New findings from Educational Neuroscience on Bilingual Brains, Scientific Brains, and the Educated Mind

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Conference on Building Usable Knowledge in Mind, Brain, & Education
Harvard Graduate School of Education
October 6-8, 2004

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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 (a) to solve prevailing problems in the lives of developing children, (b) to understand the human learning capabilities over the life span (both in brain and in behavior), and (c) to 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.

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 and specific language impairment. 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 introduce foreign languages, whether phonetic vs. whole-word reading instruction methods are most optimal, how phonological awareness teaching activities can improve good and atypical readers (e.g., dyslexics, Shaywitz et al., 1998), and the developmental sequence underlying the learning of math and science; all of which 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.)

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 science and the learning of language (especially learning two languages as in childhood bilingualism)—offer 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 underlying this article 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 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, and (4) suggest ways of learning and teaching that can be used to circumvent problems associated with traditional teaching methods.

Educational Neuroscience has indeed arrived, despite its still somewhat changing name: "Nurturing the brain," is one names 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 Fischer, Petitto, Dunbar and many 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, 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, formal physics instruction is not introduced until high school because it is feared that the child is not at that right conceptual stage to understand the material until the teenage years. (Note that similar logic underlies why most monolingual children were 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 in science. We ask why *do* students experience such great difficulties? Here we use both behavioral and brain scanning technologies (fMRI, NIRS) to understand 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, a phenomenon that is so pervasive that we in our lab have come to call it "the bilingual paradox" (Petitto, Katerelos, et al., 2001). 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 early 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 education 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.

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 over 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 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 (save studies by Petitto below).

Bilingual Maturational Milestone Studies: Here we test 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. 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 are first raised monolingual from birth and who are then exposed to a *new* language between ages 2-9 years of age *can* achieve the morphological and syntactic fundamentals of the new language within their first year of exposure. However, this rapid acquisition of new language fundamentals is possible only when extensive and systematic exposure to the ne*w* language occurs across multiple contexts, for example, in the community and home, with far less optimal dual language mastery being achieved if exposure comes exclusively within the classroom (Kovelman & Petitto, 2003; Petitto, Kovelman & Harasymowicz, 2003). (3) Bilingual children exposed to two languages from birth achieve 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, Katerelos, et al., 2001). (4) Bilingual children exposed to their *new* language between ages 2-9 years of age exhibit "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, 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 does 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 their phonetic discrimination abilities in *perception* in bilingual babies even before they could babble (for bilinguals see Norton, Baker & Petitto, 2003; for monolingual babies/adults see Baker, Sootsman, Golinkoff & Petitto, 2003, and Baker, Idsardi, Golinkoff & Petitto, in press; for monolingual babies as compared to monkey phonetic perception see Baker, Groh, Golinkoff, Cohen & Petitto, submitted). This behavioral study used the classic infant controlled habituation paradigm (Cohen, 1972) in Petitto's Infant Habituation Lab, and examined the abilities that young bilingual babies have for processing phonetic units so crucial to successful phonological segmentation of words, language learning, and later reading. Here we 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.

We found that contrary to suggestions that bilingual babies are "different" (atypical, delayed) in acquiring phonetic contrasts (proposed in the one other study in the field on this topic: Burns, Werker & McVie, 2003), early bilingual exposure yields a phonetic processing "bilingual advantage" (Norton, Baker & Petitto, 2003). 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 dramatically for the monolingual quickly in early life. These findings further 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* underlies 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 age 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 (by around 14 months, as they instead attain an increased ability to discriminate phonetic units within in their native language; Werker & Tees, 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 Near Infrared Spectroscopy (NIRS) 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. NIRS is non-invasive optical technology that, like 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, NIRS is highly portable, child-friendly, tolerates some movement, and can be used with alert babies.

We found robust activations in the classical language areas in very young bilingual and monolingual babies (Superior Temporal Gyrus, STG, for phonetic processing, Inferior Frontal Cortex, IFC, for word processing, primary visual occipital area, and V1, for the sensory processing of nonlinguistic visual checkerboard; Petitto, 2003; Petitto, Baker, Baird, Kovelman & Norton, 2004; see also Peña et al., 2003). These are very surprising findings in light of suggestions from speech perception scientists that early linguistic processing is not; it is first built up from a general auditory/perceptual processes that later 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 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 *age* when bilingual adults were first exposed to their other language on their brains' language organization using our brain imaging technology (fMRI). We especially hoped to understand how bilingual exposure impacts cerebral organization when there are two languages, as compared to adult monolingual brains.

We found that bilingual adults exposed to two languages before age 5, process their two languages in *overlapping* language areas within the left hemisphere and, crucially, the same language areas universally observed in monolinguals. Their brains do not exhibit significant bilateral and distributed frontal lobe activation. Interestingly this overlapping dual language processing is also mirrored in their overlapping, equally-high language competence (low error rates) across their two languages on classic behavioral language tasks during fMRI scanning. The areas of overlap include the classic language areas such as the Inferior Frontal Cortex, Broca's area, and the Superior Temporal Gyrus (Petitto, Kovelman, Baker, Grafton, submitted); 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 early bilingual exposure does not.

Remarkably, in the search to discover whether there is a “critical or sensitive period” (Lenneberg, 1967) for later-exposed bilingual and/or second language learning, scientists had first conducted behavioral experiments on people’s language proficiency, as a function of whether they were introduced to their other language earlier versus later in life. Theses scientists consistently found that proficiency in the later-exposed bilingual and/or second language learners declined dramatically if learned after puberty, if not earlier (Johnson & Newport, 1989; McDonald 2000). The present generation of cognitive neuroscience studies of the neural underpinnings of language processing in early vs late bilingual language learners provide stunning corroboration of these now classic psycholinguistic findings.

Bilingual and Monolingual Cognition: Are bilinguals smarter? For a more complete profile of early childhood bilingual development, we investigated the cognitive processing skills of young bilingual children, ages 4-6 years, as compared to age-matched monolingual peers in order to determine whether bilingual children have a cognitive advantage over monolinguals—a study which was conducted in collaboration with Dr. Ellen Bialystok, York University, Ontario, Canada (Baker, Kovelman, Bialystok & Petitto, 2003).

We found that children exposed to two languages from birth are indeed afforded a “cognitive advantage” over their monolingual peers on select cognitive tasks demanding them to attend to and inhibit competing cues and to switch among them; surprisingly, the data suggest that being bilingual helps the bilingual to be a better “multi-tasker” as compared to monolinguals. Importantly, our preliminary results suggest that the bilingual “cognitive advantage” spans linguistic modalities, that is, it is true of bilinguals exposed to two spoken languages as well as bilinguals exposed to one spoken and one signed language.

Bilingual and Monolingual Reading: These 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*. 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 effect 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 exposed to both of their two languages before age 3 have the best dual language reading performance as compared to their classmates in a Bilingual English-Spanish 50/50 program (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 older ages. Moreover, the type of bilingual instruction also has 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 preliminary 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. An encouraging benefit of these results is that they can serve as an important assessment tool by which teachers can situate the young bilingual reader developmentally relative to monolingual peers: early bilinguals can be expected to have reading performance comparable to that of monolinguals, whereas later exposed bilinguals (ages 3-6) 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. Additionally, bilingual instruction affords monolingual readers an advantage in select phoneme awareness skills that are ultimately crucial to successful reading (Kovelman, Baker, & Petitto, submitted).

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: linguistic, cognitive, 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 cognitive advantage. 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.

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. 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. Here, the reasoning is that because we as adults can, today, 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 (here, 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 (here, 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.

For example, we studied children in different types of bilingual programs in the United States. Young children enrolled in 50/50 (Spanish-English) bilingual schools, rather than being language delayed or confused, possessed powerful and equal dual-language competence both in Spanish and in English. Children who were bilingual in both Spanish and English from birth performed better on select reading tasks than age- and grade-matched monolingual Spanish children in Spanish and monolingual English children in English (Kovelman, Baker & Petitto, submitted). Further, children from monolingual English homes enrolled in the 50/50 program performed better than English monolinguals in monolingual English schools on key phonological tasks crucial for reading. Not only are these children linguistically advantaged, but early bilingual exposure also appears to render children more cognitively advantaged on select cognitive tasks as compared to monolingual peers (Baker, Kovelman, Bialystok & Petitto, 2003).

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 first words. By doing so, we will also provide a new way to distinguish between *deviance* and *delay* in children's phonological processing, monolingual and bilingual. 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 United States 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.

WHAT EDUCATIONAL NEUROSCIENCE STUDIES CAN TELL US ABOUT 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 key new concepts in virtually every aspect of science education, ranging from the concepts of force in Newtonian physics (e.g., McCloskey 1983; McCloskey, Caramazza, & Green, 1980), to evolutionary theory in biology (Chi & Roscoe, 2002). 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) have 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. This and dozens of other studies indicate that delineating how the mind/brain represents knowledge and how learning changes this underlying knowledge is central to designing and implementing educational practice (Baker & Dunbar, 2001; Dunbar, 1997; Dunbar, 2001; Dunbar & Fugelsang, in press a, in press b; Fugelsang & Dunbar, in press; McComas, 1998).

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 (Clement, 1982; diSessa, 1993; Hammer, 1996; McCloskey, 1983; Mestre, 1991; Reddish & Steinberg, 1999). On the basis of over twenty years of research it is now known that students possess a knowledge of physics concepts that is quite different from that being taught in physics courses, and that students tenaciously hold on to their original views despite empirical demonstrations and theoretical expositions of the correct views.

More specifically, 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 erroneous perceptions are difficult to modify through instruction. For example, McCloskey et al. (1980) conducted a study which 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 believed 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), and Galili and Bar (1992), also point to the persistence of conceptions of motion that are very different from Newtonian concepts. A primary concern of recent research has been to determine the reasons for this difficulty.

Analyses of students' conceptions, 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 (See McDermott & Reddish 1999 for a review of this literature). Following Kuhn (1972), researchers have also noted that students changing conceptions are similar to the sequences of conceptual changes that have occurred in the history of science. Theories of conceptual shifts 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, in press a; Keil, 1999; Nersessian 1998; and Thagard, 1992 for reviews of this literature). In this type of situation, it is necessary for a new conceptual system to be acquired that organizes knowledge in new ways, adds to the new knowledge, and 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. Failure to achieve this conceptual change is regarded as the major source of difficulty for students. Research on students' conceptions of motion indicate that students have extensive misunderstandings and use "naïve theories" of motion. These Naïve theories consist of erroneous beliefs about 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 appear to maintain "Impetus" notions even after one or two courses in physics. Thus, it is only after extensive learning that we see a conceptual shift from "Impetus" theories of motion to Newtonian theories.

A key issue for science education is to determine why conceptual change is so hard to achieve. The main untested assumption in much of contemporary science education is that students' naïve theories can be eliminated through presenting students with anomalies. Researchers argue that by presenting students with anomalies, students will realize that their naïve theory is incorrect and will then reorganize (restructure) their knowledge, eventually arriving at the "correct" theory. Through intensive teaching using anomalies it is thought that naïve theories are eliminated. The use of anomalies has therefore been a cornerstone of constructivist education (e.g., Baker & Piburn 1997; Mortimer & Machado 2000). It is thought that when students display a clear understanding of correct concepts a reorganizing of knowledge has occurred. However, while there clearly have 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. 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? Because cognitive neuroscientists have identified the major brain sites involved in memory, learning, attention, and reasoning, 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.

Anomalies, the brain, and conceptual change in science education: In this research, we used fMRI to investigate changes in scientific concepts that students find plausible or implausible (Fugelsang & Dunbar, in press a). 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 was consistent or inconsistent with their 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. We gave students data that were either consistent or inconsistent with a plausible or an implausible 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 even minor changes in a concept, whereas data consistent with a plausible theory would be successfully integrated with the given 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 is *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 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 that 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 naïve theories when responding to our task. That is, we expected to see the non-physics students use naïve 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 the 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 that 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 fall at the same rate, with naïve movies in which the bigger ball falls at a faster rate than the smaller ball. The behavioral data revealed that the non-physics students classified the larger ball as falling faster than the smaller ball as they had expected, whereas the physics students classified the two balls (both the larger and the smaller balls) as falling at the same rate as they had expected. Thus, physics students appeared to have made the conceptual change to Newtonian physics. An independent test of student's physics understandings (The Force Concept Inventory; Hestenes, Wells & Swackhamer, 1992) also indicated that the physics students had made the conceptual shift from a naïve theory of motion to a Newtonian theory.

The fMRI data indicate 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 naïve theory. 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 naïve movies (with the bigger ball falling faster than the smaller ball), this was inconsistent with their Newtonian theory and as a result the Anterior Cingulate and Supplementary Motor Areas showed increased activation. Thus, the physics students appeared to be regarding the naïve 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 naïve-movies. 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 naïve knowledge while concurrently activating their 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.

Implications of Educational Neuroscience Research for Science Education

The results of the fMRI experiments summarized here (Fugelsang & Dunbar, in press; Dunbar & Fugelsang, in preparation) indicate that despite students giving correct responses, their knowledge may not have undergone the type of conceptual change that many educators have assumed is taking place when students learn science. These results have important implications for many types of educational interventions and for theories of what happens when we educate our students. The standard theory 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. Many educational theorists see this conceptual reorganization as being *the* key goal of education and see conceptual change as so complete that students will not even be able to conceptualize their old theories following a conceptual change (Kuhn's notion of incommensurability). Yet the results of the experiments reported here indicate that even when conceptual change appears to have taken place, students still have access to the old naïve theories and are inhibiting their old theories in the course of processing the new. Furthermore, 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.

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 theories, particularly in physics that may never completely go away, but instead be held in check. One important question that we are currently asking is why students so tenaciously hold on to erroneous conceptions. Is it that students have acquired considerable success with using a partially correct theory and that by the time students are formally educated in physics the incorrect theories are so deeply ingrained that they cannot be modified, they can 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 to optimal learning of scientific concepts. One possible solution would be to teach physics concepts at a younger age, before students' concepts become firmly entrenched. Alternatively, it may be the case that erroneous conceptions in physics tap into core knowledge (Carey, 1991; Carey & Spelke, 1996) that can never be replaced or reorganized, but can be inhibited.

Acknowledgements

We thank all of the many children and adults, teachers, schools, parents and educational administrators who gave of their time to participant in this research. Petitto thanks Ioulia Kovelman, and Dunbar thanks Jonathan Fugelsang, two remarkable young scientists in our labs, both of whom were valued collaborators on several research projects within. We thank Elizabeth Norton for providing invaluable assistance on important aspects of manuscript preparation. We each thank the Spencer Foundation for their generous support of our research, and Dartmouth College research grants. For select papers and more information see (Petitto) http://www.dartmouth.edu/~lpetitto/ and http://www.dartmouth.edu/~lpetitto/lab/ and (Dunbar)

http://www.dartmouth.edu/~kndunbar/pubs.html and
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