholinguistic, neuroscience, developmental, and educational data; thus, there is an opportunity to consider morphology from multiple perspectives and begin to make connections across those perspectives. My own work in this area stemmed from a senior honors thesis, which was developed based on an off-hand comment that I made in my course on reading. In this course, I asked students to read an article that reported that real words composed of bound morphemes (e.g., *receive*), pseudowords composed of bound morphemes (e.g., *exceive*), and morphologically complex control stimuli (e.g., *muffler*) all elicited N400s of similar amplitude, whereas control pseudowords that could not be decomposed into meaningful elements (e.g., *flermuf*) elicited substantially larger (i.e., greater amplitude) N400s (McKinnon, Allen, and Osterhout, 2003). Thus, N400 amplitude in this study with college students appeared to be "sensitive to the presence or absence of morphemes in the string, but not to whether the morphemes combine[d] to form a word" (McKinnon, Allen, and Osterhout, 2003, p. 886). As discussed above, the N400 is typically considered to reflect lexicosemantic or meaning processing (e.g., Kutas and Federmeier, 2011; Kutas and Van Petten, 1994; Lau, Phillips, and Poeppel, 2008); why would the N400 in this particular study not be sensitive to the meaningfulness of the complete string (i.e., whether the morphemes combined to form a word)? The findings did not make sense to me, and I mentioned parenthetically in class that someone should conduct a follow-up study or attempt a replication, and that that could make a good senior thesis project.

One of the students in that class went on to design an honors thesis project that used the bound morpheme and control stimuli from that previous ERP study (McKinnon, Allen, and Osterhout, 2003), and added a new free morpheme condition (Landers, 2009). In her behavioral lexical decision task (i.e., decide whether each stimulus is a real word or not), she found that response times were longer and accuracy was lower for pseudowords composed of legal morphemes than for pseudowords composed of non-morphemes, indicating that these behavioral measures (accuracy and response time) were sensitive to the morphological status of the stimuli, similar to the N400 in the original report (McKinnon, Allen, and Osterhout, 2003). However, in working with the stimulus set, we realized that it could have been better controlled for linguistic factors that might have had an influence on the results. Thus, in our subsequent study, we used a revised stimulus set in which the words and pseudowords within each of the three morphological types (bound, free, control) were matched for linguistic variables such as length, orthographic neighborhood size (the number of words of the same length that differ by only one letter), and bigram and trigram frequency (the frequency of the two- and three-letter combinations in the stimulus item).

Using this highly controlled stimulus set, we conducted an ERP lexical decision task study similar to McKinnon, Allen, and Osterhout (2003). Our results were markedly different: Across all three morphological types, the N400 was larger to pseudowords than to words (Coch, Bares, and Landers, 2013). Thus, in our study, N400 amplitude indexed the overall lexicality of the stimulus (whether it was a real word or not) rather than the meaningfulness of its constituent parts (whether it was composed of morphemes or not). This is consistent with other literature on the N400 (e.g., Kutas and Federmeier, 2011; Kutas and Van Petten, 1994; Lau, Phillips, and Poeppel, 2008), but opposite the finding in McKinnon, Allen, and Osterhout (2003). It seems likely that differences in stimulus construction and design contributed to the different outcomes between our study and McKinnon and colleagues'. This speaks to the importance of both controlled stimulus sets in reading studies and replication in science. In terms of the processes that lead to new information in scientific research, replication or partial replication with expansion are often viable avenues.

Semantic Processing

In education, semantic processing is usually considered in terms of vocabulary, or what words a student knows. But what does it mean to *know* a word? Knowing a word is a gradual process (e.g., Carnine, Silbert, Kame'enui, and Tarver, 2004) and goes well beyond the traditional skills of providing a dictionary definition and being able to use the word in a sentence (e.g., Adams, 1990; Miller and Gildea, 1987). Most of the 3,000–4,000 words, on average, that a student learns each year (Nagy and Anderson, 1984) are learned on his or her own, through encountering the words in context. However, this is an inefficient method, as there is only an estimated 10 percent chance that a student will be able to express a clear understanding of the meaning of a word upon her first encounter with that word in a grade-level text (Adams, 1990, p. 150; McKeown, Beck, Omanson, and Pople, 1985). Thus, in order to really learn a word's meaning, a student must have multiple encounters with that word in multiple contexts (e.g., Adams, 1990; Carnine, Silbert, Kame'enui, and Tarver, 2004; McKeown, Beck, Omanson, and Pople, 1985; Moats, 2000). It is not surprising, then, that the best predictor of vocabulary size after third grade is the amount of time spent reading (e.g., Carnine, Silbert, Kame'enui, and Tarver, 2004). In a powerful iterative loop, time spent reading develops vocabulary, boosts comprehension, and builds general knowledge about the world (e.g., Cunningham and Stanovich, 1998).

That most words are learned indirectly, through encounters in context, does not mean that there is no role for direct vocabulary instruction. It is estimated that about 300 words per year, or 8 to 10 per week, can be learned through direct instruction (e.g., Carnine, Silbert, Kame'enui, and Tarver, 2004). How should an educator choose and teach these precious few words? Evidence-based recommendations are relatively consistent (e.g., Adams, 1990; Birsh, 2005; Carnine, Silbert, Kame'enui, and Tarver, 2004; Moats, 2000): Vocabulary items should be central to a semantic field, potential anchors for other words that will be important in the text (i.e., be useful); both the denotative and connotative meaning of the word should be taught; the meaning of the word should be discussed in the context of the meanings of other known words (e.g., antonyms, synonyms, super- and subordinate category words); multiple meanings of the word should be considered; the derivational morphology of the word should be discussed; and multiple, concrete exposures to the word should be provided across contexts, allowing for repeated practice. In short, as many connections as possible should be made for a student to engage in deep (as opposed to surface) processing in order to learn the meaning of a word and situate that word within her semantic network. Note that this approach is a far cry from memorizing a list of 10 vocabulary items each week or looking up dictionary definitions (e.g., McKeown, Beck, Omanson, and Pople, 1985; Miller and Gildea, 1987); yet, given how common these latter methods for vocabulary development still are, the difference in approaches appears to be a prime example of a research-to-practice gap (e.g., Carnine, 1997).

A multi-layered approach to direct vocabulary instruction is relatively consistent with the psychological and neural literature on semantics. There is growing evidence that there is not one semantic area in the brain, in the sense that there is no mental dictionary localized in a specific region. Rather, it seems that semantic representations are distributed (e.g., Allport, 1985; Goldberg, Perfetti, and Schneider, 2006; McRae and Jones, 2013; Mitchell et al., 2008; Saffran and Sholl, 1999; Thompson-Schill, 2003; Yee, Chrysikou, and Thompson-Schill, 2013). This distributed view of lexicosemantic memory means that knowledge of a word is represented in an interconnected network of patterns of activation. For example, what you know about *cat* when you read the word includes activation of phonological regions for the sound of the word, orthographic regions for the look of the word, occipital regions that process the visual features of cats, auditory regions that process the sounds that cats make, somatosensory regions that process what the fur of a cat feels like, motor regions involved in petting, and so on; the coordinated re-activation of all of these areas as you read the word represents your knowledge of *cat* (for reviews, see Binder, Desai, Graves, and Conant, 2009; Martin, 2007). Because this view of semantics involves where in the brain information is represented, methods with strong spatial resolution, like fMRI, are a good fit for investigating the semantic network from this perspective.

Nonetheless, ERPs can also be used to investigate semantics, in terms of when and how words are processed.[1] Whereas the N400 can be elicited by isolated words, as discussed above, it was first identified in a sentence processing study. In this classic research, college students read sentences with meaningful (e.g., *He spread the warm bread with butter*) or senseless (e.g., *He spread the warm bread with socks*) final words; the terminal words that did not make sense in the semantic context elicited a marked N400 (Kutas and Hillyard, 1980). Subsequent studies have shown that the amplitude of the N400 to words in written sentence contexts is modulated by cloze probability (e.g., Taylor, 1953); that is, the predictability or expectedness of a given word in a given context: Less expected words elicit larger N400s (for reviews, see Kutas and Federmeier, 2000; Lau, Phillips, and Poeppel, 2008). Developmental work has shown that this is also the case in children as young as age 7 (Holcomb, Coffey, and Neville, 1992). Overall, these findings suggest that the N400 in sentence context can serve as "an index of the ease or difficulty of retrieving stored conceptual knowledge associated with a word, which is dependent on both the stored representation itself, and the retrieval cues provided by the preceding context" (Van Petten and Luka, 2006, p. 281).

In my lab, discussions about semantic context arose when a research assistant was texting during a lab meeting. After the usual conversation about turning off gadgets during meetings, we started talking about texting, debating whether texting was a language and whether being a fluent texter was like being bilingual (it is a lab that studies language and reading, after all). A quick literature search revealed many complaints about texting corrupting students' writing and spelling (e.g., Carrington, 2005; Lenhart, Aeafeh, Smith, and Macgill, 2008), but little actual empirical evidence about texting – and no neuroscience data. And so a senior thesis research project was born. Borrowing the classic N400 sentence paradigm (Kutas and Hillyard, 1980), we compared processing of regular English sentences with meaningful and senseless (anomalous) terminal words and the texted versions of those sentences (e.g., *c u l8r*, Berger and Coch, 2010). We found that anomalous sentence-final words in both the English and texted sentences elicited an N400, but that the semantic incongruity effect in the text condition peaked later and lasted longer (Berger and Coch, 2010). Intriguingly, this pattern – a later peak and longer duration for the N400 – had been reported previously in studies with bilinguals reading in their non-native language (e.g., for reviews, see Kotz and Elston-Guttler, 2004; Moreno, Rodriguez-Fornells, and Laine, 2008). That the processing of semantic anomalies in texted sentences and second languages was similar implied that texting may be like a second language. Remarkably, this finding further suggested that semantic processing systems are plastic enough to adapt to and accommodate cultural inventions such as communication via texting (Berger and Coch, 2010).

In Honor of Popper: This paradigm in which ERPs are recorded to the terminal words of sentences has become a classic in electrophysiological research. Using this paradigm and measuring the N400 elicited by sentence-terminal words allowed for comparison between our work and previous work. Given the numerous extant studies identified in our literature review and our careful replication of the English condition, we were convinced that this paradigm and the model of language processing on which it was built would be powerful enough for our purposes.

Out of the vast universe of possible outcomes, it was striking that the N400 pattern that we observed in the texting condition – the later peak and longer duration – appeared to match the pattern reported in previous studies of bilinguals reading in their second language. What data would have convinced us that we were wrong about this apparent correspondence? Any other N400 pattern would not have led us to this conclusion. Even a later peak without a longer duration or a longer duration without a later peak would not have justified this conclusion; it was the precision of the match – for both the paradigm and the pattern of findings – that supported our interpretation.

That being said, to move beyond apparent similarity, a study with fluent texters who were also traditionally bilingual would be necessary. This would allow for direct statistical comparison of the N400s elicited by incongruent terminal words in both a text and a non-native language condition in the exact same participants. If the N400s in these two conditions were statistically indistinguishable, and different from the N400 in a native language condition, this would confirm the apparent similarity, and our interpretation of it within the bilingual model of language processing.

Connecting to Educational Practice

You may have noticed that my research as reviewed above has not directly investigated educational practice. That is because I believe that it is necessary to first build a solid, evidence-based foundation for such studies. I also believe that developmental and learning studies that might be considered basic research, which are often crucial to building that foundation, are just as important to MBE as are practice-based studies. Indeed, now that I know more about what the N400s to single word and word-like stimuli look like in late elementary school children (Coch, 2015; Coch and Benoit, 2015) and I know that single letters in pairs can elicit an ERP rhyming effect in children (Coch, Mitra, George, and Berger, 2011), I am using those same paradigms to investigate whether those ERP effects (along with standardized behavioral measures of reading) change in struggling third and fourth grade readers who receive a targeted, intensive phonics-based intervention. Although some groundbreaking studies make great leaps, much research involves a slow, methodical, incremental accumulation of knowledge.

Teacher Education

Teacher education is another means by which I have connected my laboratory work with educational practice. As a faculty member in a department of education with a small teacher certification program, I have had the opportunity to work with undergraduate students who want to become teachers (e.g., Coch, Michlovitz, Ansari, and Baird, 2009). Some of these students took my research-based course on reading, and some worked in my lab (yes, an ERP lab in an undergraduate department of education), and some did both. For each of these experiences, teaching, learning, and research are inextricably intertwined, mutually informing one another.

Theoretically, these experiences afford the opportunity to construct a rich, interdisciplinary understanding of the process of reading at multiple levels of analysis. As a department of education that takes an evidence-based approach, we would like to be able to show that preservice teachers who build an interdisciplinary knowledge base through our content courses and work in our labs, and who have strongly supervised practical experiences through our clinical practica courses that build on their coursework and lab work – that is, preservice teachers who are trained from (or develop within) an MBE perspective – teach differently and therefore have students who learn differently. Do teachers who have this research-based understanding teach reading differently? Do they think about reading differently in the context of their classrooms? For example, are they better able to unpack the components of reading and therefore recognize strengths and weaknesses in individual students, differentiating instruction to meet students where they are? These remain empirical questions. These issues are not specific to our program, but are important to all teacher education (e.g., Dubinsky, Roehrig, and Varma, 2013; Leibbrand and Watson, 2010; National Research Council, 2010).

Forces Within and Beyond Your Control: The driving force behind my research and teaching has always been using what we know about the science of learning and development in the service of education. As an undergraduate major in Cognitive Science, I was fascinated by what researchers had discovered about learning, thinking, knowing, language, perception, expertise, and a host of other processes. The idea that these processes could be studied from multiple perspectives – e.g., neural, computational, psychological, philosophical, developmental – each perspective contributing a little piece of the story and all of the pieces needing to fit together to enable deep understanding, was breathtaking for me. But even then, at the beginning, I thought: This is not just academic – we should be *using* this knowledge; this could be *powerful* in the hands of educators.

That conviction led me to a doctoral program in Human Development and Psychology at Harvard Graduate School of Education, and a focus on reading as both a crucial educational leverage point and one of those "terrain[s] for taking multiple perspectives" (Gardner, 2009, p. 69). Eventually, it led me to the education department at Dartmouth College, perhaps unique as an undergraduate liberal arts education department with an evidence-based and interdisciplinary approach as well as a teacher certification program. I have been privileged and lucky to spend over a decade working with preservice teachers in this interdisciplinary context. It has been challenging and controversial work; so controversial, in fact, that the college administration recently decided to close our teacher preparation program. Passion and commitment are within your control, but budgets, the consumer model of education, and personnel issues are often beyond your control. My faith in an interdisciplinary and evidence-based model of teacher education (e.g., Leibbrand and Watson, 2010) at an undergraduate level is still strong, although I no longer have the opportunity to actively participate in that model at Dartmouth.

I also include discussions and interactions with practicing teachers under the umbrella of teacher education (e.g., Coch, Michlovitz, Ansari, and Baird, 2009). For me, this works in at least two ways: First, I get to share and talk about information from the scientific literature with teachers, and, second, I have the opportunity to learn about what teachers are thinking about and doing in their classrooms. As you might imagine, given my experience with my rhyme studies noted above, I agree that "a bidirectional relationship between research and practice is needed to help teachers understand scientific findings and to steer researchers toward questions that are relevant to educational practice" (Hinton and Fischer, 2008, p. 158). Recognizing that educators, as experts in guiding children's learning on a daily basis, have unique insight into learning and development is a key component of MBE, and part of the process that can create new knowledge (e.g., Coch, Michlovitz, Ansari, and Baird, 2009). If you are looking for ideas to investigate in MBE research, talking to teachers can be a good place to start. Following that, an interdisciplinary literature review can show you what relevant research has been done, how it was done, and what remains to be done. That, in turn, can lead you to a specific research question and design. Working in collaboration with teachers is one way to put the useable knowledge aspect of MBE at the forefront (e.g., Hinton and Fischer, 2008; McCandliss, Kalchman, and Bryant, 2003): It is more powerful to create new knowledge *with* educators than to create new knowledge *for* educators, if usability is a primary concern.

From the Lab to the Classroom?

Most of our studies start out with an educationally relevant question that eventually takes the shape of a combined neuroscience and behavioral study. Sometimes it is difficult to trace back that evolution and see the educational kernel at the core, and other times it is easier. Although we often start with an educational question, none of our studies are directly translatable from the lab to the classroom. This is one of the primary challenges of MBE research, and direct translation may be impossible (e.g., Daniel, 2011). Some of the undergraduate thesis studies conducted in my lab illustrate these points, and show how students can meaningfully participate in the field.

For example, one thesis project built on a previous study (Petit, Midgley, Holcomb, and Grainger, 2006) and compared two ERP components elicited by single real letters and made-up letter-like forms, finding that both types of stimuli elicited both components (Mitra and Coch, 2009). In publication, this study addressed specific questions about what sorts of processing those two ERP components indexed, which has implications for the nature of the neural letter processing system. In conceptualization, this study began as discussions about specialized neural processing for words (e.g., McCandliss, Cohen, and Dehaene, 2003), and similar specialized processing for letters (e.g., James, James, Jobard, Wong, and Gauthier, 2005). Clearly, children need to master letters before they can tackle words (e.g., Adams, 1990; Treiman, 2000), but little was known about the timing of specialized letter processing in the brain. Although the initial interest and motivation were about how children learn letters and how the brain becomes specialized for letter processing, we needed to build on the available literature; this shaped the eventual design of the study and the interpretative frame for the results.

Another thesis study began with the conviction of an accomplished flutist (and research assistant in my lab) that her brain must be different, in some way, than comparable students' who had not studied music intensively for many years. Thus, a personally relevant question about the potential neural effects of a specific kind of training (education) led to a critical literature search and the hypothesis that music training might be related to improved working memory. This hypothesis was confirmed, as, behaviorally, college-aged, nonprofessional musicians outperformed their non-musician counterparts on standardized tests of visual, phonological, and executive memory, and, neurally, musicians demonstrated faster updating of both auditory and visual working memory in a classic ERP paradigm (George and Coch, 2011). Overall, each of these projects began with an educationally relevant question (about neuroplasticity) that was reshaped both to build logically on the available literature and to fit within the constraints of research with ERPs. And each began with the curiosity of an undergraduate student, whose work eventually contributed meaningfully to the peer-reviewed literature.

Conclusion

In this chapter, I have discussed some of the practical and conceptual tools that I have used as a reading researcher and teacher in MBE, attempting to share how I both think about and conduct research. I have contextualized this focus on the process of research within selective discussions about the products of research, the findings that provide the conceptual and methodological framework for future studies. Despite the abundance of research on reading, there are many questions still to be answered and much work still to be done. Along these lines, I have highlighted the role of students in my research lab, and how they began to explore their own questions and participate in the MBE conversation.

While understanding both the process and products of research is a prerequisite to contributing meaningfully to a field, it is a necessary but not sufficient prerequisite. I believe that curiosity is one of the most important tools that educators and researchers need to have. Wanting to know how something works, why something happens, or if something will happen provides the motivation to ask interesting questions, persevere in doing difficult (often frustrating) but important work, discover novel findings, and create new knowledge – in action research or lab research. I also believe that an understanding of the amazing plasticity of the human brain is crucial for educators and researchers in MBE. A growth mindset (e.g., Dweck, 2008) allows for an appreciation of the diversity of developmental pathways and precludes giving up on learning, for both yourself and your students. In my view, these are additional vital tools for those who are studying and facilitating the active construction of a brain that can read, in all of its complexity.

Note

1 Considering my own ERP work on semantic processing, we have already discussed one in-depth example above: my study on the N400, the fourth grade shift, and the automaticity of word processing; you can find out what happened in that study by reading the articles that we published (Coch, 2015; Coch and Benoit, 2015).

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