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Educational Neuroscience: New Discoveries from Bilingual Brains, Scientific Brains, and the Educated Mind

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INTRODUCTION

Educational Neuroscience is an exciting and timely new discipline. It brings together individuals from diverse backgrounds, including cognitive brain scientists, learning scientists, medical and clinical practitioners, and those in educational policy and teaching. These individuals are joined in their *mutual* commitment to (a) solve prevailing problems in the lives of developing children, (b) understand the human learning capabilities over the life span (both in the brain and in behavior), and (c) ground educational change in the highly principled application of research that employs both behavioral as well as a multitude of modern methodologies, including brain imaging. This discipline provides the most relevant level of analysis for resolving today's core problems in education. Educational Neuroscience draws its empirical strength from its sister discipline, Cognitive Neuroscience, which combines decades of experimental advances from cognitive, perceptual, and developmental psychology with a variety of contemporary technologies for exploring the neural basis of human knowledge over the life span.[1]

The unique interdisciplinary discipline of Educational Neuroscience has already yielded remarkable advances in the understanding of particular developmental disorders, as there has already been a whole host of more appropriate assessment tools, treatment, and educational intervention for children with, for example, Attention Deficit and Hyperactivity disorders, Asperger Syndrome, and Autism. This is also true for children with atypical language development such as Dyslexia, Specific Language Impairment, and Dyscalculia. Identification of "sensitive periods" in development has yielded insights into when learning of key content is especially optimal. For example, new insights have come regarding *when* in the curricula to teach young bilingual children in their two languages (Berens, Kovelman & Petitto, 2009, submitted; Kovelman, Baker & Petitto, 2008), whether and when phonetic vs. whole-word reading instruction methods are most optimal for monolingual and, especially novel, bilingual children (Kovelman, Berens & Petitto, 2006; in preparation), how phonological awareness teaching activities can improve both good and atypical readers (e.g., dyslexics) (Shaywitz et al., 1998), how best to teach spelling (Norton, Kovelman & Petitto, 2007), and the developmental sequence underlying the learning of math and science. All of these advances have already begun to impact educational curricula. (For excellent discussion of all such advances see Byrnes & Fox, 1998; Geake, 2003; Geake & Cooper, 2003; Goswami, 2004; Ito, 2004; O'Boyle & Gill, 1998.)

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[1] The term "Educational Neuroscience" first appeared in the mission and vision statements on Dartmouth College's website (Hanover, New Hampshire, USA), as of July, 2002 (and remained thereafter), for the newly created "Department of Educational Neuroscience and Human Development." It was written by Laura-Ann Petitto to launch her 5-year tenure as Chair (2002-2007) and was a department and discipline promoted and advanced by Petitto, with the help of key cognitive neuroscience faculty, especially K. Dunbar, as well as D. Coch, and D. Ansari. Public presentations of this new field and term ensued by Petitto and Dunbar, and others. In their presentations, and subsequent report (Petitto and Dunbar, 2004), grants, and publications, they defined the field and provided clear instantiations of what Educational Neuroscience is, and how it can bridge the gap between academic theories and real-world educational problems.

What happens in the brain when we are educated? Whether knowledge of brain functions and learning can be used to benefit education has been a topic of great controversy over the past decade. Some have argued that studies in neuroscience are so far removed from educational practice that they have little relevance to education (e.g., Bruer, 1998, 2002). This has spurred an understandable worry in the education community that research on brain function is not relevant to education. Neuroscience is a discipline involving studies at the cellular level of the brain and is distinct from the discipline of cognitive neuroscience, which focuses on the brain's neural anatomy and systems of neural structures, and the knowledge functions that they mediate. While it is certain that neuroscience studies of the brain *will* ultimately contribute to our most *complete* understanding of human brain functions and behavior, it is routine knowledge among scientists that we must provide answers to all questions at their most appropriate level of analysis.

Here, we will show how Educational Neuroscience has the fullest potential to fundamentally advance contemporary educational policy and practice—and soon. We will show how key studies involving the learning of language (especially learning two languages as in childhood bilingualism) and the learning of science offer a new understanding of the timing, sequencing, and methods of learning these core content areas in education that in turn can influence the quality and methods of teaching and instruction. The fundamental premise within is that modern studies of the brain and learning can (1) reveal vital information about timing in education (i.e., when is exposure to core content optimally learned), (2) tell us about the mechanisms and the developmental sequence that underlie the learning of core content and related concepts, (3) explain why certain content and concepts are difficult for students to learn in early life—and why others are easier to learn, (4) suggest ways of learning and teaching that can be used to circumvent problems associated with traditional teaching methods, and (5) reveal optimal ways to promote conceptual change in science education.

Educational Neuroscience has indeed arrived, despite its still somewhat changing name: "Nurturing the brain," is one name that has appeared for this new field (Ito, 2004), "Neuroscience and Education" is another (Goswami, 2004), "Neurolearning" another (Bruer, 2003) and "Educational Neuroscience" is still yet another (e.g, researchers such as Petitto, Dunbar, Fischer, and others). As with any new discipline, the name will soon stabilize and the name for this innovative discipline used here will be "Educational Neuroscience."

In turning to our examples, language learning (bilingualism) and science learning in physics, chemistry, and biology have both been the subject of considerable controversy in education over the past 50 years. In both, a "hold-back" approach has dominated. In childhood bilingualism, it had been assumed that young bilinguals must be given a strong base in one language (e.g., English) before receiving instruction in their other language (e.g., Spanish) for fear that the child's other language might disrupt full acquisition of English. Similarly, in science education, such as physics and chemistry, instruction is not introduced until high school because it is feared that the child is not at the right conceptual stage to understand the material until their teenage years (Note that similar logic underlies why most monolingual children are not introduced to a "foreign" language until high school.) Implicit in the "hold-back" approach are assumptions about *timing* (when content should be introduced) and *sequencing* (what content must come first before exposure to other content, which carries additional presuppositions about the direction that conceptual mapping in humans obligatorily flows). These assumptions, in turn, have directly impacted prevailing *methods of instruction* and curricula in language and science, even though educators are highly aware that our students are having great difficulty in learning second languages and certain science concepts. We ask *why* do students experience such great difficulties? Here we use both behavioral and brain scanning technologies (fMRI, fNIRS) to gain exciting and useful new insights into what students are learning and when, why they have difficulties in learning these content areas (and related concepts), and what might be new forms of instruction that can aid learning.

WHAT EDUCATIONAL NEUROSCIENCE STUDIES CAN TELL US ABOUT BILINGUAL LANGUAGE LEARNING

For nearly a century, parents, educators, and scientists have been of two minds about the bilingual child. This phenomenon is so pervasive that our lab has come to call it “the bilingual paradox” (Petitto, Katerelos, Levy, Gauna, Tetreault, & Ferraro, 2001b). We freely marvel at the seemingly effortless ways that young children can acquire two or more languages simultaneously if exposed to them in early life. At the same time, we view early simultaneous bilingual exposure with suspicion, fearing that exposing a young child to two languages, too early, may cause language delay, and worse, language confusion. Indeed, the general perspective that young children are somehow harmed by bilingual exposure that occurs “too early” is reflected both in educational settings and in comments made by the many parents raising bilingual children who visit our laboratory. As support for this view, some have invoked the dreaded notion of “language contamination” that ostensibly results from early exposure to another language (e.g., Crawford, 1999). For example, in many educational settings in the United States, the fear that exposing a child to a *new* language (in addition to the majority language, such as English) or to two languages simultaneously (such as English and Spanish) too early may interrupt “normal” language development in the majority language (e.g., English), is reflected in contemporary educational practice. Most generally, we see this reflected in the fact that many children in the United States receive their first formal schooling in another language in high school, well after the developmentally crucial toddler years for language learning. More specifically, we see this reflected in the fact that bilingual policy in some U.S. States (e.g., Massachusetts) has undergone a dramatic policy reversal, whereby Spanish is withheld from young children from Spanish-speaking homes in their public-school classrooms, which now must be conducted in English-only. Following this general spirit, parents visiting our laboratory often opt to “hold back” one of the family’s two languages in their child’s early life. They believe that it may be better to establish one language firmly before exposing their child to the family’s other language so as to avoid confusing the child. They also worry that very early bilingual language exposure may put their child in danger of never being as competent in either of the two languages as monolingual children are in one (Petitto et al., 2001b).

To shed light on such “holding-back” views, researchers have examined the impact that acquiring two languages simultaneously has on the young child in early life. Two general classes of hypotheses have dominated the field, each echoing one side of the bilingual paradox. Genesee (1989) first termed these two classes of hypotheses the “unitary” and “differentiated” language system hypotheses. In the unitary language system hypothesis, researchers assert that children exposed to two languages initially have a single “fused” linguistic representation (they don’t know that they are acquiring two languages), and that they only begin to differentiate their two native languages around age 3 and beyond (e.g., Redlinger & Park, 1980; Vihman, 1985; Volterra & Taeschner, 1978). The assertion that bilingual children’s initial linguistic knowledge is “fused” implies that they undergo protracted (or delayed) language development (relative to monolingual peers) until they sort out their two input languages during early life. Indeed, for nearly two decades, one prevailing hypothesis in the scientific literature that spread into educational policy was that bilingual children do not initially differentiate between their two input languages and are thus slower—more delayed overall—in language learning as compared to their monolingual peers. By contrast, researchers who advocate the differentiated language system hypothesis assert that bilingual children can and do differentiate their two input languages (Genesee; Genesee, Nicoladis & Paradis, 1995; Lanza, 1992; Meisel, 1989, 2000), although the question of precisely when (what age) remains unanswered (see studies by Petitto below).

Bilingual Maturational Milestone Studies

In this series of studies, we tested hypotheses of delay and confusion in very young bilingual language learning, and examine indices of when (what age) bilingual language differentiation begins. In this first series of cognitive and developmental psychology behavioral studies, we investigated the impact of the age when a bilingual child is first exposed to a second language on the child's dual language mastery; that is, where first bilingual exposure occurs from birth as compared to first dual language exposure from age 3, from age 5, from age 7, or from age 9, whereupon the ages correspond to key ages of brain myelinization and maturation.2 The studies included the investigation of (1) the optimal age of first bilingual language exposure, (2) how long it takes for bilingual children to achieve mastery in a new language depending on the age of first bilingual language exposure and the type of language learning environment (home, community, classroom), (3) the development of linguistic milestones in bilingual children, because it is important to know what constitutes “normal” language acquisition in a *bilingual* child as compared to widely known monolingual norms, (4) normal/typical stages of bilingual language development, which helps teachers identify when a bilingual child is truly “language delayed” due to a language impairment versus simply undergoing the normal/typical sequence of bilingual language development, and (5) the impact of the introduction of a *new* language on a child's first/*home* language, which addresses the important educational question of language attrition; does learning a *new* language harm the old?

We found that (1) early (before age 5) bilingual language exposure is optimal for dual language development and dual language mastery (Kovelman & Petitto, 2002). (2) Those bilingual children who were first raised monolingual from birth and who were then exposed to a *new* language between 2–9 years of age *did* achieve the morphological and syntactic fundamentals of the new language within their first year of exposure. However, we found that the rapid acquisition of new language fundamentals was possible only when extensive and systematic exposure to the *new* language occured across multiple contexts. For example, we observed that the community and home were most optimal learning contexts, with far less optimal dual language mastery being achieved if exposure came exclusively within the classroom (Kovelman & Petitto, 2003; Petitto, Kovelman & Harasymowicz, 2003). (3) Bilingual children exposed to two languages from birth achieved their linguistic milestones in each of their languages at the same time and, crucially, at the same time as monolinguals (Holowka, Brosseau-Lapré & Petitto, 2002; Kovelman & Petitto, 2002; Petitto & Kovelman, 2003; Petitto et al., 2001b). (4) Bilingual children exposed to their *new* language between 2–9 years of age exhibited “stage-like” language development in their *new* language. Surprisingly, this stage-like development is highly comparable in content to the stage-like language development typical of monolingual children acquiring the language from birth,

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[2] Readers interested in knowing the details of the children and adult participants' specific language backgrounds, language use and language community contexts, and other important details of their SES, age, dual language maintenance, language preferences, etc., as well as the empirical methods by which all such information was rigorously gathered and assessed, are invited to refer to the individual articles cited in each summarized research section. Space restrictions do not permit extensive elaboration here except to say that no participant could be classified as an “English Language Learner.” In the United States, this is a term typically used to refer to a child from one home language background, say Spanish, who arrives at Kindergarten (and/or school grades beyond) and who is educated exclusively in the majority language, English. For many of these children, their formal language education begins with the introduction of English (again, in Kindergarten and/or beyond), is exclusive to English, and is accompanied by little or no formal language and reading instruction in their native home language (e.g., Spanish) after the onset of English training; hence, they have been termed “English Language Learners.” Rather than being English Language Learners, the children and adult participants in the Petitto studies summarized within would be classified as “bilingual,” those with dual language exposure, dual language education (in language, reading, etc.) and, crucially, dual language maintenance over the life span.

differing of course in the age when it occurs given the later exposure to the child's other language (Kovelman & Petitto, 2003). (5) Importantly, introduction of the *new* language did not 'damage' or 'contaminate' the *home* language of the child (Petitto et al., 2003).

Bilingual Infant Language Perception

Having found behavioral evidence that young bilinguals can differentiate their two languages from as early as the onset of first words (production studies), we turned to explore the phonetic discrimination abilities in *perception* in bilingual babies even before they could babble (For bilingual babies, see Norton, Baker & Petitto, 2003; Dubins, Berens, Kovelman, Shalinsky & Petitto, 2009; for monolingual babies/adults see Baker, Sootsman, Petitto & Golinkoff, 2003; Baker, Michnick-Golinkoff, & Petitto, 2006; Baker, Idsardi, Golinkoff & Petitto, 2005; Petitto, 2007; White, Kovelman, Shalinsky, McKenney, Berens, Dubins & Petitto, 2008; Dubins, White, Berens, Kovelman, Shalinsky & Petitto, 2009; for papers related to early phonetic processing/babbling see also Petitto & Marentette, 1991; Petitto, Holowka, Sergio, & Ostry, 2001a). These studies used either the classic infant controlled habituation paradigm (Cohen, 1972) in Petitto's Infant Habituation Lab or the Habituation paradigm in combination with new brain imaging technology in our lab, called functional Near Infrared Spectroscopy (fNIRS; discussed below). We examined the abilities that young bilingual and monolingual babies have for processing phonetic units, which is crucial to successful phonological segmentation of words, language learning, and later reading. We also investigated whether bilingual infants achieve developmental milestones for phonetic perception at the same ages as monolingual infants by testing bilingual babies' phonetic perception at two developmentally important ages, 4 months and 14 months. From birth to around age 4 months, monolingual babies have been shown to have the capacity to discriminate categorically the smallest "building blocks" of language—*the phonetic units such as in [ba] [da]*—from any of the world's languages. By around age 14 months, however, they lose this universal capacity, and, instead, hone in on the phonetic inventory of their native language with increased precision (e.g., Baker, Golinkoff & Petitto, 2006; Jusczyk, (1997); Kuhl & Padden, 1983). We especially wondered whether *bilingual* babies learning two languages show a similar pattern and developmental trajectory as monolingual babies, as evidenced in their behavioral phonetic discrimination abilities and neural tissue recruitment when learning the two sets of sounds in their two native languages?

We found that contrary to suggestions (e.g., Burns, Werker & McVie, 2003), bilingual babies are not "different" (atypical, delayed) in acquiring phonetic contrasts. Instead, our experimental results suggested to us that early bilingual exposure yields a phonetic processing "bilingual advantage" (Norton, Baker & Petitto, 2003). That is, relative to monolinguals, bilingual babies show an increased sensitivity to a greater range of phonetic contrasts, and an extended developmental window of sensitivity for perceiving these phonetic contrasts relative to monolingual children. This fascinating finding is under further study, as it suggests the possibility that bilingual phonetic perception in early life can function as a kind of "perceptual wedge" to keep open a child's capacity to discriminate phonetic units, while the same capacity attenuates quickly and dramatically for the monolingual child in early life. Furthermore, these findings suggest that bilingual children should *not* experience difficulty with phonological word segmentation in two languages at the same time, a capacity that is crucial for language learning and, especially, for successful reading acquisition in two languages; indeed, this hypothesis is returned to below in our comparative studies of the acquisition of reading in bilingual and monolingual children.

Imaging the Brains of Bilingual and Monolingual Infants

Having behaviorally explored young bilingual babies' phonological processing, tantalizing questions include what types of *neural tissue* underlie this capacity. Is it specific to language or general auditory processing tissue? Does neural participation change over time, and could an understanding of the tissue that supports language processing in bilingual and monolingual infants help us identify all babies at risk for language problems, even before they utter their first words? The educational implications of this would be significant as, today, we must wait until babies grow older (around 3 years) before they are definitively diagnosed with language problems, which is often well beyond the time when phonological processing tissue has lost the ability to discriminate all possible phonetic units in world languages (again, by around 14 months, as they instead attain an increased ability to discriminate phonetic units within their native language; e.g., classic discoveries by Werker & Tees, 1983; Kuhl & Padden, 1983). Standardized behavioral tasks with babies (mean age 3 months) involving (i) visual perception, (ii) speech recognition, and (iii) native and non-native phonetic perception were used with infants while undergoing functional Near Infrared Spectroscopy (fNIRS) recordings to test specific *within-hemisphere* neuroanatomical hypotheses about specific neural tissue (and networks of neural tissue) regarding their linguistic versus general perceptual processing functions. fNIRS is a non-invasive optical technology that, like functional Magnetic Resonance Imaging (fMRI), measures cerebral hemodynamic activity in the brain and thus permits one to "see" inside the brains of children and adults while they are processing specific aspects of a task. Unlike fMRI, fNIRS is small, highly portable (the size of a desktop computer), highly child-friendly, and can be used with alert babies. fNIRS is a closer measure of hemodynamic change than fMRI, as it provides information about oxygen rich (HbOxy), oxygen depleted (HbDeoxy), and total oxygen change (HbT), unlike fMRI that provides total Blood Oxygen Level Density/BOLD measures, and it has excellent spatial and temporal resolution. While the depth of measurement into the brain that fNIRS can accomplish (~5cm), is surpassed by fMRI (which can measure deep in the human brain), it is nonetheless ideal for the measurement of higher cognitive functions such as language. It is also quiet, free of the loud pings common to fMRI, and its tolerance of subtle movements makes it a stunning advance in the study of the full complement of human language, including language reception, speaking/signing language production, writing and reading across the lifespan.

Using fNIRS, we found robust activations in the brain's classic language areas in very young bilingual and monolingual babies. Bilingual and monolingual infants showed the same recruitment of language-dedicated neural tissue (including, for example, the Superior Temporal Gyrus, STG, for phonetic processing, the Left Inferior Frontal Cortex, LIFC, for word processing, as well as the primary visual occipital area, V1, for the sensory processing of nonlinguistic visual checkerboard; Petitto, 2003; Petitto, Baker, Baird, Kovelman & Norton, 2004; see also Peña et al., 2003).

Fascinating brain changes were seen over early life dependent on the baby's age and the classic language milestone associated with its age. We observed brain changes according to the baby's age, which were related to the achievement of well-known language milestones, provided among our first glimpses into the brain-based mechanisms that make possible the "developmental change" seen on the outside. The similarities between bilingual and monolingual babies' brains and performance also suggested that bilingual infants hone in on their native language in similar ways, and on the same time-table, as monolinguals. For example, the Superior Temporal Gyrus (STG), known for its key role in phonetic processing, was functioning even in our youngest babies (~2–6 months). Because of its early brain activation, this finding suggests a biological foundation for the phonological level of human language processing, and it further suggests that this brain tissue may be mediating all infants' universal phonetic discrimination milestone. Remarkably, Broca's area/LIFC, known for being the site of the brain where we search and retrieve information about the meanings of words, comes on-line later (~10–14 months), and may govern the first word milestone (Dubins, Berens, Kovelman, Shalinsky, Petitto, 2009, a & b).

A further piece of converging evidence regarding the unique status of the brain tissue related to phonetic processing comes from another study of young monolingual babies; here, we found that babies show *different* developmental trajectories in the brain depending on whether the stimuli perceived was linguistic/phonetic or non-linguistic/tone sounds. In this series of fNIRS brain imaging studies of adult and baby participants processing native English language phonetic contrasts, Zulu click syllables, and tones, English-speaking adults showed reliable left lateralization for processing English phonetic contrasts, but no lateralization differences for tones. A similar pattern was observed in our youngest monolingual babies (White, Kovelman, Shalinsky, McKenney, Berens, Dubins, & Petitto, 2008), and a similar pattern was observed in our bilingual babies (Dubins, Berens, Kovelman, Shalinsky, Petitto, 2009a&b; see also Dubins, White, Berens, Kovelman, Shalinksky, & Petitto, in preparation).

These are very surprising findings in light of suggestions from speech perception scientists who have argued that early linguistic processing is not based on the processing of language units. Instead, it is argued to be built up from a general auditory/perceptual processes and, later (around 6–8 months) to become linguistic (Jusczyk, 1997). These findings provide a new window into the nature and timing of early language processing in a way never before possible. These ongoing brain imaging studies figure prominently in the type of cognitive neuroscience studies that have great potential to make significant contributions to education and will be returned to below in Educational Implications.

Imaging the Brains of Bilingual and Monolingual Adults

To track the trajectory of bilingual language development into adulthood, we investigated the impact of the (1) *age* when bilingual adults were first exposed to their other language on their brain's neural organization. We were also curious about any (2) *brain differences* that might exist between bilingual and monolingual brains. We indeed wondered whether there is a "neural signature" of bilingualism? Finally, we hoped to understand whether there are any brain (3) differences within bilinguals based on the *linguistic structure* of the two languages being learned. Using fMRI and fNIRS, we examined the bilingual brain's language organization while performing language processing tasks in each of their languages and while switching between their languages (in addition to examining their brain's organization on a variety of higher cognitive and executive processing tasks).

Age—We found that "*early-exposed"* bilingual adults (i.e., exposed to two languages before age 5, or the period during which the brain exhibits its most exuberant neural plasticity) process their two languages in highly similar ways as monolinguals. These bilinguals utilize *overlapping* classic language areas within the *left hemisphere* for each of their languages, and, crucially, the same language areas universally observed in monolinguals. Their bilingual brains do not exhibit significant bilateral or distributed frontal lobe activation. Interestingly, this overlapping dual language processing is also mirrored in their equally-high language competence (low error rates) across their two languages on classic behavioral language tasks during our fMRI and/or fNIRS scanning. The areas of overlap include the classic language areas such as the Broca's area, Left Inferior Frontal Cortex, and the Superior Temporal Gyrus (Kovelman, Shalinsky, White, Schmitt, Berens, Paymer, & Petitto, 2009; Kovelman, Shalinsky, Berens, White, & Petitto, revise & resubmit); this finding has been corroborated in other bilingual brain scanning studies (Kim, Relkin, Lee & Hirsch, 1997; Wartenburger et al., 2003; Weber-Fox & Neville, 1999). However, "*later-exposed"* bilinguals exhibit more *bilateral* activation, recruit more distributed frontal lobe tissue (including working memory and inhibitory areas) and frequently exhibit more cognitive effort as measured in analyses of their greater errors on the language behavioral tasks during scanning (Kim et al.; Wartenburger et al.; Weber-Fox

& Neville; Perani et al., 1996). Thus, *later* bilingual exposure does *change* the typical pattern of the brain's neural organization for language processing, but earl bilingual and monolingual exposure does not.

Bilingual and monolingual brains compared—An important difference between Bilingual and monolingual brains was that bilinguals had a significantly greater increase in the blood oxygenation level-dependent signal in the LIFC (BA 45) when processing English tan the English monolinguals. The results provide insight into the decades-old question about the degree of separation of bilinguals' dual language representation. The differential the activation for bilinguals and monolinguals opens the question as to whether there may possibly be a "neural signature" of bilingualism. Differential activation may further provide a fascinating window into the language processing potential not recruited in monolingual language. (Kovelman, Shalinsky, Berens, & Petitto, 2008; Shalinsky, Kovelman, Berens & Petitto, 2006; we also found cross-linguistic, cross-modal results in hearing sign/speech bilinguals (Kovelman, Shalinsky, White, Schmitt, Berens & Petitto, 2008).

Differences in linguistic structure—Kovelman, Baker, & Petitto, 2008 also found that highly proficient and early-exposed adult Spanish–English bilinguals, who completed a syntactic "sentence judgment task" (Caplan, Alpert, & Waters, 1998) in each language, showed neural differences in principled and predictable ways based on the morphosyntactic differences between Spanish and English.

In the search to discover whether there is a "critical or sensitive period" (Lenneberg, 1967) for later-exposed bilingual or second language learning, scientists had first conducted *behavioral* experiments on bilinguals' language *proficiency,* as a function of whether they were introduced to their other language earlier versus later in life. These behavioral studies consistently found that proficiency in the later-exposed bilingual and/or second language learners declined dramatically if learned after puberty, and not earlier (Johnson & Newport, 1989; McDonald 2000). The present generation of cognitive neuroscience studies of the neural underpinnings of language processing in early versus late bilingual language learners provide clarification of the brain's mechanisms underlying these now classic psycholinguistic findings. In addition, the above findings on phonological processing, which is important to successful reading mastery, have led to the following generation of studies regarding how bilingual and monolingual children and adults read.

Bilingual and Monolingual Reading in Children

Our behavioral studies, crucial to Educational Neuroscience studies of bilingualism, now follow the young bilingual child into the early school years (ages 6–9 years, spanning grades 1–3), to study the effects of having a bilingual child learn to read in two languages either at the same time—that is *simultaneously*—or first in one language and then later in their other language—that is *sequentially*. Specifically, "simultaneously" refers to *"50/50 bilingual"* instruction in two languages in relatively equal amount during the school week throughout elementary school (e.g., Spanish and English), and "sequentially" refers to "90/10 bilingual" instruction, whereupon, initially, most of the instruction is conducted in the child's dominant language (e.g., Spanish), with instruction in the new language (e.g., English) slowly increasing in amount throughout elementary school. As throughout, we investigated how the age of first bilingual exposure and the type of reading instruction impact reading development in bilingual and monolingual children.

We found that the *age* of first bilingual language exposure has a strong impact on a young bilingual's ability to achieve successful reading acquisition. Age of first bilingual exposure *predicts* how strong a reader they can and will become in each of their two languages.

Spanish-English bilingual children (in 50/50 bilingual programs) who were exposed to both of their two languages before age 3 had the best dual language reading performance as compared to their classmates who had later exposure by the time they were in grades 2–3. But we also observed ways that reading mastery in all young bilinguals could be improved, even involving those children who had bilingual language exposure at much older ages. Moreover, the type of bilingual instruction also had a significant impact: Most surprisingly, and most exciting regarding its educational policy implications, children from *monolingual* homes in *bilingual* schools were better readers than language/age-matched *monolingual* children in *monolingual* schools. Specifically, our results have revealed that children from monolingual English homes who were educated in a Bilingual English-Spanish 50/50 program performed better on phoneme awareness tasks (which are reading precursor tasks) than their peers educated in English-only programs. Thus, these children were afforded an important *reading advantage* in select phoneme awareness skills that are ultimately crucial to successful reading; in our lab, this is among our most exciting and telling findings, and may suggest the rather bold hypothesis that a monolingual child may be afforded particular educational advantages perhaps by simply being placed in bilingual schooling (Kovelman, Baker, & Petitto, 2008; Berens, Kovelman, & Petitto, 2007, 2009; Berens, Kovelman, and Petitto, submitted; Berens, Kovelman, Shalinksy, & Petitto, in preparation).

Another encouraging benefit from the above studies on the impact of age of first bilingual language exposure on bilingual language and reading mastery is that they can serve as an important assessment tool (a yardstick) for teachers. Here, teachers can better situate the young bilingual reader developmentally relative to monolingual peers: early-exposed bilinguals can be expected to have reading performance comparable to that of monolinguals, whereas later-exposed bilinguals (ages 3–7) may have lower reading performance in their *new* language (relative to their home language) due largely to the incomplete acquisition of the new language and *not* due to a reading disability.

Finally, we also noted fascinating ways that different bilingual schooling impacted our young Spanish-English bilinguals: Initially, 50/50 bilingual schooling advantaged the children’s processing of the underlying grammatical/structural components of reading, while 90/10 schooling advantaged the children’s surface phonetic analyses in reading. Keeping in mind that, over time, successful reading necessitates a movement away from a reliance on phonologically-based components of letter-to-grapheme decoding to more abstract grammatical processing in reading, these findings have intriguing and important implications for bilingual educational policy.

Imaging the Brains of Bilingual and Monolingual Reading in Children

Following from our child bilingual reading studies, as well as our adult bilingual brain imaging studies, we wondered whether young bilingual children show any brain activation differences when reading words in each of their two languages. The answer is yes they do! In Berens, Kovelman, Dunbins, Shalinsky, & Petitto (2009), we found that Spanish-English bilingual children’s brain reflects their acquisition of language-specific *deep/English* versus *shallow/*Spanish orthography by showing greater recruitment of the right Superior Temporal Sulcus region during *Pseudoword* reading, potentially reflecting more efficient shallow-language decoding strategies (even when reading in one language). We also found increased bilateral Inferior Frontal activation in bilingual children, which may reflect the extra, dual lexical accessing demands associated with the IFC. These findings were consistent with the same observed with adult bilinguals, but here in young bilingual children thereby providing support for “*The Bilingual Signature”* hypothesis (Kovelman, Baker, & Petitto, 2008).

Summary

Overall, the above research bears directly on the nation's educational priorities, policy, and practice regarding the education of bilingual children, especially "holding-back" views. In both behavioral and brain-imaging studies, we found that the age of bilingual language exposure has a significant impact on children's dual language mastery. Remarkably, early-age bilingual exposure has a *positive* impact on multiple aspects of a child's development: here, involving language and reading. Children who experience *early*, *extensive,* and *systematic* exposure to both of their languages quickly grasp the fundamentals of both of their languages and in a manner virtually identical to that of monolingual language learners. As adults, these bilingual individuals, in addition to their good behavioral performance on language tasks, also show that their brains are processing their two languages in a similar manner, and virtually identical to monolingual adults. The field raised concerns that early bilinguals may be linguistically, cognitively and academically disadvantaged. Our findings suggest that early bilingualism offers no disadvantages; on the contrary, young bilinguals may be afforded a linguistic and a reading advantage (for a theoretical account about the brain-based mechanisms that may make possible early bilingual and monolingual language acquisition, see Petitto, 2005). Early dual language exposure is also key to skilled reading acquisition. Moreover, learning to read in two languages may afford an advantage to children from monolingual homes in key phoneme awareness skills vital to reading success. Finally, the brains of bilinguals are not deviant relative to monolingual brains, and such findings support the educational benefits of early and systematic dual language and reading exposure. Early-exposed bilinguals utilize overlapping classic areas within left hemisphere for each of their languages, and the same language areas universally observed in monolingual. Differential activation between bilingual and monolingual brains may provide a new window into the language processing potential not recruited in monolingual brains and reveal the biological extent of the neural architecture underlying all human language. Neural differences are further principled and predictable based on the morphosyntactic differences between the dual language structures and provide benefits to the processing of each language.

Implications of Educational Neuroscience Research for Bilingual Education

While the above work addresses one prevailing bilingual myth that has impacted educational policy—exposure to two languages "too early" can cause developmental language delay and confusion—it also addresses the flip-side of this myth: Later exposure is better. Here, the view is that later exposure to another language has little consequence on a child's ability to master the said language and thus the brain has little to do with later-bilingual and second language learning. The reasoning is that because we as adults can go out and take courses in, for example, Japanese, and achieve fluent conversational skills, there is thus ostensibly no critical or sensitive period for second language learning (as there is for first language learning). Given this, and following this line of reasoning, it is therefore better to provide a young child (say from a Spanish-speaking home) with a strong linguistic and cognitive base first in the *majority* language (e.g., English, holding back formal instruction in Spanish) and, then, later, building on this solid foundation in English, introduce the child to language study and reading in her other language (e.g., Spanish). Although the premises of this method are scientifically false, it could be said that it is still better to embrace in our nation's schools because it is more sympathetic with the social reality of bilingualism. In the real world, childhood bilingualism is not frequently simultaneous and balanced, and normal population migration, as well as socio-political conditions in the world, often causes large groups of children from outside the language community to enter schools at varying stages of life, even well into the teenage years.

Bilingual language learning and reading indeed provide complex educational challenges for today's teachers and schools. But what the above landscape of scientific discoveries teaches us unequivocally is that the age of first bilingual language exposure directly and seriously impacts children's ability to achieve linguistic fluency and reading in the new (later-exposed) language, as well as the neural processing of this newer language in the brain. "Hold-back" educational policies that fly in the face of biology need not be so.

Our goal here was not to prescribe what should and must be done for all young bilinguals, but instead, working within an Educational Neuroscience paradigm, to discover empirically what are the most *optimal* learning conditions for bilingual language mastery and what happens when life's vagaries prevent the most optimal conditions from occurring. What we have discovered here is very positive and very encouraging. We saw that while early dual language exposure is most optimal to achieve highly proficient and equal dual language mastery, children arriving late to a bilingual context can and do achieve language competence in their new language. Key here was our empirical discovery of the obligatory factors required to achieve this outcome: Full mastery of the new (later-exposed) language needs to occur in highly systematic and multiple contexts that are richly varied involving both home and community and, remarkably, can*not* be achieved through classroom instruction alone.

In general, the present Cognitive Neuroscience findings, which now constitute a part of the growing field of Educational Neuroscience, can teach our educational institutions a lot: Young children, from say a Spanish-speaking home, entering kindergarten, first-grade, or the like, need not have Spanish withheld from them due to a fear that any exposure to Spanish in the schools will prohibit them from achieving fluency in English. These same children need not have Spanish books withheld from them due to a fear that any exposure to Spanish texts will prohibit their capacity to achieve successful reading in English. Teachers and parents need not fear using a Spanish word to a young child from a Spanish-speaking home (as a conceptual bridge) when teaching this child English. The November 5, 2002 public referendum banning bilingualism in the Commonwealth of Massachusetts need not have occurred.

Our next step is to identify and track the neural underpinnings of bilingual and monolingual language processing in babies from the age of two days. Only the exciting technological advances from Cognitive Neuroscience, in combination with the goals and methods from Educational Neuroscience, will permit us to address this question. Following from our previous study of infant language and perceptual processing described above, we will be conducting a series of studies that use innovative NIRS technology, which, for the first time, will permit us to evaluate highly specific (within hemisphere) neuroanatomical hypotheses about the brain tissue that participates in infant bilingual language processing in a manner hitherto not possible in science. By doing so, this research will help adjudicate a classic scientific debate about whether language-specific versus perception-general mechanisms initiate/govern early language learning. This research will thus provide important answers to scientific questions about (a) the *multiple factors* that underlie early language acquisition and the specific type of processing tissue that underlie them, (b) the *developmental trajectories* of linguistic processing tissue, and (c) the *peaked sensitivity* that linguistic processing tissue has to certain kinds of linguistic input over other input in early development.

Our NIRS studies will also yield guidelines for the principled use of NIRS with infants that ultimately (after experimental replication/standardization) can have important diagnostic, remediation, and teaching utility in the following way: Our earlier studies had established that the Superior Temporal Gyrus (STG), particularly the Planum Temporale (PT), is dedicated to processing specific rhythmically-alternating patterns at the core of phonology in adults (e.g., Penhune, Cismaru, Dorsaint-Pierre, Petitto & Zatorre, 2003; Petitto et al., 1997, 1998, 2000), with evidence that this is also true in infants as young as 5 months old (Holowka & Petitto, 2002) and 3 months (Petitto, Baker et al., 2004). Our present studies will evaluate whether this is true in much younger infants (from ages 2 days old). The scientific establishment of the neural tissue that underlies early phonological segmentation and processing, and its typical onset age in development, can ultimately be used (in combination with standardized NIRS data from typically developing babies) to *identify and predict* babies at risk for language and phonological sequencing disorders (e.g., dyslexia) in very early life, indeed even *before* they babble or utter their first words. By doing so, we will also provide a new way to distinguish between *deviance* and *delay* in children's phonological processing in bilingual and monolingual children. These findings about children's phonological capacity will thus provide scientific evidence-based information vital to word segmentation at the core of successful language learning and reading and will impact educational policy regarding early language remediation and teaching. To be sure, Educational Neuroscience will yield advances that have great potential to impact education policy and practice, including those that will change our understanding of childhood bilingualism—indeed, all human language processing.

THE EDUCATIONAL NEUROSCIENCE OF LEARNING SCIENTIFIC CONCEPTS

The important foundational question for the field of Educational Neuroscience is whether neuroscience can be used to elucidate prevailing issues in contemporary education and whether research from Educational Neuroscience can inform teaching practices in the classroom. Here, we turn our focus to Science Education and ask why are some science concepts so difficult to learn? Students have great difficulty learning new key concepts in virtually every aspect of science, ranging from the concepts of force in Newtonian physics (e.g., McCloskey 1983; McCloskey, Caramazza, & Green, 1980), to changes of state in chemistry, such as from a liquid to a gas (Nelson, Lizcano, Atkins, & Dunbar 2007), to the evolutionary theory in biology (Chi & Roscoe, 2002; Chi, 2008), or to changing theories in the face of overwhelming inconsistent evidence (Tweney, Doherty, & Mynat, 1981; Fugelsang & Dunbar, 2005). This is not just an academic matter, people routinely misunderstand how medications work, often resulting in debilitating illnesses or even death (Horowitz, Rein, Leventhal, 2004), and misunderstandings of dietary intake (Schwartz, 2009) and human effects on the environment are ubiquitous (Bierbaum & Raven, 2007; Bierbaum, 2008). The goal of our work is to use an educational neuroscience framework to highlight the sources of different impediments to understanding science and suggest strategies that can be used to ameliorate these difficulties. This approach can be used in conjunction with some strategies that are currently being used, to deepen an understanding of scientific concepts and mechanisms that have a real impact on education as well as the ways that people interact with science in their everyday lives. We propose that findings from Educational Neuroscience suggest that certain teaching and learning strategies will be most effective with specific types of scientific concepts, whereas other strategies will be most successful with other types of scientific concepts. Just to preview the rest of this section of the article, we will show that certain concepts that are based on perceptual phenomena involve a specific type of conceptual change, whereas other scientific concepts that are based on conceptual knowledge involve different types of conceptual change that suggest different teaching and learning methods in science education. Educational Neuroscience does not give one-size-fits-all educational solutions, but instead narrows down the range of educational interventions to ones that are appropriate for specific types of conceptual change.

Before we discuss our work on Educational Neuroscience and education, we will provide a mini-review of some of the approaches that have been used in science education. For over 100 years, different theories of learning have been brought into education in the hope that students would more easily acquire these critical concepts. However, despite intensive behaviorist, cognitivist, and social constructivist approaches to learning science, students are still failing to grasp key concepts in science (cf. AAAS Project, 1989; Ravitch, 2000). For example, Stein and Dunbar (2003) found that a widely used NASA video intended to educate students on what causes the seasons, actually leads to more errors in tests of conceptual transfer than those seen before the video was presented. Similarly the private universe project at Harvard University shows that despite the best educational practices at leading schools and universities, students are failing to learn basic concepts in science. Educational researchers and educators themselves are acutely aware of these problems and much recent research on cross-cultural approaches to math education indicates that the wide variety of teaching and learning strategies across the world can lead to vastly different educational outcomes (e.g., Richland, Zur, & Holyoak, 2007). Another approach to science education has been to turn scientific concepts from cold decontextualized knowledge to emotionally relevant recontextualized knowledge so that students want to learn and love learning (e.g., Atkins et al. 2009). All of these different approaches have added to our understanding of potentially effective ways of producing robust learning, yet no unifying framework for understanding how, why, and when these different techniques work has been offered. Here, we propose that by combining educational practitioners, policy makers, parents, clinicians, and neuroscientists, we have a new Educational Neuroscience framework for transforming science education into robust useable knowledge.

Educational Neuroscience and the learning of Physics, Biology, and Chemistry

In this section, we will turn to students learning physics, biology, and chemistry and show the ways in which neurioimaging research combined with traditional educational research and cognitive research sheds light on the sources of difficulty of learning key scientific domains that students across the world are learning. One area where important barriers to effective learning of science occur is in the domain of physics. Many physics concepts such as Newtonian conceptions of mechanics are very difficult for students to acquire. This issue has been the focus of much research in the physics education and cognitive science communities (Adams 2005, Boudreaux et al., 2008; Brown & Hammer, 2008; Clement, 1982; diSessa, 1993; Hammer, 1996; Heron et al. 2005; Lee & Kwok, 2009; McCloskey, 1983; Mestre, 1991; Redish, Scherr & Tuminaro, 2006). On the basis of a quarter century of research, it is now known that students use physics concepts in a way that is quite different from that being taught in physics courses, and that students hold on to their original views despite empirical demonstrations and theoretical expositions of the correct views. Note that while some researchers have labeled the students' views "misconceptions," other researchers, such as David Hammer have convincingly shown that many of the views expressed by the students can change depending on the types of questions asked and the context in which students express their answers. Thus, terminologies used in the above referenced articles for describing students' accounts of physical phenomena have ranged from misconceptions, preconceptions, alternate conceptions, to contextually bounded constructions. These are important distinctions that we will return to later in this article, but the key idea here is that students' explanations are often at variance with the explanations and theories being taught in middle schools, high schools, and universities. One way of capturing these diverse types of descriptions of students' learning of these concepts has been to borrow the term "conceptual change" from the philosophy of science. The idea is that students' conceptions can undergo different types of change, ranging from the addition of a new feature to a concept, to the massive reorganization of a concept, or the construction of different concepts depending on the context.

One area of physics where students' initial conceptions are different from those that are taught is in theories of motion. Cross-sectional studies comparing students with and without formal education in physics have found that discrepancies between fundamental laws of motion and people's explanations are difficult to modify through instruction. For example, McCloskey et al. (1980) conducted a study that tested people's understanding of the principle that objects move in straight lines in the absence of external forces. To do this, they asked participants to draw the expected trajectories of a series of objects released from curved enclosures and from continuous rotations. Surprisingly, they found that many of the participants did not know that objects move in straight lines when no external force is applied to them. Most of the students that drew curved pathways stated that an object forced to travel in a curved path (e.g., via a tube) "acquires a force or momentum that causes it to continue in curvilinear motion for some time after it emerges from the tube" (pg. 1140). Other research, such as that of Clement (1982), Hestenes, and Halloun (1995), as well as Galili and Bar (1992), also point to the persistence of explanations of motion that are very different from Newtonian concepts. A primary concern of recent research has been to determine the reasons for this difficulty.

More recent research referenced in the preceding paragraphs has discussed similar phenomena in terms of conceptual change. However, the same issue exists: students have difficulty learning the physical concepts that are central to Physics education. Thus, analyses of students' explanations, using interviews, verbal protocols, and behavioral outcome measures, indicate that large-scale changes in students' concepts can occur in physics education, but with great difficulty and with extensive learning (e.g., Reddish et a. 2006; Brown & Hammer, 2008). Following Kuhn (1972), researchers have noted that students changing conceptions are similar to the sequences of conceptual changes that have occurred in the history of science (e.g., Nersessian, 1998; Thagard, 1992, Wiser & Carey, 1982). Theories of conceptual change have tended to focus on two main types of shifts. One is the addition of knowledge to a preexisting conceptual structure. Here, there is no conflict between the pre-existing conceptual knowledge and the new information that the student is acquiring. Thus, these minor conceptual shifts are relatively easy to acquire and do not demand an underlying restructuring of the representations of scientific knowledge. The second type of conceptual shift is what is known as "radical conceptual change" (see Dunbar, Fugelsang & Stein, 2007; Keil, 1999; Nersessian 1998; Strike &Posner, 1992; and Vosniadou, 2007 for differing views of conceptual change as applied to science education). For radical conceptual change, it is necessary for a new conceptual system to be acquired that: (1) Organizes knowledge in new ways, (2) Adds to the new knowledge, and (3) Results in a very different conceptual structure. This radical conceptual change is thought to be necessary for acquiring many new concepts in science in general and in physics in particular. Many of the above mentioned researchers have argued that a failure to achieve this conceptual change is a major source of difficulty for students. For example, research on students' explanations of motion indicate that students use extensive alternative explanations and of motion similar to a medieval "Impetus" theory (e.g., Clement, 1982; Kozhevnikov & Hegarty, 2001; McCloskey, 1983; McCloskey et al., 1980; McCloskey, Washburn & Felch, 1983). Furthermore, students provide "Impetus" explanations even after one or two courses in physics. Thus, it is only after extensive learning that we see a conceptual shift from "Impetus" accounts of motion to Newtonian accounts.

A key issue for science education is to determine why conceptual change is so hard to achieve. One very difficult to test assumption that exists in much of contemporary science education is this: students' explanations (or naïve theories) can be eliminated by presenting them with anomalies. Researchers argue that by presenting students with anomalies, students will realize that their current explanation (or naïve theory) is incorrect and will then reorganize (restructure) their knowledge, eventually arriving at the "correct" theory or explanation. Through intensive teaching using anomalies, it is thought that naïve theories are eliminated. The use of anomalies has therefore been one method of moving students to explanations more consistent with the models presented in the classroom (e.g., Baker & Piburn 1997; Mortimer & Machado, 2000). It is thought that when students display a clear understanding of the concepts being taught, a reorganizing of the students' knowledge has occurred. However, while there have clearly been some success stories in teaching scientific concepts through anomalies, it is not clear that restructuring has really occurred. Numerous studies indicate that scientific knowledge can be unstable and hard to achieve, leading some researchers to propose that rather than there being conceptual change, the types of questions being asked, and the contexts under which the students are probed can lead to vastly different explanations that are sometimes indicative of the impetus theory, and sometimes the Newtonian theory (cf. the work of David Hammer). How can we determine what has happened when a student acquires a new scientific concept? The approach that we take here is to look inside the brain and ask what networks of brain sites are activated when we learn scientific knowledge and how they change under different contexts. Cognitive neuroscientists have identified the major brain sites involved in memory (e.g., Schachter et al., 1995; Davachi et al., 2004), attention (e.g., Fan et al., 2003), analogical reasoning (Green et al., 2006; Holyoak, 2005), deductive reasoning (Parsons & Osherson, 2001; Goel & Dolan, 2004), and causal reasoning (see Fugelsang & Dunbar, 2006; Sapute et al., 2005), and how evidence is interpreted depending on one's theory (Fugelsang & Dunbar, 2009). These psychological processes are central to Scientific Thinking and Reasoning (see Dunbar & Fugelsang, 2005), and thus form the foundation for the Educational Neuroscience approach to Science Education. It is now possible to understand the types of cognitive and neural changes that occur in educationally relevant learning. In the next section we provide an overview of our recent findings on conceptual change in science.

Responding to anomalies: Ignoring data inconsistent with a favored theory

A major issue in science education is peoples' interpretation of data. Starting with research in the 1970s, researchers have repeatedly found that students and scientists alike ignore data that are inconsistent with their favored hypothesis. Furthermore, researchers such as Gorman, and Tweney have found that despite instructions to pay attention to and use inconsistent data, subjects find it extremely difficult to do so. In our recent work using fMRI, my colleagues and I investigated the brain mechanisms underlying this confirmation bias (e.g., Fugelsang & Dunbar, 2005). Many of the scientific concepts that students have difficulty with are implausible for the students. Furthermore, we wanted to mirror educational settings by presenting students with data that were consistent or inconsistent with their favorite theory. This is similar to many science classrooms where students have to collect data that maybe inconsistent with their favorite theory and consistent with what the students think is an implausible theory. After presenting students with either a consistent or an inconsistent theory, we scanned students' brains using fMRI as they received the data. What we were interested in was what regions of their brains would be activated by data that were consistent versus inconsistent with their theories. Our hypothesis was that data that were inconsistent with a plausible theory would be ignored, and not result in changes of a concept, whereas data that were consistent with a plausible theory would be successfully integrated with the concept.

We found that when people were given data that were consistent with their preferred theories, regions of the brain known to be involved with learning (e.g., Caudate and Parahippocampal Gyrus) showed increased levels of activation relative to baseline. However, when the students were presented with data that were inconsistent with their preferred theory, the Anterior Cingulate and Dorsolateral Prefrontal Cortex (DLPFC) showed increased levels of activation. The Anterior Cingulate is thought to be a region of the brain associated with error detection and conflict monitoring whereas the DLPFC is thought to be one of the prime components of working memory. These results indicate that when data are *consistent* with a theory, changes in concepts are achieved through standard learning structures. However, and most remarkably, when students receive information that is *inconsistent* with their preferred theory, activation occurs in their Anterior Cingulate and the DLPFC, which has led us to hypothesize that students are *inhibiting data* that are *inconsistent* with their theories. Thus, merely presenting students with anomalous data does not produce learning. Instead, our results indicate that prior belief in a theory influences the interpretation of data in a highly specific way: Data inconsistent with a theory are treated as errors. Furthermore, we see little activation of learning mechanisms when data are inconsistent with a preferred theory. Only after extensive presentation of data inconsistent with a favored theory did we see activation associated with learning mechanisms.

The results of this study suggest that when students are presented with information that they do not believe (because they think the theory is implausible, or because they have a prior commitment to a different theory), they *inhibit* the information and this will make new concepts extremely difficult to acquire. Most importantly, we find that presenting students with information inconsistent with their theory (i.e., anomalies) results in *inhibition* rather than a restructuring of knowledge. Thus presenting students with anomalies may not be as effective a teaching strategy in science education as is currently thought.

Physics, the brain, and conceptual change in science education—In this next set of studies, we sought to take a different approach that more directly addressed the effects of education on the brain. Here, we used students who had taken no high school or college level physics courses and compared them to students who had taken at least five college level physics courses. Students were the same in all other respects having equal SAT scores, ages, and an equal distribution of genders. The basic idea here is that the physics students will have undergone a conceptual change in their concept of motion, and the non-physics students will not have undergone this conceptual change and will be relying on their alternate conceptions when responding to our task. That is, we expected to see the non-physics students use impetus theories, and students with an extensive physics education use Newtonian theories. Our goal here was to use fMRI to determine what changes occur in the brain as a result of learning new scientific concepts through formal science education, including in the lab and in the classroom. Naturally, we also used a standardized behavioral task (The Forces Concept Inventory, Hestenes, Wells & Swackhamer, 1992), which allowed us to assess whether students had indeed made the conceptual leap from a naïve theory to a Newtonian theory.

We showed our students movies of two balls falling and asked the students to press a key if this was the way that the balls should fall in a frictionless environment, or to press another key if the balls were falling in a way that was not what they would expect in this environment. Students saw the two balls falling at the same rate or at a different rate. The balls could be of the same size (both large or both small), or could be of different sizes (one large and one small). We scanned the brains of the students while undergoing fMRI scanning. We were particularly interested in comparing what we call Newtonian movies, where two balls of unequal size fell at the same rate, with impetus movies in which the bigger ball fell at a faster rate than the smaller ball. The behavioral data revealed that both the physics and non-physics students classified the balls as falling at the same rate as they had expected. Thus, in using the button presses data only, both the physics and non-physics students appeared to have made the conceptual change to Newtonian physics. However, the Force Concept Inventory indicated that only the physics students had made the conceptual shift from an impetus explanation to a Newtonian theory.

The fMRI data also indicated important differences between the non-physics students and the physics students. When the non-physics students saw the two balls of different sizes falling at the same rate, this was inconsistent with their impetus explanation. Consequently, the Anterior Cingulate and Supplementary Motor Area showed increased activation, indicating that they regarded these events as strange or erroneous, thus resulting in response conflict. Conversely, when the physics students saw the impetus movies (with the larger ball falling faster than the smaller ball), this was inconsistent with their Newtonian explanations and as a result the Anterior Cingulate and Supplementary Motor Areas showed increased activation. Thus, the physics students appeared to regard the impetus movie as erroneous, whereas the non-physics students saw the Newtonian movie as erroneous. Clearly, this provides evidence that there has been a change in students' conceptual knowledge. There were further indices of the effects of education on the brain: Physics students showed increased activation in the medial frontal cortex for Newtonian movies, whereas non-physics students showed increased medial frontal activation for impetus movies (larger ball falling at a faster rate than the small ball). These results are consistent with the hypothesis that the medial-frontal cortex is activated by pre-existing representations (e.g., Benefield et al., 2000). Therefore, activity in the medial frontal cortex is one measure that can be used to determine whether students have a representation of a concept. These results thus suggest that levels of activation of the medial frontal cortex are an index of conceptual understanding. An important question for education is whether this change in representation is a restructuring of students' knowledge. Our data suggest a new and different understanding: *Students have not reorganized their knowledge, but instead may be inhibiting their old knowledge while concurrently activating their newer Newtonian knowledge*. This is because physics students show activation in the medial frontal lobes for both impetus and for Newtonian concepts, but the impetus concepts also have activation in the Anterior Cingulate suggesting that the medial frontal representation is being inhibited. We are currently conducting new studies to test this hypothesis as this type of finding has the potential to elucidate the nature of conceptual change for the teaching of complex scientific concepts.

Acquiring new concepts in Chemistry: Mechanisms underlying state changes

A further question we asked regarding conceptual change was whether we would see similar changes in brain activation patterns for chemistry and non-chemistry students when shown phase changes in going from a liquid to a gas (Nelson, Lizcano, Atkins & Dunbar, 2007). Students from Hong-Kong to Helsinki have been shown to have many alternate conceptions of what happens when a liquid such as water is heated and steam is produced. Students routinely say that the water molecules break apart producing single hydrogen atoms and single oxygen atoms. Another frequent alternate conception of what happens when water undergoes a state change is a diatomic model where oxygen atoms bond to form O_2 molecules and hydrogen atoms bond to form H_2 molecules. The standard model in chemistry and physics is that the weak bonds between the H_2O models break and the visual representation that best captures this is increased distance between the H_2O molecules. We presented students with diagrams of water, showing H_2O molecules, and then showing diagrams of the water as it changes to steam (we also used other substances that undergo state changes, i.e., ammonia and carbon monoxide). What we were interested in were the differences between students who had a chemistry background versus those who did not. Just as previously demonstrated in the chemistry education literature, (Harrison & Treagust, 2002; Adbo & Taber, 2008), students with little chemistry background chose the uni-atomic or the diatomic diagrams as correct, and the increased space between the molecules as incorrect. The chemistry students showed the opposite pattern.

Turning now to the fMRI data, we found a very different pattern from our physics students' data. Here we found that the non-chemistry students showed relatively high activation in the bilateral occipital, inferior temporal (BA 18, 37), and right parietal cortices (BA 40, 7). However, the chemistry students showed relatively high activation in the left prefrontal cortex, in the middle frontal gyrus (BA 9) and in the inferior frontal gyrus (BA 45). The activations that we found in the non-chemistry students are similar to the activation patterns that Stanescu et al. (2000) found when students were estimating the number of dots in an array. This suggests to us that the non-chemistry students were treating the task as a visual estimation task rather than as a conceptual task, perhaps counting the numbers of atoms and molecules. However, the chemistry students' brain activation patterns were different, with activation in left prefrontal regions and the frontal gyrus. These results are consistent with the hypothesis that the chemistry students were treating the diagrams conceptually, whereas the non-Chemistry students were treating the diagrams as visual, perhaps counting the numbers of atoms and molecules. The chemistry data are consistent with Chi's (2008) hypothesis that conceptual change is a recategorization of knowledge, rather than a reorganization of knowledge. In our case, the non-chemistry students treated the diagrams visually as individual atoms using visual estimation strategies, whereas the chemistry students treated the diagrams in terms of molecules and retrieved conceptual knowledge of chemistry.

Jonathan Fugelsang and I (Fugelsang & Dunbar, 2009) have recently collected data that are consistent with this perceptual to conceptual shift. We showed students short movies of one ball hitting another ball and asked the participants whether the first ball caused the second ball to move. In this situation we found activation in the right superior frontal and inferior parietal cortices (see also Fugelsang et al., 2005; Roser et al. 2005). What we also did with the participants (counterbalanced and within subject design) was tell them that these are two positively charged subatomic particles and asked them whether the first ball caused the second ball to move. In this situation, even when the balls are spatially separated, one particle should cause the other to move without touching it. The participants readily understood this, and pressed the "caused to move" key even when the balls were separated by a centimeter. Note that in both conditions, the students were seeing the same movies and the only things that differed were the instructions or context. The fMRI data also revealed a different pattern of activations for the billiard ball vs. the subatomic particle condition. For the subatomic particle condition, there was both right and left hemisphere activation in the same regions. Again, this is consistent with the hypothesis that in one situation the students see the task as perceptual, whereas in the other, it is conceptual. These findings show one way in which context can change the types of activations occurring in the brain and are consistent with the idea that students can construct different representations of the same phenomena depending on their interpretation of the context.

Implications of Educational Neuroscience Research for Science Education

The results of the fMRI experiments summarized here show a number of different mechanisms of conceptual change. First, when data is consistent with a preexisting concept, we see indicators of learning, which while not often considered as conceptual change, does allow learning to take place. Second, when data are presented that are inconsistent with current concepts; we see specific brain structures, such as the anterior cingulate, activated that may prevent conceptual change from occurring. These results have important implications for many types of educational interventions and for theories of what happens when we educate our students. One often used teaching method is that by presenting students with either large amounts of data, key anomalies, or new theories, we can induce students to abandon their old theories and reorganize their knowledge. Third, the results of the experiments reported here indicate that even when conceptual change appears to have taken place, students may still have access to the old explanations and are inhibiting their old theories in the course of processing the new information. Fourth, our finding that students activate inhibitory networks when they encounter data that are inconsistent with a plausible theory, sheds new light on why it is so difficult for students to adopt new theories–they may be encumbered by having to inhibit information inconsistent with their current representation. Fifth, our neuroimaging data on chemistry concepts indicate that other mechanisms of conceptual change such as the placing of concepts into different categories (e.g., Chi 2008) can be seen using fMRI. The findings that fMRI can be used to distinguish between different forms of conceptual change and also lack of conceptual change both validates the use of Neuroimaging techniques to understand the ways that education influences the brain and provides key evidence on the components of conceptual change that are important to science education.

What do these results mean for education? First, they provide a clearer picture of the mental processes that take place when students learn new scientific concepts. Inhibitory mechanisms are a great stumbling block to acquiring new concepts. Second, these results indicate that students enter science education with strong types of explanations, particularly in physics, that may never completely go away, but instead be held in check. One hypothesis that we are currently exploring is that some of the physics concepts that are tied to perceptual phenomena may need to be inhibited for students to acquire the standard concepts. However concepts that are less perceptually grounded, may be easier to change by recategorizing the phenomena of interest as our chemistry students may have been doing. One further question that we are currently asking is why students find it so difficult to abandon their alternate conceptions. Is it that students have acquired considerable success with using a partially correct account and that by the time students are formally educated in physics, biology and chemistry, that some of the alternate theories (particularly those based on perception) are so deeply ingrained that they cannot be modified, and only be inhibited? If this is the case, then the present educational practice to "*hold-back*" physics education in young children until they are older may not be ideal for optimal learning of scientific concepts. One possible solution would be to teach scientific concepts at a younger age, before students' concepts become firmly entrenched. Alternatively, it may be the case that alternate conceptions in physics and chemistry tap into core knowledge (Carey, 1991; Carey & Spelke, 1996) that can never be replaced or reorganized, but can be inhibited.

What is next for Educational Neuroscience?

While the overall framework for Educational Neuroscience is now taking hold, one challenge for the field will be to integrate the different strands of the discipline into the practice of Education, and to do so in highly principled ways. Another challenge will be to move beyond any "one-way" direction of the flow of information. Rather than information flowing from the university laboratories into the community (e.g., schools, medical facilities, clinical practices, museums), it is essential that there be a "two-way" mutual flow of information, questions, ideas, and solutions. An exciting goal will be for Educational Neuroscience to be a truly collaborative discipline in which teachers and scientists across multiple disciplines, students, policy makers, parents, and clinicians are working together. Formal mechanisms need to be established within the discipline and within the institutions in which Educational Neuroscience is housed to ensure that this is held as an important goal, and that it is achieved. To be sure, an essential component of the research that we report here has been the active, two-way involvement of teachers, policy makers, students, parents, and clinicians in the entire process.

We hope to suggest to the field a novel approach to discipline building: Rather than building departments of Educational Neuroscience within (or on top of) traditional departmental boundaries (e.g., Departments of Psychology or Departments of Education), an exciting direction would be for new Educational Neuroscience departments to be created based on drawing together researchers in the five core areas that make up the developing child: broadly defined here as language (and bilingualism), reading, math, science, and social-emotional development.

One major component of this discipline is the realization that Educational Neuroscience is not a reductionist process of merely saying which brain sites are important for teaching and practice, but one in which everyday issues such as Socioeconomic status, gender, immigration, poverty, city planning (e.g., Florida, 2009), etc., are seen in an integrative manner.

Our vision is that Educational Neuroscience is vastly different from Medical Research, where it can take decades to see if a particular therapy or medication works. Educational Neuroscience is and must be evidenced-based, yet, at the same time, it also must be highly focused on important contemporary issues that have direct relevance to tangibly contributing to the well being of the whole child.

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