13 Cortical images of early language and phonetic development using near infrared spectroscopy

Laura-Ann Petitto

Overview

Educational neuroscience provides powerful tools and new knowledge to help researchers and educators to build on cognitive neuroscience to open new perspectives for education and for remediation of young children at risk. A promising new tool is Near-Infrared Spectroscopy (NIRS), which can be used with very young children to explore many cognitive capacities and performances. In particular, NIRS gives solid evidence for the existence of language-specific neural networks in infants well before they can speak. For linguistic stimuli, the networks include the left superior temporal gyrus and Broca's area, areas that are strongly involved in language in older children and adults. Brain imaging research can provide new arguments and tests for a model of language acquisition based on the early endowment of specific linguistic areas. Educational neuroscience research can address many other educationally relevant questions in a similar way.

The Editors

Revolutions can start in unlikely places. Beginning around twenty years ago, researchers in hospital sub-basements began using new brain imaging technology to look inside the skulls of volunteers while they were alive and performing a variety of cognitive tasks. This exciting imaging technology, designed to detect brain areas that drank up more oxygen than others during specific cognitive tasks, was used to discover how the brain was organized and which systems of neural areas made possible the spectacular mental functions that we humans enjoy. Alongside these cognitive neuroscience studies of adults, researchers in the disciplines of cognitive science, cognitive psychology, social psychology, and others, were making fundamental advances regarding our perceptual, cognitive, and social worlds.

Using elegant behavioral experimentation, other researchers in the fields of child development and child language began the careful study of children. They examined both the learned and unlearned capacities that infants bring to bear when they hear sounds, babble, understand, and produce language, discover concepts of numbers and math, perceive faces and objects in their world, learn and grow, as well as how these capacities interact with crucial features in the environment en route to becoming healthy adults. Following quickly was the use of new brain imaging technology with children to identify the neural pathways that contribute to the child's mastery of such content, with a new thrust toward studying the *time course* and *sequence* when the child is most likely to develop and grow in these capacities. These research findings suggested optimal points of entry for teaching, motivating, and learning specific content at specific ages across development. Furthermore, new research findings emerging from scientists, medical and clinical practitioners, and educators confirmed that the growing child's social context was vital: families, communities, and schools have the potential to positively influence children's development through systematic and well-timed interventions.

Soon, a collection of people from a variety of disciplines were making extraordinary discoveries about how children grow, acquire language, think, reason, learn a variety of skills and knowledge (including reading, math, and science), and how they conceptualize their social, emotional, and moral world. Hence, the revolution in education was born!

Researchers and educators alike began to converge on educationally important basic mechanisms in learning across diverse content areas that dynamically interact and change over time. Indeed, these extraordinary discoveries about the child's developing brain and environment have yielded a revolution within education of the magnitude seen only once before in the last century when Piaget's stages of child development swept the world and served as the Holy Grail upon which school programs were based. Recently, this exciting new union among researchers, educators, and practitioners has been called *Educational Neuroscience* (e.g., Petitto & Dunbar, in press). Educational Neuroscience brings together individuals from diverse backgrounds, including cognitive brain scientists, learning scientists, medical and clinical practitioners, and those in educational policy and teaching, who are joined in their mutual commitment to solve prevailing problems in the lives of developing children, understand the human learning capabilities over the life span (both in brain and in behavior), and 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 (e.g., Petitto & Dunbar).

The biggest dangers will be to avoid the reductionist expectation (Mittelstrass, this volume) that each aspect of mental life can and must be identified by specific neural activity before going forward with educational policy building, and we must forever remain aware that the developing brains of children are directly impacted by the situations and contexts that they find themselves in; biology and environment must work hand in hand (Singer, this volume). With these factors in mind, however, the unique interdisciplinary field of Educational Neuroscience has already yielded remarkable advances in our understanding of optimal ways to educate young children in a variety of content areas (e.g., language and bilingualism, reading, math, science) and it has already provided important insights into particular developmental disorders. For example, 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's 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 a critical view see Bruer, this volume). 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 discussions of such advances see Byrnes & Fox, 1998; Geake, 2003, 2004; Geake & Cooper, 2003; Goswami, 2004; O'Boyle & Gill, 1998.)

Below, I provide one example of a new Educational Neuroscience research finding. It is an "Educational Neuroscience" finding specifically because it unites (i) cognitive neuroscience imaging findings about the brain, (ii) established behavioral methods and content (here, from child language), and (iii) a principled application to national educational priorities (here, the early identification and remediation of young children at risk for language disorders). Crucially, the Educational Neuroscience finding at hand can advance both the said field (child language) as well as the greater field of education *in ways that could not have been done previously simply by using behavioral or observational methods alone*.

Our specific example will ask how do young infants discover the finite set of phonetic units that will form the basis of their entire language from the constantly varying linguistic and perceptual stream around them? Traditional attempts to answer this question have largely used behavioral methods with young infants *to infer* whether specific-linguistic versus general-perceptual mechanisms underlie this capacity. Here we show how a new brain imaging technology can shed new light on resolving this decades-old question in child language, while providing a new tool that can aid the early identification and education of young babies at risk for language disorders even before they utter their first words.

Out of the chaos of sights and sounds in our world, all human babies discover the finite set of phonetic units that form the basis of their entire native language by approximately age 10 months. For four decades, heated scientific debate has centered on how this is possible – how do infants come to have this remarkable capacity? Some have argued that this capacity reflects the neural superiority of our species to process specific properties of natural *language*, while others have argued that this capacity is built up from mechanisms of general *perception*.

The question of how young infants discover the phonetic building blocks of their language from the constantly varying stream of sounds and sights around them has been the looming question in early child language acquisition since the 1960s. Decades of research showed that young babies (under age 6 months) demonstrate an initial capacity to discriminate all of the world's languages' phonetic contrasts, including both native and non-native (foreign language) oral phonetic contrasts, without ever having heard them before. But, by 10–12 months of age, babies perform like adults and discriminate only their native phonetic contrasts – as if their initial open capacity had, over development, set on (or deduced or neurologically tuned to) the specific language contrasts present in their environment (for a review see Jusczyk, 1997; also Eimas, 1975; Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Kuhl, 1979; Polka & Werker, 1994; Stager & Werker, 1997; Werker, Cohen, Lloyd, Casasola, & Stager, 1998; Werker & Lalonde, 1988; Werker & Stager, 2000; Werker & Tees, 1983, 1999). Thus, human infants were thought to be innately endowed with a specialized *language* mechanism for segmenting and processing phonetic units *per se*.

The claim for a specialized language mechanism in young infants has been challenged by several lines of research, however. It has been weakened by research showing that certain non-human animals also exhibit categorical discrimination for human speech sounds (Kluender, Diehl, & Killeen, 1987; Kuhl, 1981; Kuhl & Miller, 1975, 1978; Kuhl & Padden, 1982, 1983; Morse & Snowdon, 1975; Waters & Wilson, 1976), and by research demonstrating categorical discrimination in infants for some non-speech sounds (Jusczyk *et al.*, 1977). It has also been shown that both human infants and cotton-top tamarin monkeys can discriminate sentences from unfamiliar languages such as Dutch and Japanese when sentences are played forwards but not backwards (Ramus, Hauser, Miller, Morris, & Mehler, 2000). Additionally, it has been shown that both human infants and cotton-top tamarins can discriminate between syllables that differed only in the frequency with which they occurred in streams of input speech (Hauser, Newport, & Aslin, 2001; Saffran, Aslin, & Newport, 1996). Based on these findings, many researchers have rejected the view that infants have specialized mechanisms for linguistic/phonetic processing. Instead, it has been suggested that speech/language perception in young infants can be best explained by general *auditory* (perceptual) mechanisms also present in other species (Aslin, 1987; Jusczyk, 1985).

One intriguing reason for the remarkable perseverance of this debate is due to the fact that the empirical question – in both its previous and its present guise – has been *a priori* largely unanswerable. Specifically, all research to date has used speech and sound to test whether speech and sound are key to this categorization capacity. As a result, the specific (phonetic/language) versus general (auditory/perceptual) distinction for the processes driving language perception have not been able to be teased apart experimentally, leaving contemporary science unable to adjudicate between the phonetic representation hypothesis and the general auditory (general perceptual) representation hypothesis. Recent evidence from Baker, Sootsman, Golinkoff, and Petitto (2003), Baker, Idsardi, Golinkoff, and Petitto (2005), Baker, Golinkoff, and Petitto (in press), and Baker, Groh, Cohen, and Petitto (submitted) has shed new light on this debate by providing behavioral evidence that these early phonetic processing abilities are specific to language rather than general-auditory/perceptual. Moreover, they are specific to humans, as they are not observed in non-human primates such as the monkeys that Petitto and colleagues also studied in comparison to the infants (Baker, Groh, Cohen, & Petitto, submitted). Using Petitto's Infant Habituation Laboratory, Petitto and colleagues showed that hearing, speech-exposed 4-month-old infants were able to discriminate American Sign Language (ASL) phonetic handshapes by category membership. That is, they treated them like true linguistic/phonetic units in the same way that young hearing infants, for example, exposed to English can nonetheless discriminate phonetic units in Hindi (even though the infants have never before encountered them; Stager & Werker, 1997; Werker *et al.*, 1998; Werker & Stager, 2000; and other classic studies: for a review see Jusczyk, 1997). Crucially, these infants did not discriminate the handshapes at 14 months, just as in speech perception results. The monkeys never showed the ability to discriminate phonetic sign-handshape units, and performed similarly to the non-categorizing 14-month-olds. Thus, based on these *behavioral* studies, early phonetic processing and the development of phonetic categories may be "linguistic-specific" and not a result of general perceptual processing.

New contributions from NIRS neuroimaging

While our behavioral studies of phonetic discrimination provided tantalizing clues as to how the young baby may analyze the input stream, one important piece of the puzzle is missing: whether the *brains* of young children actually recruit classically-understood, specifically *linguistic sites* and *linguistic neural networks* to perform these phonetic discriminations or other areas associated with the general perception of stimuli (either visual or auditory)? If the former, what is the developmental time course of these neural areas underlying language processing? Knowing this important information constitutes a crucial "missing piece" of this prevailing puzzle and it would indeed fundamentally advance our knowledge of this vital issue in human development in a manner not previously possible.

To answer this question, we built on previous behavioral experiments with a series of new related experiments utilizing state-of-the-art optical neuroimaging technology, *Near-Infrared Spectroscopy* (NIRS), to probe the neural correlates of young infants' developing phonetic processing capabilities. 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 more movement than fMRI, and can be used with alert (vocalizing and/or talking) participants.

Only three studies had used the NIRS technology to study human infants' cognition, specifically, object permanence (Baird *et al.*, 2002) and emotions (Sakatani, Chen, Lichty, Zuo, & Wang, 1999; Zaramella *et al.*, 2001) – all with great success. Moreover, one study had looked at the processing of language in young infants (Peña *et al.*, 2003), though they used very gross comparisons of whether activation occurred in the right or the left hemisphere. With the exception of the present research, no study had looked at the *focal* activation of language development in children, analyzing *within-hemisphere* differences in infants.

In our NIRS studies of infant neural processing of language and perceptual stimuli, we used standardized behavioral tasks (including general visual perception and language processing), which were conducted with infants while in our Habituation Laboratory (classic infant looking/discrimination paradigm). At the same time, the infants were also undergoing NIRS brain recordings to test specific within-hemisphere neuroanatomical hypotheses about focal neural tissue (and networks of

(a)

Photo 13A Typical temporal placement (Infant).

neural tissue) regarding their general perceptual versus linguistic processing functions. A silicon probe set (or probe holder) contained the optical fibers, and the probes were held in place on the participant's head by a soft terrycloth runner's headband (see Photo 13A). Several pilot studies were conducted with infants and adults of which only a subset with the infants are reported here (a full report appears in Petitto, Baker, Baird, Kovelman, & Norton 2004; Petitto, Baker, Kovelman, & Shalinsky, in preparation).

For NIRS recording, we used the standard brain imaging system presently available and used by others: the Hitachi ETG-100 NIRS device that records simultaneously from 24 channels on the cortex. Channels mostly record and measure vascular changes from the cortex that is 2–3 cm below the scalp. The ETG-100 emits infrared light at two wavelengths, 780 and 830 nm, through the fibers (inter-optode distance 2 cm). Two different wavelengths are used because of the differential characteristic absorption patterns of oxyhemoglobin (HbO) and deoxyhemoglobin (Hb) (Villringer & Chance, 1997). The non-absorbed light is sampled once every 100 ms. The incoming signal at a given detector is composed of both source wavelengths, which is separated by synchronous (lock-in) detection using the two source signals as a reference. These two components are low-pass filtered at 20 Hz to remove autonomic signals (e.g., heart beat and respiration), and digitized by a computer. A computer converts the changes in oxygen absorption at each wavelength into relative concentration changes in cerebral chromophores HbO and Hb. The sum of changes in HbO and Hb enables the calculation of the changes in total hemoglobin (THb) in response to task, control, and baseline conditions.

Two types of NIRS probe set placements were used, Temporal and Occipital. To ensure neuroanatomical accuracy in the placement of probe sets, they were placed on the skull using the following highly systematic method. The first position, *Temporal Probes*, utilizes two probe sets, each containing nine optical fibers of 1 mm in diameter. One set was placed over the left hemisphere (LH) and the other was placed over the right hemisphere (RH). Probes were positioned so as to maximize the likelihood of monitoring the frontal and temporal areas, specifically Broca's Area and the Superior Temporal Gyrus. Of the nine fibers per probe, five were emitters and four were detectors. Fibers were placed 2 cm apart, providing twelve recording sites per hemisphere (channels = 24). Each channel corresponds to the central zone of the light path between each adjacent emitter-detector fiber pair. As in the published study with NIRS and infants (Peña *et al.*, 2003), we placed the probe sets using the skull landmark system that is standardly used in Event Related Potential (ERP) brain recording research, called the 10–20 system (see Photos 13 A–B): the vertex was determined as the site where the midpoint of a line going from the nasion to the inion intersects the midpoint of another line going from the left to right prearicular lobule. The second position, the *Occipital Probes*, is where one probe set was placed over the occipital lobe, containing fifteen fibers of 1 mm in diameter (three rows with five probes each, see Photo 13B). Probes were positioned so as to maximize the likelihood of monitoring the visual areas. Of the fifteen fibers in the probe set, eight were emitters and seven were detectors (see Figure 13.1). Fibers were placed 2 cm apart, providing collection for 22 channels. As in the 10–20 system, the probes were positioned such that the bottom row was aligned with the inion.

Six full-term, healthy monolingual English infants (mean age 3 months 29 days) completed three tasks that included exposure to (i) Non-native phonetic units (i.e., real phonetic units, but those that were not present in the child's native language), (ii) English "infant-directed speech" (i.e., the exaggerated sing-song speech in simple but grammatically-correct sentences that adults typically use with young babies and children, e.g.,

(b)

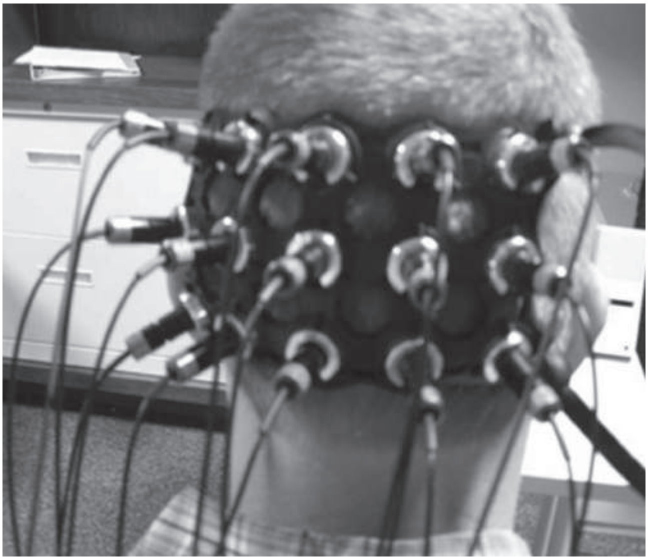

Photo 13B Typical occipital placement (Adult).

Fernald *et al.*, 1989), and (iii) visual checkerboards (i.e., a flashing black and white checkerboard image; for a full report see Petitto, Baker, Baird, Kovelman, & Norton, 2004; Petitto, Baker, Kovelman, & Shalinsky, in preparation).

We found activation within the classic language areas (Broca's Area and Superior Temporal Gyrus-STG) for tasks (i-ii), which were linguistic stimuli, but not for (iii), which was (nonlinguistic) visual stimuli. Taken together, all three sets of data (see Figures 13.2–13.4) imply that the infants' brain honors a distinction between linguistic versus general visual processing areas depending on the specific nature of the stimuli at hand.

This pattern of activation in the infants was exciting both because the infants were so young and because it was the same neural areas observed for language processing as has been observed in the classic studies in adults. Moreover, the activation in the infants was significantly greater in their Left STG and Left Broca's Area as compared to right hemisphere activation in these areas. Thus, the infants' pattern of results, albeit preliminary, suggests that the processing of linguistic information in very young infants is indeed utilizing classic language tissue as it has been known to be used in adults. It also suggests that our language processing areas may be "on-line" and functioning from an early age

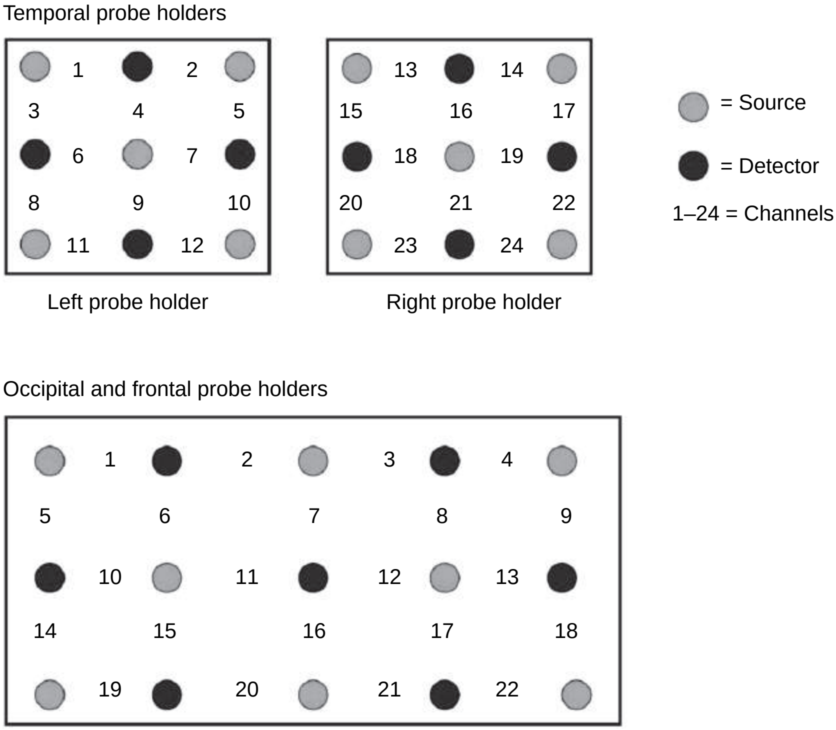

Figure 13.1 Schematic diagram of probes. Schematic diagram of the configuration of the source and detector pairs in the probe holders that were placed on the participant's scalp, as well as the corresponding channels that were used in the analyses. The top two boxes show the temporal probe holders (left probe holder was placed over the participant's left hemisphere temporal lobe; right probe holder was placed over the participant's right hemisphere temporal lobe). The bottom box shows the configuration of the occipital/frontal probe holders that were placed either on the participant's frontal lobe, or on their occipital lobe.

and that these areas may constitute endowed neural sites for language processing in humans; of course, this latter point is a preliminary hypothesis to be tested further in many future studies. To be clear, for the linguistic stimuli, we found only linguistic tissue being engaged, not tissue that would be commensurate with general perceptual processing.

Significance: For decades, scientists and educators alike have been fascinated with the question of how young infants discover the elementary building blocks of language – their phonetic inventory – from the

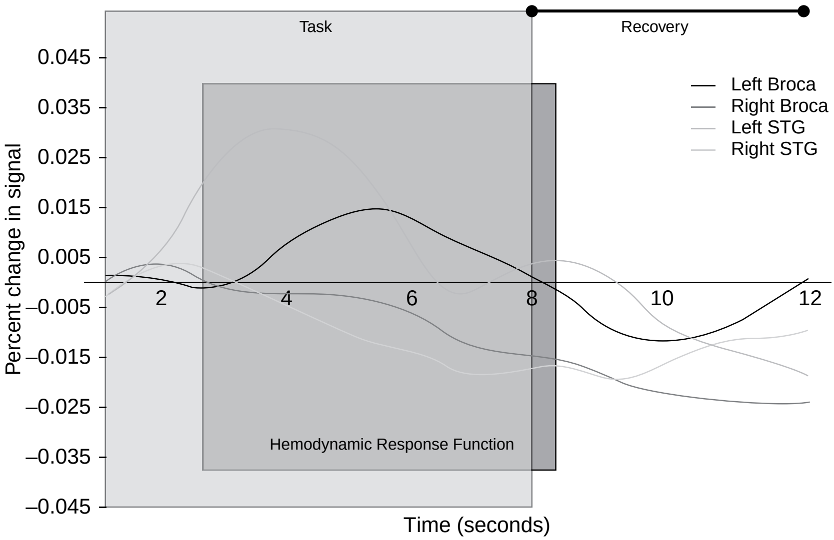

Figure 13.2 Non-Native Phonetic Units: The figure shows that when the linguistic/phonetic stimuli were presented to the infants their brain's classic linguistic Broca's Area and Superior Temporal Gyrus area (STG) in their left hemispheres became activated. Note that activation was not seen in the corresponding tissue in their right hemisphere regarding those areas corresponding to Broca and STG; this can be seen by observing that both lines fall under the horizontal line. (Increases in the signal relative to baseline were found in both left Broca's Area and left STG, r =.25, r =.38 respectively).

steady stream of sounds and sights around them. Indeed, the infant's capacity to segment the linguistic stream (to discover its native set of small meaningless phonetic units and to categorize them) is central to her ability to discover the "word" (and its boundaries), learn word meanings, and to discover the patterned ways that strings of words are arranged in phrases, clauses, and sentences. In essence, the early infant capacity to discover and categorize phonetic units is a central component of the human language acquisition process, with phonological processing resting at the heart of a child's capacity to learn words, language and, ultimately, to be a successful reader! It is little wonder therefore that there have been many years of hot pursuit into the question of how infants do this: what is at the basis of the infant's extraordinary capacity to discover and categorize phonetic units?

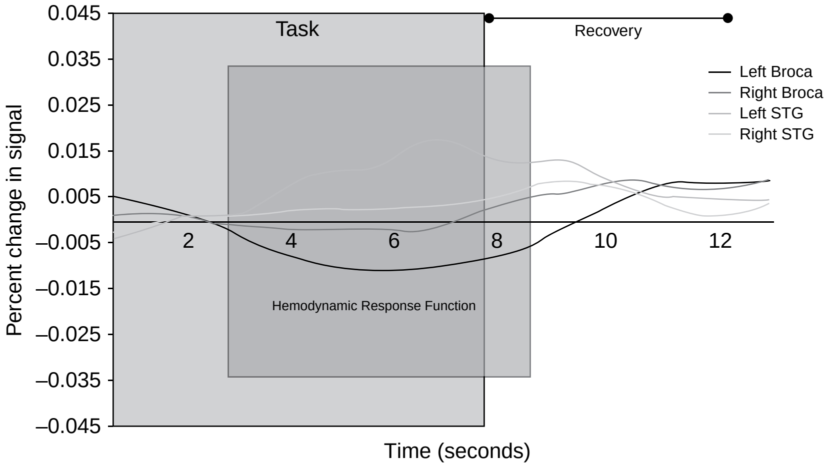

Figure 13.3 Infant Directed Speech: The figure shows that when infant directed speech (sing-song sentences) was presented to the infants their brain's classic linguistic Superior Temporal Gyrus (STG) area in the left hemisphere became robustly activated, and this left hemisphere activation was more robust than that of their right hemisphere's STG activation. As predicted for this type of linguistic task, neither the left hemisphere Broca's Area nor the corresponding area in the right hemisphere showed robust activation; this can be seen by observing that both lines fall under the horizontal line. Interestingly, that the STG activation was greater in the left hemisphere as compared to the right hemisphere suggests that the infants were processing this linguistic information as linguistic and not as general (auditory) perceptual stimuli. If the infants were using general auditory perceptual processing, then we should have seen greater and more comparable bilateral STG activation, which we did not. (An increase in signal relative to baseline was found in left STG, $r = .16$).

Although *behavioral* studies from my own laboratory and others have provided important support for the hypothesis that specialized linguistic mechanisms must be at work in young infants' acquisition of phonology and language (Holowka, Brosseau-Lapré, & Petitto, 2002; Petitto, 2000, 2005; Petitto & Holowka, 2002; Petitto & Marentette, 1991; Petitto, Holowka, Sergio, Levy, & Ostry, 2004; Petitto, Holowka, Sergio, & Ostry, 2001; Petitto, Katerelos, Levy, Gauna, Tétrault, & Ferraro, 2001), key evidence about the infant's *brain* was largely absent.

The present finding provides a new look at an old question. As history taught us, the question of whether young infants are processing linguistic

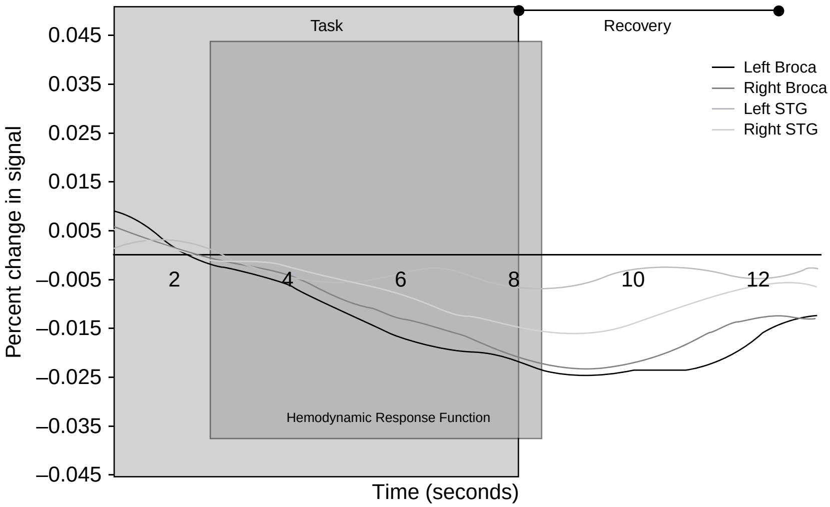

Figure 13.4 Visual Checkerboard Task: The figure shows that when the infants were processing the black and white flashing checkerboard image, no significant activation was observed in classic linguistic processing areas in either hemisphere. This can be seen by observing that all four lines (left Broca, right Broca, left STG, right STG) fall under the horizontal line. Specifically, there were no significant changes in activation observed in linguistic left Broca's area (or corresponding right Broca's) during this visual perception task. Additionally, there were no significant changes in activation observed in linguistic left STG (or corresponding right STG, which would be predicted if processing stimuli as general auditory perceptual information) during this task. Overall, there were no significant differences between right and left hemisphere regions. Recall that the probes were over the left and right temporal lobes and thus these findings were predicted (because of our *a priori* knowledge that the stimuli were perceptual in nature) and are thus encouraging results regarding the efficacy of using NIRS with infants. This suggests that the infants were not processing the visual perceptual stimuli with classic linguistic areas of the brain. Crucially, the results provide exciting confirmation that the identical brain tissue is responding differentially to different input stimuli.

(phonetic) stimuli through linguistic versus general perceptual means was impossible to resolve through the exclusive use of behavioral methods.

From the outside looking in, the infant's behavioral performance did not permit us to adjudicate which types of mental processing were being employed as they engaged in a task. This is the first experiment to demonstrate that we can obtain *within-hemisphere* focal neuroanatomical activation for highly specific tasks in awake, behaving infants as young as 3 months old. To be sure, many more studies will follow to determine the finding's generalizability. Nonetheless, this preliminary evidence suggests that the brains of young infants may be using specific linguistic mechanisms when processing phonetic information rather than general perceptual mechanisms. These results suggest a resolution to a forty-year-old debate in child language.

Educational Neuroscience: From the laboratory to education

We conducted a study that uses innovative NIRS technology, which, for the first time, permitted us to evaluate highly specific neuroanatomical hypotheses about the brain tissue that participates in infant language processing in a manner hitherto not possible in behavioral studies. By doing so, this research helps adjudicate a classic scientific debate about whether language-specific versus perception-general mechanisms initiate and govern early language learning. Research of this sort can 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.

Beyond clear advances to our scientific understanding of brain processes in early life, such studies also have important applications to education. Following more experimental replication and standardization studies with NIRS and young babies, we plan to establish and offer the field guidelines for the principled use of NIRS with children that could have important diagnostic, remediation, and teaching utilities 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 (e.g., Penhune, Cismaru, Dorsaint-Pierre, Petitto, & Zatorre, 2003; Petitto *et al.*, 1998, 2000). We also have evidence that this is true in infants from as early as 4–5 months old (Holowka & Petitto, 2002; Norton, Baker, & Petitto, 2003). Our present studies will evaluate whether this is true in much younger infants (from 2 days old). The scientific establishment of the neural tissue that underlies early phonetic segmentation, categorization, and processing – as well as its typical onset age in development – can ultimately be used (in combination with standardized NIRS data from typically developing babies) as one component in the toolkit of diagnostic measures to *identify and predict* babies at risk for language and phonological sequencing disorders (e.g., dyslexia) in very early life 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. *Note that this outcome would not have been possible through behavioral studies alone as children's language and reading problems reveal themselves behaviorally over many years.*

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 successful reading (Goswami, this volume). The studies will thus impact US educational policy by providing a tool for the early identification of a core component underlying reading (phonological processing) that will enable more appropriate language remediation programs and methods of classroom teaching. For example, cognitive neuroscience research from our lab and other labs has already provided insights to educational policy and practice regarding when in the curricula to introduce foreign languages, whether phonetic versus whole-word reading instruction methods are most optimal, how teaching phonological awareness can improve both good and atypical (e.g., dyslexic) readers, and the developmental sequence underlying the learning of language (Goswami and Wolf, this volume). All of this research has already begun to impact educational curricula in the United States. To be sure, the coming century of Educational Neuroscience research has the potential to continue to make such advances to educational practice and policy worldwide.

Acknowledgments

It was indeed my distinct honor and privilege to have been invited to speak before The 400th Anniversary of the Foundation of the Pontifical Academy of Sciences in Vatican City, Italy (November 7–11, 2003), and to have had the great honor to meet personally Pope John Paul II. I shall be forever grateful to Professors Kurt Fischer and Antonio Battro for giving me the amazing opportunity to do so. I thank the parents of the babies who participated in this study (as well as the babies!). I thank Elizabeth Norton and Rachael Degenshein for their brilliant assistance on aspects of manuscript preparation and I also thank Elizabeth Norton, as well as this study's other collaborators, Abigail Baird, Stephanie Baker, and Ioulia Kovelman for pioneering together this challenging new NIRS technology. Finally I thank those who funded this research: The Spencer Foundation and Dartmouth College, the Dana Foundation for the Arts, and I am especially grateful for the generous support of the National Institutes of Health (Grant Nos. R01-HD045822–03, R21-HD050558–02).

For reprints and more information, see Petitto's Research web site: www.utsc.utoronto.ca/~petitto/.

Please address correspondence to Laura-Ann.Petitto@utsc.utoronto.ca.

References

Aslin, R. N. (1987). Visual and auditory development in infancy. In J. D. Osofsky (ed.), *Handbook of Infant Development* (2nd edn., pp. 5–97). Oxford, UK: John Wiley.

Baird, A. A., Kagan, J., Gaudette, T., Walz, K., Hershlag, N., and Boas, D. (2002). Frontal lobe activation during object permanence: Data from near infrared spectroscopy. *NeuroImage*, 16, 1120–1126.

Baker, S. A., Golinkoff, R., and Petitto, L. A. (in press). New insights into old puzzles from infants' categorical discrimination of soundless phonetic units." *Learning Languages and Development*.

Baker, S. A., Groh, J. M., Cohen, Y. E., and Petitto, L. A. (submitted). The perception of soundless phonetic units in rhesus macaques. Manuscript submitted for publication.

Baker, S. A., Idsardi, W. J., Golinkoff, R., and Petitto, L. A. (2005). The perception of handshapes in American Sign Language. *Memory & Cognition*, 33 (5), 887–904.

Baker, S., Sootsman, J., Golinkoff, R., and Petitto, L. A. (2003, April). *Hearing four-month-olds' perception of handshapes in American Sign Language: No experience required*. Proceedings of the Society for Research in Child Development 2003 Biennial Meeting, Tampa, FL.

Byrnes, J. P. and Fox, N. A. (1998). The educational relevance of research in cognitive neuroscience. *Educational Psychology Review*, 10(3), 297–342.

Eimas, P. D. (1975). Auditory and phonetic coding of the cues for speech: Discrimination of the (r-l) distinction by young infants. *Perception & Psychophysics*, 18(5), 341–347.

Eimas, P. D., Siqueland, E. R., Jusczyk, P., and Vigorito, J. (1971). Speech perception in infants. *Science*, 171, 303–306.

Fernald, A., Taeschner, T., Dunn, J., Papousek, M., Boysson-Bardies, B., and Fukui, I. (1989). A cross-language study of prosodic modifications in mothers' and fathers' speech to preverbal infants. *Journal of Child Language*, 16, 477–501.

Geake, J. G. (2003). Adapting middle level educational practices to current research on brain functioning. *Journal of the New England League of Middle Schools*, 15, 6–12.

(2004). Cognitive neuroscience and education: two-way traffic or one-way street? *Westminster Studies in Education*, 27(1), 87– 98.

Geake, J. G. and Cooper, P. W. (2003). Implications of cognitive neuroscience for education. *Westminster Studies in Education*, 26(10), 7–20.

Goswami, U. (2004). Neuroscience and education. *British Journal of Educational Psychology*, 74(1), 1–14.

Hauser, M. D., Newport, E. L., and Aslin, R. N. (2001). Segmentation of the speech stream in a nonhuman primate: Statistical learning in cotton top tamarins. *Cognition*, 78, B53-B64.

Holowka, S., Brosseau-Lapré, F., and Petitto, L. A. (2002). Semantic and conceptual knowledge underlying bilingual babies' first signs and words. *Language Learning*, 52(2), 205–262.
Holowka, S. and Petitto, L. A. (2002). Left hemisphere cerebral specialization for babies while babbling. *Science*, 297, 1515.
Jusczyk, P. W. (1985). On characterizing the development of speech perception. In J. Mehler and R. Fox (eds.), *Neonate Cognition: Beyond the Blooming, Buzzing Confusion* (pp. 199–229). Hillsdale, NJ: Erlbaum.
(1997). *The Discovery of Spoken Language*. Cambridge, MA: MIT Press.
Jusczyk, P. W., Rosner, B. S., Cutting, J. E., Foard, C. F., and Smith, L. B. (1977). Categorical perception of non-speech sounds by 2-month-old infants. *Perceptual Psychophysics*, 21, 50–54.
Kluender, K. R., Diehl, R. L., and Kileen, P. R. (1987). Japanese-quail can learn phonetic categories. *Science*, 237, 1195–1197.
Kuhl, P. K. (1979). Speech perception in early infancy: Perceptual constancy for spectrally dissimilar vowel categories. *Journal of the Acoustical Society of America*, 66, 1669–1679.
(1981). Discrimination of speech by nonhuman animals: Basic auditory sensitivities conductive to the perception of speech-sound categories. *Journal of the Acoustical Society of America*, 70, 340–349.
Kuhl, P.K. and Miller, J.D. (1975). Speech perception by the chinchilla: Voiced-voiceless distinction in alveolar plosive consonants. *Science*, 190, 69–72.
(1978). Speech-perception by chinchilla: Identification functions for synthetic VOT stimuli. *Journal of the Acoustical Society of America*, 63, 905–917.
Kuhl, P. K. and Padden, D. M. (1982). Enhanced discriminability at the phonetic boundaries for the voicing feature in macaques. *Perceptual Psychophysics*, 32, 542–550.
Kuhl, P. K. and Padden, D. M. (1983). Enhanced discriminability at the phonetic boundaries for the place feature in macaques. *Journal of the Acoustical Society of America*, 73, 1003–1010.
Morse, P. A. and Snowdon, C. T. (1975). An investigation of categorical speech discrimination by rhesus monkeys. *Perception & Psychophysics*, 17(1), 9–16.
Norton, E. S., Baker, S. and Petitto, L. A. (2003, June). *Bilingual infants' categorical perception of phonetic handshapes in American Sign Language*. Poster presented at the University of Pennsylvania Institute for Research in Cognitive Science Summer Workshop, Philadelphia.
O'Boyle, M. W. and Gill, H. S. (1998). On the relevance of research findings in cognitive neuroscience to educational practice. *Educational Psychology Review*, 10, 397–400.
Peña, M., Maki, A., Kovacic, D., Dehaene-Lambertz, G., Koizumi, H., Bouquet, F., and Mehler, J. (2003). Sounds and silence: An optical topography study of language recognition at birth. *Proceedings of the National Academy of Sciences*, 100(20), 11702–11705.
Penhune, V., Cismaru, R., Dorsaint-Pierre, R., Petitto, L. A., and Zatorre, R. (2003). The morphometry of auditory cortex in the congenitally deaf measured using MRI. *NeuroImage*, 20, 1215–1225.

Petitto, L. A. (2005). How the brain begets language: On the neural tissue underlying human language acquisition. Chapter in J. McGilvray (ed.), *The Cambridge Companion to Chomsky*. (pp. 84–101) Cambridge: Cambridge University Press.

(2000). On the biological foundations of human language. In H. Lane and K. Emmorey (eds.) *The Signs of Language Revisited* (pp. 447–471). Mahwah, NJ: Erlbaum.

Petitto, L. A., Baker, S., Baird, A., Kovelman, I., and Norton, E. (2004, February). Near-infrared spectroscopy studies of children and adults during language processing. Presentation at the International Workshop on Near-Infrared Spectroscopy, Cambridge, MA.

Petitto, L. A., Baker, S., Kovelman, I., and Shalinsky, M. (in preparation). Near-Infrared Spectroscopy studies of children and adults during language processing. Manuscript in preparation.

Petitto, L. A. and Dunbar, K. (in press). New findings from Educational Neuroscience on bilingual brains, scientific brains, and the educated mind. In K. Fischer and T. Katzir (eds.) *Building Usable Knowledge in Mind, Brain, & Education*.

Petitto, L. A. and Holowka, S. (2002). Evaluating attributions of delay and confusion in young bilinguals, *Sign Language Studies*, 3(1), 4–33.

Petitto, L. A., Holowka, S., Sergio, L., and Ostry, D. (2001). Language rhythms in babies' hand movements. *Nature*, 413, 35–36.

Petitto, L. A., Holowka, S., Sergio, L., Levy, B., and Ostry, D. (2004). Baby hands that move to the rhythm of language: Hearing babies acquiring sign languages babble silently on the hands. *Cognition*, 9, 43–73.

Petitto, L. A., Katerelos, M., Levy, B., Gauna, K., Tétrault, K., and Ferraro, V. (2001). Bilingual signed and spoken language acquisition from birth: Implications for mechanisms underlying bilingual language acquisition. *Journal of Child Language*, 28(2), 1–44.

Petitto, L. A. and Marentette, P. (1991). Babbling in the manual mode: Evidence for the ontogeny of language. *Science*, 251, 1493–1496.

Petitto, L. A., Zatorre, R., Gauna, K., Nikelski, E. J., Dostie, D., and Evans, A. (2000). Speech-like cerebral activity in profoundly deaf people while processing signed languages: Implications for the neural basis of human language. *Proceedings of the National Academy of Sciences*, 97(25), 13961–13966.

Petitto, L. A., Zatorre, R. J., Nikelski, E. J., Gauna, K., Dostie, D., and Evans, A. C. (1998). By hand or by tongue: Common cerebral blood flow activation during language processing in signed and spoken languages. *NeuroImage*, 7(4), 193.

Polka, L. and Werker, J. F. (1994). Developmental changes in perception of nonnative vowel contrasts. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 421–435.

Ramus, F., Hauser, M. D., Miller, C., Morris, D., and Mehler, J. (2000). Language discrimination by human newborns and cotton-top tamarin monkeys. *Science*, 288, 349–351.

Saffran, J. R., Aslin, R. N., and Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, 274, 1926–1928.

Sakatani, K., Chen, S., Lichty, W., Zuo, H., and Wang, Y. P. (1999). Cerebral blood oxygenation changes induced by auditory stimulation in newborn infants measured by near infrared spectroscopy. *Early Human Development*, 55(3), 229–236.

Shaywitz, S., Shaywitz, B., Pugh, K., Fulbright, R., Constable, R., Mencl, W., Shankweiler, D., *et al.* (1998). Functional disruption in the organization of the brain for reading in dyslexia. *Proceedings of the National Academy of Sciences*, 95, 2636–2641.

Stager, C. L. and Werker, J. F. (1997). Infants listen for more phonetic detail in speech perception than in word learning tasks. *Nature*, 388, 381–382.

Villringer, A. and Chance, B. (1997). Non-invasive optical spectroscopy and imaging of human brain function. *Trends in Neuroscience*, 20(10), 435–442.

Waters, R. S. and Wilson, J. R. (1976). Speech perception by rhesus monkeys: The voicing distinction in synthesized labial and velar stop consonants. *Perception and Psychophysics*, 19(4), 285–289.

Werker, J. F., Cohen, L. B., Lloyd, V. L., Casasola, M., and Stager, C. L. (1998). Acquisition of word-object associations by 14-month-old infants. *Developmental Psychology*, 34, 1289–1309.

Werker, J. F. and Lalonde, C. E. (1988). Cross-language speech perception: Initial capabilities and developmental change. *Developmental Psychology*, 24(4) 672–683.

Werker, J. F. and Stager, C. L. (2000). Developmental changes in infant speech perception and early word learning: Is there a link? In J. Pierrehumbert and M. Broe (eds.), *Papers in Laboratory Phonology 5*, (pp. 181–193). Cambridge: Cambridge University Press.

Werker, J. F. and Tees, R. C. (1983). Developmental changes across childhood in the perception of non-native speech sounds. *Canadian Journal of Psychology*, 37(2) 278–286.

(1999). Experiential influences on infant speech processing: Toward a new synthesis. In J. T. Spence (ed.), *Annual Review of Psychology, Vol. 50* (pp. 509–535). Palo Alto, CA: Annual Reviews.

Zaramella, P., Freato, F., Amigoni, A., Salvadori, S., Marangoni, P., Suppjei, A., *et al.* (2001). Brain auditory activation measured by near-infrared spectroscopy (NIRS) in neonates. *Pediatric Research*, 49(2), 213–219.