Untangling the Temporal Dynamics of Bilateral Neural Activation in the Bilingual Brain

by

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Abstract

A persistent unanswered question in cognitive neuroscience has been what are the neural origins of human brain lateralization? Language is strongly lateralized to the left-hemisphere, however, lateralization varies with language experience. Bilinguals demonstrate a greater extent and variability of right-hemisphere involvement for language relative to monolinguals. Here, bilingualism is used as a lens into the conditions that drive brain lateralization. Why does bilingual language processing yields more robust bilateral neural activation relative to monolingual language processing?

Neural activation and functional connectivity were measured to test hypotheses about the temporal dynamics of hemispheric recruitment during language processing in monolingual and bilingual children with varying ages of first bilingual language exposure. Hypothesis (1), The human brain is strongly left-hemisphere lateralized for language, but, when faced with the demands of two languages, additional right-hemisphere resources are recruited. Hypothesis (2), The human brain has the potential for enhanced dual hemispheric language processing that can be either potentiated or not based on early life bilingual versus monolingual language experience. If dual language experience places increased cognitive demands on the bilingual brain requiring
additional right-hemisphere resources, asynchronous neural activation in left and right hemispheres was predicted. If dual language experience potentiates dual hemispheric language processing, synchronous neural activation in left and right hemispheres was predicted. Furthermore, only early-exposed bilinguals—but not later-exposed bilinguals—or monolinguals, would show synchronous neural activation across the hemispheres.

Early experience with one language (monolinguals) or two languages at different times during a child’s development (early-exposed bilinguals, later-exposed bilinguals) revealed differences in the time-course of activation across the two hemispheres’ language areas, supporting Hypothesis (2). Monolinguals and later-exposed bilinguals showed asynchronous activation between the hemispheres. Early-exposed bilinguals showed synchronous activation between the hemispheres.

The results provide a new view on how different experiences can drive lateralization in development and reveal the neural basis of bilateral activation in the bilingual brain. Synchronous temporal accessing of the hemispheres in bilinguals suggests early life bilingual language experience may support more equal and efficient hemispheric involvement, and, in turn, constitute the brain-based mechanism that makes possible the widely observed linguistic and cognitive advantages in young bilinguals.
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Chapter 1: Introduction

1 Questions about Hemispheric Lateralization in the Bilingual Brain

Early life experiences can have a profound impact on the developing brain and its organization (Greenough, Black & Wallace, 1987; Mechelli et al., 2004; Nelson, 2000; Neville & Bruer, 2001; Newman, Bavelier, Corina, Jezzard & Neville, 2002; Ohnishi et al., 2001). Acting in unison, development and experience change the brain’s physical structure and functional organization, allowing it to adapt to its environment (Hebb, 1949). Studies from our laboratory have found differences in the pattern of neural activation between monolinguals and bilinguals; bilinguals show greater extent of neural recruitment within the brain’s left hemisphere “classic language” areas (e.g., Left Inferior Frontal Gyrus; LIFG, Superior Temporal Gyrus; STG) and greater neural recruitment of their right hemisphere homologue regions (Berens, Kovelman, Dubins, Shalinsky & Petitto, 2009; Jasińska & Petitto; 2013a;b; 2011; Kovelman, Baker, Grafton & Petitto, 2005; Kovelman, Baker & Petitto, 2008a; Kovelman, Shalinsky, Berens & Petitto, 2008; Petitto, 2009; Petitto, Berens, Kovelman, Dubins, Jasińska & Shalinsky, 2013; 2010; Shalinksy, Kovelman, Berens & Petitto, 2006), which has recently been corroborated (Hull & Vaid, 2007; Parker Jones et al., 2011; Peng & Wang, 2011; Wang et al., 2011). In the present work, the neural basis of laterality is examined through the lens of bilingualism. The key question is why does bilingual language processing yield more robust bilateral activation relative to monolingual language processing? Answering this question provides a new view on neural change in development as a function of experience and allows us to address recent questions concerning the significance of bilateral neural activation and the nature of the bilingual brain.

1.1 Neural Organization for Language

Our species has a virtually limitless capacity to express infinite concepts through a generative, recursive and hierarchically organized language system. Given a set of general environmental conditions, which include systematic and regular exposure to a given language, the language
system will be acquired, without any instruction or formal training, by all human children almost entirely before three years of age. Generativity refers to a feature of human language in that it permits the speaker the capacity to generate an infinite number of new sentences from a finite set of units using a finite set of rules. Recursivity refers to the idea that languages allow unlimited extensions by embedding clauses within a sentence. Both generativity and recursivity are essential properties of human language (Chomsky, 1965). Importantly, our capacity for language includes an understanding of the various levels of language knowledge: phonology, morphology, semantics, and syntax. At the phonetic and phonological level, meaningless units called phonemes, which make up the sound inventory of a speaker’s language, are combined according to phonotactic and phonological rules into words. For example, in English, the pronunciation of the plural marker –s depends on the voicing properties of final phoneme of the word (e.g., cats /kats/, dogs /dogz/). Morphology includes our knowledge of the basic meaningful units of our language, or morphemes, stored in a ‘mental dictionary’ or lexicon. Morphemes encode a range of concepts, from concrete to abstract (e.g., cat, freedom, of) and include words as well as parts of words such as suffixes that mark tense and number (e.g., -ed, -s). Morphology includes the system underlying how morphemes are combined (e.g., neighbour, neighbourly, unneighbourly, neighbourhood, neighbourhoods) and the meaning, or semantics, which are conveyed. Syntax includes the principles by which words are combined into phrases and sentences. This is done through a system that arranges words within phrases, and phrases within a larger phrase. For instance, in English, verbs (e.g. slept) and verb phrases (e.g. happily slept) are positioned with respect to other nouns (e.g. dog) and noun phrases (e.g. the big brown dog with the blue collar) in a sentence such that the verb phrase follows the subject. Word order is one of the possible mechanisms by which semantic relations such as who did what to whom and what is where are expressed. In an English sentence such as John kissed Mary, English speakers know that John is the subject, the person doing the action, and Mary is the object, or the person who receives the action. These relations are expressed through word order. Other languages rely on different mechanisms, such a morphological case and agreement markers, to convey semantic relations, and conversely have far greater flexibility in word order. For example, the Polish sentences

(1) Jan pocalował Marysie

(2) Marysie pocalował Jan
both mean *John kissed Mary*, whereas

(3) *Marysia pocałowała Jana*

(4) *Jana pocałowała Marysia*

both mean *Mary kissed John*. Despite the different word orders, the morphological markers (*Marysie* versus *Marysia*, *Jan* versus *Jana*, *pocalowal* versus *pocalowala*) indicate which nouns serve as subject and object in the sentence.

This complex system constitutes the human language faculty. Understanding how this system is represented in the brain and what neural sites and system underlie our capacity to acquire and use language has been the focus of much research in the neurosciences. A large, and ever-growing, body of research indicates that brain areas in the temporal and inferior frontal cortex support these different aspects of language processing, including phonetic and phonological processing, morphological and word processing, syntactic and sentence-level semantic processing, as well as prosodic processing (Friederici, 2011; Price, 2012; 2000). While the whole brain participates in language, the lion’s share of activation occurs in the left hemisphere’s IFG, Broca’s Area and STG. The spatial and temporal patterns of neural activation across these and other neural sites and system underlie language function (see Figure 1; Friederici & Gierhan, 2013).

1.1.1 Phonological Processing

A finite repertoire of phonemes, each of which is defined by articulatory and acoustic features such as voicing, place and manner of articulation, serve as components of speech segments that are combined in patterned, rhythmic, rule-governed ways into meaningful words. Languages differ in the phonemes that make up their respective sound inventories and in the constraints, or rules, by which phonemes can be combined and how they affect the pronunciation of other adjacent phonemes. Yet, all languages posses this level of language structure, namely, a combinatorial system that allows a fixed inventory of sounds (dozens) to be encoded into a far greater number of words (tens of thousands). This system of sound patterns and the constraints that govern how they can be combined in a given language is the subject of phonology.

Neuroscience has probed how the human brain represents this level of language structure, revealing that certain neural sites and systems, notably the Superior Temporal Gyrus, are
crucially involved in phonological processing (e.g., Petitto, Zatorre et al., 2000; Zatorre & Belin, 2001; Zatorre, Meyer, Gjedde & Evans, 1996). Phonological processing largely occurs during the first 100 ms after first presentation of the sound stimulus in brain regions within the Superior Temporal Gyrus (STG, Brodmann’s area, BA 22/42), namely the Primary Auditory Cortex (BA 41/42) and the Planum Temporale (a part of Wernicke’s area, and located posterior to the Primary Auditory Cortex). Information from the Primary Auditory Cortex and the Planum Temporale is transmitted to the anterior and posterior STG and Superior Temporal Sulcus (STS). The STS is involved in integrating visual and auditory information (Stevenson & James, 2009) and becomes activated for human speech, particularly as a function of the intelligibility of the speech signal (Scott, Blank, Rose & Wise, 2000). Increased neural activation in posterior temporal regions and temporoparietal regions has been observed while participants completed tasks such as rhyme judgment, as in the words *house* and *mouse* or as in letters B and T (Paulesu, Frith & Frackowiak, 1993; Petersen, Fox, Posner, Mintun & Raichle, 1989). Zatorre et al. (1996) also observed increased activation in the left posterior temporal cortex, including the posterior STG, for the initial perceptual analysis of the incoming speech signal. This brain region is not activated by simple tones or noise, but rather by phonological stimuli. Zatorre et al. (1996) also observed activation in the LIFG when phonetic segments of speech were processed, which may operate on the syllabic or word level leading to word retrieval.

1.1.2 Lexical Processing

Words are a distinctive part of human language knowledge and serve to link phonological, semantic and grammatical structures. Humans have a capacity to represent and learn new words throughout the lifespan, which are stored in long-term memory (the lexicon). The meanings of words are defined by the abstract relationship between a word and its referent, as well as the relationship between a word and other words in the lexicon. As a consequence, words are organized into sets such as sub- and supraordinates, antonyms, synonyms, related concepts (semantic neighbourhoods). Words and their meanings can be ‘semantically primed’ by related words. That is, if a speaker is presented with the word *coffee*, they will more readily access a related word such as *tea*, as compared with an unrelated word such as *house* as evidenced through faster processing times (e.g. response times to reading a word) for semantically primed versus unprimed words (Lucas, 2000; Meyer & Schvaneveldt, 1971; 1976; Meyer, Schvaneveldt
& Ruddy, 1974). Thus, accessing words from the lexicon (lexical access) is partially dependent on linguistic context.

ds and their phonological code (Mesulam, 2000)

1.1.3 Sentence Processing

The syntactic level of language structure dictates how words are combined into meaningful phrases and sentences. The syntactic system must identify syntactic categories of words when encountered in a sentence (e.g., noun, verb, preposition, etc.). Information about syntactic categories serves to build local phrase structure (e.g., noun phrase, verb phrase, prepositional phrase, etc.), which is then combined into larger sentences structures.

Sentence processing involves the LIFG, anterior and posterior STG/STS, MTG, and Angular Gyrus (Friederici, 2011; Price, 2010). The anterior STG is a possible site for initial local syntactic structure building during 120-200 ms that is connected through a ventral pathway (uncinate fasciculus) to the LIFG (Brennan, Nir, Hasson, Malach, Heeger & Pylkkanen, 2012; Friederici, Meyer & Von Cramon, 2000; Humphries, Binder, Medler & Liebenthal, 2006). When violations of phrase structure are encountered, such as through experimental manipulation whereby syntactic categories are deliberately marked with an erroneous morphologically marker (Dikker, Rabagliati & Pylkkanen, 2009) this produces a neural response to the error in the form of greater neural response during the first 125ms of sentence processing. The posterior STG/STS, connected to the LIFG through a dorsal pathway. The LIFG typically participates in syntax, morphology, semantics and phonology (Caplan, 2001; Price, 2000; Foundas, Eure, Luevano & Weinberger, 1998). The integration of syntactic and semantic information during sentence processing occurs approximately 600 ms after stimulus presentation and includes the posterior STG/STS, the LIFG, as well as right hemisphere homologues of these sites, connected through the posterior portion of the corpus callosum (Friederici, 2011; Vigneau et al., 2011).

Sentence processing has been studied by comparing grammatically correct, plausible sentences to implausible sentences (Caplan, 2001). Greater activation in the left anterior and posterior MTG was observed by Mashal, Faust, Hendler and Jung-Beeman (2008) for semantically plausible sentences as compared with implausible sentences. When sentences were primed with a sentence with the same meaning versus a sentence of a different meaning, Devauchelle,
Oppenheimer, Rizzi et al. (2009) also observed greater left anterior MTG activation. Obleser and Kotz (2010) also observed greater left anterior MTG activation for sentence where meanings were difficult versus easier to predict. Similar effects have been found for written sentences as well. For example, Snijders, Vosse, Kempen et al. (2009) found activation in the anterior MTG while participants read sentences versus unrelated word sequences.

1.2 Left Hemisphere Lateralization for Language

The human brain’s two hemispheres appear to be nearly identical, but there exist functional differences between the hemispheres despite their structural similarities. Perceptual, motor and cognitive functions are lateralized to one hemisphere or the other (Corballis et al., 2000). The specialization of the left hemisphere for language processing is one of the earliest observations of brain asymmetry first reported by Broca (1861) and Wernicke (1874), who found that language was more severely impaired in response to lesions (tumours or strokes) in the left hemisphere. Left-lateralization for language is observed in over 95% of the right-handed population (Corballis, 2003). Functional asymmetry tests such as the Wada test (Zatorre, 1989; Wada, Clarke & Hamm, 1975) and dichotic listening tasks (Deutsch, 1985; Janchke, Steinmetz & Volkmann, 1992; Kimura, 1961) reveal left-lateralization for language. In the Wada test, one hemisphere is temporarily anaesthetized revealing the function of the other hemisphere. Dichotic listening tasks reveal that verbal material presented to the left hemisphere via the right ear is more readily processed than verbal material presented to the right hemisphere.

Evidence indicates that left lateralization for language is present early in development; infants and children show left hemisphere language specialization (auditory evoked potentials in infants, children and adults; Molfese & Molfese 1985; Molfese, 1978a;b; morphological asymmetry of the planum temporal in infant and adult brains; Hiscock & Kinsbourne, 1987; Wada et al., 1975; vocal babbling and mouth asymmetries in young hearing infants; Holowka & Petitto, 2002; Dehaene-Lambertz, Dehaene & Hertz-Pannier, 2002; verb generation in children; Szaflarski et al., 2012) and there is evidence of cerebral asymmetry in the human fetus (asymmetry of some cortical structures at 10-44 weeks gestation; Penhune, Zatorre, MacDonald & Evans, 1996; Grimshaw, Bryden & Finegan, 1995; Rademacher, Caviness, Steinmetz & Galaburda, 1993); greater development of the right hand relative to the left at 7 weeks gestation (Falzi, Perrone &
Vignolo, 1982), preferential right thumb sucking at 15 weeks gestation (Amunts et al., 1996). Thus, there is strong evidence of an innate predisposition to left-hemisphere specialization for language from birth, and perhaps even earlier.

However, the degree of lateralization for language increases over development (Everts et al., 2009; Hahn, 1987; Holland et al., 2007, 2001; Spironelli & Angrilli, 2009; Szafarski et al., 2012; Szafarski, Holland, Schmithorst & Byars, 2006) and is influenced by early life experiences (Marcotte & Morere, 1990; Neville et al., 1998). Lenneberg (1967) postulated a gradual development of functional lateralization over the lifespan. Under this view, the human species may begin with an equipotential base for language representation in either or both hemispheres, which is progressively refined to the left hemisphere over development.

Szafarski et al. (2012) examined developmental changes in language lateralization among left- and right-handed children between 5 and 18 years of age using a verb generation task while participants underwent fMRI neuroimaging. The majority of participants in this study demonstrated classic left hemisphere lateralization patterns for language processing, yet age-related changes in lateralization were observed. Szafarski et al. (2012) observed a correlation between age and left hemisphere lateralization, which may reflect an increase in specialization for language in the left hemisphere that arises from language asymmetries already present in early life (Dehaene-Lambertz et al., 2002) and/or anatomical asymmetries present in the developing fetus (Chi et al., 1977; Wada et al., 1975).

Neville et al. (1998) observed that the degree of left hemisphere lateralization for language varies as a function of the age of language exposure. In this study, the neural responses for language processing among deaf individuals who acquired American Sign Language (ASL) at birth and English in childhood with hearing individuals who acquired ASL and English simultaneously at birth were compared. All participants showed left hemisphere activation in classic language areas while processing their native language (ASL or English). However, deaf individuals who learned English later in life did not show this pattern for English language processing. The findings indicate that early life language experience is a crucial component of the lateralization of language to the left hemisphere (Neville et al., 1998).

Moreover, hemispheric asymmetries have been founds to differ among younger and older adults (Cherry & Hellige, 1999; Faust & Balota, 1997). Certain aspects of attention have revealed
differences in hemispheric asymmetry, for example, young adults do not demonstrate visual field asymmetry when attention is cued to either the left or right visual field by presenting a target to the respective visual field. In contrast, older adults demonstrate differences in response times when their attention is cued to the left visual field or right hemisphere as compared to the right visual field or left hemisphere (Faust & Balota, 1997). During a attentional monitoring task, participants were presented with a cue to either the left or right visual field. The cue either appeared in the same visual field as an earlier fixation cross (a prime) or in the opposite visual field. When different visual fields were stimulated (e.g. the prime presented to the left visual field, but the cue presented to the right visual field), response times were longer then when the same visual fields were stimulated. Consistent with functional lateralization of attentional monitoring to the right hemisphere (or left visual field), the effect (differences in response times) was greater in the right hemisphere. However, an age-related difference emerged: older adults only showed this pattern of results if they responded with their left hand. Cherry and Hellige (1999) concluded that hemispheric asymmetries related to attention processing change over the lifespan.

Effects of age and experience on left hemisphere language lateralization remain inconclusive (Hiscock, 1998); findings vary depending on the language task uses, the modality (visual or auditory), brain sites (frontal or temporoparietal regions), and age ranges (Everts et al., 2009; Gaillard et al., 2003; Haag et al., 2010; Holland et al., 2001; Szafarski et al., 2012; 2006; Wood et al., 2004). Moreover, age-related changes in language lateralization may be confounded by concomitant maturational changes related to myelination, synaptic pruning, brain size, and length of white matter tracts (Benes, Turtle, Khan & Farol, 1994; Courchesne et al., 2000; Huttenlocher, 1979; Huttenlocher & Dabholkar, 1997; Lenneberg, 1967; Paus et al., 1999; Pfefferbaum et al., 1994; Reiss, Abrams, Singer, Ross & Denckla, 1996; Ringo, Doty, Demeter & Simard, 1994; Schmithorst, Wilke, Dardzinski & Holland, 2002). The developing brain must organize such that adequate connectivity among neurons for information processing is established, but fits within the allotted spaces within the skull. If all $10^{11}$ neurons were fully interconnected with a 0.1 mm radius axon, a space over 20 km in diameter would be required (Nelson & Bower, 1990). Thus, the organization of the brain strongly favors local connectivity, with fewer long-distance projections with significant communicative roles (Plaut & Behrmann, 2011). These constraints
are particularly relevant for the organization of the two hemispheres, as inter-hemispheric connectivity is largely restricted to homologous regions.

Plaut and Behrmann (2011) propose an experience-driven competition model of cerebral asymmetry among homologous brain regions suggesting that lateralization results from competing pressures among cognitive processes for neural resources. To present this view, Plaut and Behrmann (2011) examine neural processing for faces and words. These classes of stimuli share few common visual features and are differentially acquired. Faces are among the most ecologically relevant visual stimuli, with infants gaining exposure to faces from birth and continuously throughout development. Words, as a class of visual stimuli, have only recently been introduced into our species’ history, dating back a few thousand years. This recency of words in our lineage precludes any natural selection bias the human brain might have undergone to support word processing. Thus, the evolutionary trajectories for words and faces are markedly different. Moreover, words are explicitly taught around 5-6 years of age, at which point the hemispheric organization for language is already established (Bates & Roe, 2001), thus experience with this class of visual stimuli is largely absent during critical brain development periods in early life.

There is evidence for separate neural mechanisms underlying word and face processing systems. Word processing is lateralized to the left hemisphere and largely involves a region of the left fusiform gyrus named the “visual word form area” (VWFA), which has been found to selectively respond to words and letter strings (Cohen et al., 2000; Cohen et al., 2003; Dehaene & Cohen, 2011; Fiez, Balota, Raichle & Petersen, 1999; Mechelli, Gorno-Tempini & Price, 2003; Pinel & Dehaene, 2010). Conversely, face processing is lateralized to the right hemisphere and also involves a region of the right fusiform gyrus named the “fusiform face area” (FFA), which is selectively activation for faces over other non-face visual stimuli (Kanwisher, 2010; Kanwisher, Woods, Iacoboni & Mazziotta, 1997; Puce et al., 1995). Given that words carry linguistic information, it follows that word processing is lateralized to the left hemisphere, where words can interact with other aspects of language function that are left lateralized. That face processing is located in the homologous regions in the right hemisphere follows from a representational competition and cooperation model, whereby specialization for word processing emerges from regional interactions with language areas in left hemisphere (Price & Devlin, 2011).
Such a view of experience-driven, competition-based hemispheric lateralization is supported by the observation that increasing literacy is accompanied by a decreased response to faces in the left hemisphere’s VWFA (Dehaene et al., 2010). With reading acquisition, the VWFA begins to respond to orthographic stimuli (Baker et al., 2007; Cohen & Dehaene, 2004; Maurer et al., 2006; Shaywitz et al., 2002). Reading is too recent of a cultural invention to involve innate biological mechanisms, thus, reading may operate on cortical space dedicated to other functions, which may suffer as reading expertise is established (Dehaene, 2010; Dehaene et al., 2010; Dehaene & Cohen, 2007). Dehaene et al. (2010) compared the brain responses to spoken and written language, visual faces, and non-face, non-orthographic visual stimuli among adults with various levels of literacy. Neural responses to non-orthographic stimuli in the VWFA decreased with reading performance. By comparing literate and illiterate adults, Dehaene et al. (2010) observed a significant reduction of face response, but not non-face/non-orthographic stimuli, in the VWFA among literate adults as compared to illiterate adults. As literacy was acquired, competition for face processing in the VWFA was evoked. Thus, literacy may create cortical competition effects that drive the lateralization of orthographic processing to the left hemisphere (VWFA) and face processing to homologous regions in the right hemisphere (FFA).

Furthermore, competition may account for aspects of lateralization involved in auditory processing. When auditory input is presented to each ear, it is represented by both hemispheres, with an advantage for contralateral over ipsilateral pathways (Fujiki et al., 2002; Hall & Goldstein, 1968; Papanicolaou, DiScenna, Gillespie & Aram, 1990). Thus, if the auditory input presented to each ear is different, using a dichotic listening task, there is preferential processing of input presented to the left hemisphere through contralateral pathways from the right ear (Bryden, 1988; Kimura, 1967). This finding raises questions about why input from the right ear reaches the left auditory cortex before it reaches the right auditory cortex (and vice versa). One account proposed by Kimura (1967) posits that contralateral pathways inhibit ipsilateral pathways. That is, competition for cortical resources drives the inhibitions of ipsilateral pathways such that the contralateral hemisphere processes auditory input. This competition-based account is supported by studies of split-brain patients, that is, patients who have undergone a collostomy whereby the cortical commissures are severed typically to relieve epileptic seizures. When the same consonant-vowel (CV) syllables are presented to each ear, patients were able to correctly report the syllable (Springer & Gazzaniga, 1975). However, when different syllables were
presented to each ear, patients had difficulty reporting syllables presented to the left ear. In normal, brain-intact individuals, the left hemisphere can process the auditory signal presented to the left ear because it passes the right auditory cortex and crosses the collosal pathway. However, among split-brain patients, this collosal pathway is severed, and thus the only pathway that connects the left ear with the left hemisphere is the ipsilateral pathway. This ipsilateral pathway is inhibited when two different syllables are presented and compete to be processed.

More recent neuroimaging research shows that neural responses in the right auditory cortex are inhibited when stimulus is presented in the contralateral ear (Brancucci et al., 2004). Della-Penna et al. (2007) observed the inhibition of one auditory pathway using dichotic presentation of CV syllables and observing the M100 auditory response in the auditory cortex using EEG neuroimaging. Della-Penna et al. (2007) presented stimuli with increasing intensity to one ear, while holding the intensity of stimuli to the other ear constant, revealing that the pathway from the ear receiving the intense stimuli could be inhibited. The M100 response is proportional to the intensity of the auditory stimulus; thus, this paradigm was able to show that ipsilateral pathways underwent greater inhibition, as revealed by an attenuated M100 response, as compared with contralateral pathways. However, this was a lateralized effect, ipsilateral pathways were inhibited to a greater degree in the left auditory cortex as compared with the right auditory cortex. This effect occurs when different, competing stimuli are presented to each ear (Della-Penna et al., 2007). Thus, ipsilateral pathway inhibition, which contributes to contralateral activation reflecting hemispheric lateralization for syllable processing, at least partially arises out of competition for cortical and processing resources.

This model of experience-driven lateralization through cortical competition provides a compelling account, with substantial explanatory adequacy, of hemispheric lateralization. However, this explanation nonetheless warrants further examination. Reading involves left hemisphere areas dedicated to language processing, despite the fact that written language is a late cultural invention. Moreover, reading is not acquired until childhood, at which point the brain has already undergone significant maturational changes. Thus, questions still remain as to the driving forces behind left hemisphere lateralization for language, upon which reading processes depends, and the degree of dedicated genetic and developmental mechanisms governing the neural origins of left hemisphere lateralization for language.
Hemispheric lateralization is, at least partially, under genetic control. It has been proposed that genetic mutations are some point in the human lineage gave rise to hemispheric asymmetries (Annett, 2002; 1995; 1972; Corballis, 1997; McManus, 1999). Indeed, language lateralization is correlated with handedness (Knecht et al., 2000), which is genetically influenced (Annett, 1972; McManus & Bryden, 1992). Right-handed individuals carry a right-shift allele (RS+), which shifts an otherwise normal distribution of intermanual difference to the right hand. McManus (1999) also proposes a genetic model of handedness based on a two-allele system whereby a dextral (D) allele specifies right-handedness. Both accounts also explain the relation between handedness and hemispheric lateralization; over 90% of right-handed individuals demonstrate left hemisphere lateralization for language and about 70% of left-handed individuals also demonstrate left hemisphere lateralization for language. Thus, the underlying genetic influence is proposed to operate on cerebral dominance, which in turn, gives rise to handedness. In fact, many genes are asymmetrically expressed in fetal development (Francks et al., 2007; Leonard, Eckert & Kulda, 2006; Sun, Collura, Ruvolo & Walsh, 2006; Sun, Patoine, Abu-Khalil, Visvader & Al, 2005).

The experience-based “competition model of lateralization” and a biologically-based “genetic model of lateralization” provide a partial explanation of hemispheric lateralization. Thus, there are remaining questions about the origins of left-hemisphere specialization for language in ontogeny. Genetic inheritance models of cerebral asymmetry (Annett, 2002; 1972; Corballis, 1997; McManus, 1999) and experience-based competition models of cerebral asymmetry (Dehaene et al., 2010; Della-Penna et al., 2007; Kimura, 1967; Plaut & Behrmann, 2011) each provide accounts of the ontogenetic origins of left-hemisphere specialization. Yet, the relative contributions of biology and environment in the development of left-lateralization for language remain unclear. One strong possibility is that an innate predisposition (i.e., genetic) for left hemisphere language lateralization exists in our species, but is mediated by environmental factors and undergoes maturational changes as the brain continues to develop into early adulthood (Klingberg, Vaidya, Gabrieli, Moseley & Hedeus, 1999; Yakovlev & Lecours, 1967).

Hemispheric lateralization is not unique to the human species. Evidence of functional asymmetries has been documented in other species (Broadfield, 2005; Gannon, Holloway, Broadfield & Braun, 1998; Hopkins & Morris, 1989; Hopkins, Morris, Savage-Rumbaugh &
Rumbaugh, 1992; Hopkins & Nir, 2010; Hopkins, Washburn & Rumbaugh, 1990; LaMendola & Bever, 1997; Phillips & Sherwood, 2005). Yet, functional specialization among the hemispheres is most pronounced among humans. An evolutionary account of increased hemispheric specialization in the human brain posits that evolutionary adaptations are more likely to be implemented more effectively in one hemisphere as a direct consequence of existing asymmetries. For example, if the left hemisphere was already specialized for temporal/sequential processing, then language capacity may have also specialized in the left hemisphere because the capacity to process temporal information (i.e., the speech signal) is a crucial component of language (Calvin, 1982).

Indeed, there is evidence that temporal processing is lateralized to the left hemisphere, while the right hemisphere houses a greater extent of spectral processing (Efron, 1963; Zatorre & Belin, 2001). Zatorre and Belin (2001) varied spectral and temporal properties of an auditory signal and measured the response of the auditory cortex using positron emission tomography (PET) neuroimaging. To vary temporal information, a standard auditory stimulus was presented where the spacing of each tone remained constant, but the speed of alternation increased. Conversely, to vary spectral information, the same auditory stimuli were presented but instead the speed of alternation remained constant, whereas the spacing of each tone increased. Using this paradigm, Zatorre and Belin (2001) observed greater neural response to temporal features in the left hemisphere and greater neural response to spectral features in the right hemisphere. That the left hemisphere demonstrated specialization for rapid temporal processing, a characteristic of speech processing, whereas the right hemisphere demonstrated complementary specialization for spectral information, a characteristic of tonal processing, provides an brain-based framework to account for hemispheric asymmetries in speech and tone processing (Zatorre & Belin, 2001).

The visuospatial and spectral processing features of the right hemisphere and the temporal processing features of the left hemisphere are further highlighted by an occurrence of ‘apparent motion’. Apparent motion is perceived if a participant is presented with two spatially displaced visual stimuli in rapid succession. That is, one visual element follow the presentation of the other such that the participant will perceive these two elements are being only one element that moves between two locations. This perception of apparent motion is dependent on the time interval between the presentation of the two elements. If the time interval is too short, then no motion is perceived. Using this task, Corballis (1996) observed an advantage for perceiving
apparent motion among split-brain patients in the right hemisphere versus the left. However, when the timing of stimulus presentation occluded the perception of apparent motion, split-brain patients demonstrated an advantage for discriminating the order of stimulus presentation in the left hemisphere versus the right. This results of this study imply that the temporal information, in this case, the perception of sequentiality, is preferentially processed by the left hemisphere, whereas spatial information, in this case, the perception of apparent motion, is preferentially processed by the right hemisphere (Corballis, 1996). Indeed, the left hemisphere demonstrates impoverished processing of visual information relative to the right (Corballis, Fendrich, Shapely & Gazzaniga, 1999), which may suggest that the right hemisphere’s increased capacity for visual processing is not a result of the right hemisphere improving visual processing, but rather, it is the result of the left hemisphere losing a capacity it may have had previously (Corballis et al., 2000).

The specialization of such a complex system such as language in the left hemisphere could have occurred by co-opting existing left-lateralized mechanisms for temporal processing. Over the course of human evolution, this asymmetry would continue to increase (Corballis et al., 2000; Hellige, 1993; Kosslyn, 1987). Corballis, Funnell & Gazzaniga (2000) argue that hemispheric specialization for specific functions confers benefits to overall processing, yet, this occurs at the expense of processing within each hemisphere. Specifically, the evolution of language in the left hemisphere could have occurred at the expense of the left hemisphere’s capacity for aspects of visuospatial processing. In an intact brain, this cost to left hemisphere visuospatial processing is not apparent as the right hemisphere is still capable of performing these functions. However, in a split-brain patient, the left hemisphere’s deficient visuospatial processing as well as the right hemisphere’s correspondingly deficient linguistic processing become apparent (Gazzaniga & Hillyard, 1971).

What advantage does hemispheric lateralization offer? One view postulates that when one hemisphere becomes specialized for a specific function, the homologous region in the other hemisphere is now ‘free’ to perform other functions (Corballis et al., 2000). Thus, lateralization permits the development of new, more complex functions while utilizing the exiting neural architecture. Though this appears to be a clear advantage in terms of more efficient allocation of cortical space, hemispheric specialization is accompanied by a possible cost (Corballis et al., 2000; Vallortigara & Rogers, 2005)
The left hemisphere dominance for language does not imply that the right hemisphere is not involved in language processing. For instance, the right hemisphere is involved in prosodic processing and pitch discrimination (Gandour, 2007; Klein, Zatorre, Milner & Zhao, 2001; Tong et al., 2005; Zatorre, Evans, Meyer & Gjedde, 1992), sentence processing and the integration of semantic information, and appears to be important in tasks that rely on the processing of context (Beeman, Bowden & Gernsback, 2000; Beeman & Bowden, 2000; Berl et al., 2010; Eviatar & Ibrahim, 2007; Luke, Liu, Wai, Wan & Tan 2002; Petitto, Zatorre et al., 2000; Vigneau et al., 2011) and metaphor (Bottini, Corcoran, Sterzi & Paulesu, 1994). On the other hand, the right STG does not appear to be recruited for phonological processing tasks such as rhyming (Roskies, Fiez, Balota, Raichle & Petersen, 2001) and nonsense word reading (Paulesu et al., 2000; Riecker et al., 2000), or lexico-semantic tasks such as verb generation (Thiel et al., 2005), and object naming and word reading (Fedio, August, Patronas, Sato & Kufta, 1997). While left-hemisphere dominance, that is, strong left hemisphere activation with correspondingly little right hemisphere activation, is observed during language processing, right hemisphere activation during language processing co-occurs with left hemisphere activation (Vigneau et al., 2011). This is a strong indication that activation in the right hemisphere results from interactions with the left hemisphere.

### 1.3 Lateralization in the Bilingual Brain

The question of left hemisphere versus bilateral hemispheric involvement for language processing has been controversial at best. Recent research suggests that the classic left hemisphere language dominance observed in monolinguals is different for bilinguals. However, studies of bilingual processing show inconsistent observations of patterns of lateralization that may arise from variations across studies such as participants’ language proficiency and age of bilingual exposure. Early-exposed bilinguals, who acquired both languages early in life, show greater bilateral hemisphere involvement in each of their two first languages relative to monolinguals (Kovelman, Baker & Petitto, 2008a; Kovelman, Shalinsky, Berens & Petitto, 2008; Hull & Vaid, 2007). Later-exposed bilinguals show greater left hemisphere involvement in their first language, but greater bilateral involvement in their second language. Among later-exposed bilinguals, those who were less proficient in their second language showed greater bilateral
recruitment (Dehaene et al., 1997; Hahne & Freiderici, 2001; Hull & Vaid, 2007; Marian, Spivey & Hirsch, 2003; Wartenburger et al., 2003). For example, later-exposed bilinguals showed neural activation in left and right temporal and frontal areas while listening to a story in their second language relative to their first language (Dehaene et al., 1997).

Studies of bilingual language processing differ with respect to whether the experimental tasks and their findings are based on the bilingual’s first or second language. A vast majority of research has compared the processing of early versus late or high versus low proficiency bilinguals in their second language. (Abutalebi, Cappa & Perani, 2005; Hull & Vaid, 2007; Obler, Zatorre, Galloway & Vaid, 1982; Sebastian-Galles, Echeverria & Bosch, 2005). Certain levels of linguistic organization, critically phonology, aspects of morphology, and syntax, require exposure during key maturational age periods in order to achieve full behavioural mastery and native-like neural organization (Lenneberg, 1967). Early bilingual exposure yields high language competence outcomes (Kovelman, Baker & Petitto, 2008b; Johnson & Newport, 1989; McDonald, 2000; Weber-Fox & Neville, 2001; 1996). Whereas, later second language acquisition impacts the attainment levels in the second language (Johnson & Newport, 1989; Lardiere, 1998; Montrul, 2009a;b).

Typological differences among the languages of the bilinguals may also contribute to differences in lateralization. Wang et al. (2011) found stronger gamma-band ERS using magnetoencephalography (MEG) in right hemisphere sites including right Wernicke’s area, the right insula, the right thalamus, right cingulate cortex, and right medial frontal gyrus in Mandarin-English bilinguals, who began acquiring English around age 10, performing a single-word task in Mandarin versus in English. Further, Wang et al. (2011) also observed greater right hemisphere recruitment by Mandarin-English bilinguals relative to English monolinguals when they were performing the same task in English. These findings can be predicted from the differences between logographic Chinese and alphabetical English and the tonal aspects of the Chinese language because tonal aspects of language prosody have been associated with the right hemisphere (Gandour, 2007; Klein, Zatorre, Milner & Zhao, 2001; Tong et al., 2005; Zatorre et al., 1992).

Furthermore, the processing demands of the task may also affect the pattern of lateralization. Meyer et al. (2000) found greater bilateral neural recruitment when the linguistic demands of a
sentence judgment task were increased. Monolingual participants were asked to judge the grammaticality of a sentence, which elicited neural activation in the left temporal areas. However, Meyer et al. (2000) observed additional robust recruitment of the right IFG and the right middle STG when the linguistic demands of the task were increased by having participants additionally correct the ungrammatical sentences.

In a landmark study, Petitto et al. compared the pattern of neural activation in monolingual’s language processing in their one language with early-exposed, highly-proficient bilinguals in each of their two languages, thereby directly comparing for the first time in the literature monolingual and bilingual language processing, while minimizing the potential confounds that arise from differences in language proficiency and age of bilingual exposure (Kovelman, Baker & Petitto, 2008a; Kovelman, Baker, Grafton & Petitto, 2005; Kovelman, Shalinsky, Berens & Petitto, 2008; Shalinsky, Kovelman, Berens & Petitto, 2006). Of note, the Petitto team observed a surprising difference in the pattern of neural activation between monolinguals and bilinguals. Early Spanish-English bilingual adults were found to recruit a greater extent of the left hemisphere inferior frontal gyrus (LIFG) and its right hemisphere homologue during a language task relative to monolingual (Kovelman, Baker & Petitto, 2008a; Kovelman, Baker, Grafton & Petitto, 2005; Kovelman, Shalinsky, Berens & Petitto, 2008; Shalinsky, Kovelman, Berens & Petitto, 2006). Petitto et al. (Kovelman, Baker & Petitto, 2008a; Kovelman, Baker, Grafton & Petitto, 2005; Kovelman, Shalinsky, Berens & Petitto, 2008; Petitto, 2009; Shalinsky, Kovelman, Berens & Petitto, 2006) offered the novel hypothesis that this brain difference between monolinguals and bilinguals was the “neural signature” of the bilingual brain.

This finding has since been corroborated in further studies in our laboratory (Kovelman, Shalinsky, Berens & Petitto, 2008; Jasińska & Petitto, 2013a;b; 2011; 2010; Petitto, Berens, Kovelman, Dubins, Jasińska & Shalinsky, 2012). Our laboratory has observed a greater extent and variability of neural recruitment in bilingual children (Jasińska & Petitto, 2013a;b; 2011; 2010). In order to control for topological differences between languages that may result in differences between monolinguals and bilinguals, we selected bilingual participants that speak topologically distinct languages covering analytical languages (e.g., English), morphologically rich languages (e.g., Russian, Spanish, Urdu), different writing systems (e.g., Cyrillic), and word orders (e.g., SVO; German, VSO; Arabic). Had we only selected one language pairing, for example French-English, we could not ensure that a difference observed between monolinguals
and French-English bilinguals was not a result of some topological feature of the French language. This design feature permits a direct comparison between monolingual versus bilingual brains and differences found are generalizable to all bilinguals versus all monolinguals.

In a first study of word reading, we used functional Near Infrared Spectroscopy (fNIRS) neuroimaging to examine the neural activation patterns of bilingual and monolingual children (ages 6-10) and adults as they read aloud single words. We found that these young bilingual readers showed a greater extent and variability of neural activation in classic language (LIFG, STG) as well as their right hemisphere homologues relative to young monolingual readers (Jasińska & Petitto, 2013a; 2011).

In a second study of syntactic processing, we also compared how typically-developing bilingual and monolingual children (ages 7-10) and adults recruit classic language and cognitive brain areas during a syntactic processing task and asked whether the “neural signature” of bilingualism varies with age of bilingual exposure (Jasińska & Petitto, 2013a;b; 2010). Bilingual participants were comprised of early-exposed individuals who received extensive dual language exposure from birth, and later-exposed individuals who received exposure to their second language between the ages of 4 and 6. fNIRS analyses revealed differences in the pattern of neural activation between monolinguals and bilinguals. Both bilingual children and adults showed greater extent and variability in neural recruitment of classic language brain areas during syntactic processing. However, an important difference was observed between early-exposed and later-exposed bilinguals. Later-exposed bilinguals showed more robust recruitment of frontal brain areas relative to both early-exposed bilinguals and monolinguals.

Finding from these two studies indicate that bilingual language experience can modify the neural circuitry underlying language and cognitive processing. Moreover, the extent of the modification in neural circuitry is, at least partially, dependent on the age of bilingual exposure with early-exposed and later-exposed bilinguals showing differences in neural recruitment. Importantly, although bilingual participants showed greater recruitment of the right hemisphere during language tasks relative to monolingual participants, both monolingual and bilingual participants showed left hemisphere dominance for language. That is, bilinguals demonstrate left hemisphere lateralization for language with greater right hemisphere involvement relative to their monolingual peers.
2 Early Life Experience and Neural Plasticity

While the brain continues to mature well into early adulthood (e.g., myelination continues until age 30; Benes, Turtle, Khan & Farol, 1994; Paus et al., 1999; Pfefferbaum et al., 1994; Reiss, Abrams, Singer, Ross & Denckla, 1996) extensive neural reorganization occurs in the frontal lobes between the ages of 3 and 6 years (Huttenlocher & Dabholkar, 1997). The brain has reached 90% of its adult volume/weight by age 6 years and it is also 4 times its birth size (Courchesne et al., 2000; Lenneberg, 1967). Thus, it is possible that early bilinguals form bilateral cortical organization for language, taking fullest advantage of the brain’s plasticity and capacity for language learning in early life (Petitto, Berens, Kovelman, Dubins, Jasińska & Shalinsky, 2012; Peng & Wang, 2011; Kovelman, Baker & Petitto 2008a;b; Kovelman, Shalinsky, Berens & Petitto; 2008; Petitto, Levy, Gauna, Tetreault & Ferraro; 2001).

Other early life experiences also have the potential to yield neural changes (Bengtsson et al., 2005; Bermudez, Lerch, Evans & Zatorre, 2009; Elbert, Pantev, Wienbruch, Rockstroh & Taub, 1995) that may contribute to changes in cognition (e.g., musical training is related enhanced general IQ; Schellenberg, 2004; 2006; and enhanced visuospatial discrimination; Brochard, Dufour & Despres, 2004). For example, early life musical training yield greater bilateral spatial attention in musicians relative to non-musicians (Patston, Corballis, Hogg & Tippett, 2006; Patston, Kirk, Rolfe, Corballis & Tippett, 2007). Using event-related potentials (ERPs), Patston et al. (2007) found that musicians had similar N1 latencies in both hemispheres when stimuli were presented to either the left or right visual fields. In contrast, non-musicians showed faster N1 latencies in the left relative to the right hemisphere. Musicians also show bilateral activity during musical feature processing (Ono et al., 2011). Using MEG, Ono et al. (2011) found symmetrical mismatch fields (MMFs) and electrical activity supporting bilateral neural activation in musicians relative to non-musicians performing an oddball musical task.

These studies suggest that early experiences contribute to developmental changes that have the potential to yield more equal, and potentially enhanced, neural development and equally efficient connections between the hemispheres. Thus, experience, and importantly, the timing of that experience in development, can result in changes in the patterns of neural activation, specifically reflecting more bilateral neural recruitment.
3 Bilateral Activation

Thus, one hypothesis is that bilateral activation may be associated with experience-dependent cortical organization in early life. Early life experiences such as exposure to two languages from birth can provide enriching stimulation to the developing brain, making possible greater development of bilateral language pathways during a time when the brain’s capacity for language learning is greatest. A second hypothesis is that the functional significance of bilateral activation may be to meet increased processing demands resulting from the challenges bilingualism poses for the developing brain. Here, bilingual language processing may be more difficult and more taxing on the brain. If this hypothesis were true, it would be evidenced by a deviant pattern of development among bilingual children. Our laboratory’s research on bilingual language acquisition raises questions about the strength of this hypothesis (Holowka, Brosseau-Lapré & Petitto, 2002; Petitto & Holowka, 2002; Petitto et al., 2001).

That bilateral recruitment is increased with greater demands on processing has been seen elsewhere in the literature (Duncan & Owen, 2000; Grady, McIntosh & Craik, 2005; Klingberg et al., 1997; Vallesi, McIntosh & Stuss, 2011). Bilateral recruitment was observed by Klingberg et al. (1997) when the demands of a working memory task were increased. During a delayed matching task, in which monolingual participants were asked to match colours and patterns to a reference picture, neural activation in regions of the left frontal lobe was observed. When the demands of the task were increased by having participants alternate matching on colour or on pattern, increased activation was observed in the right superior and middle frontal gyrus and the bilateral DLPFC and inferior parietal cortex (Klingberg et al., 1997).

Findings from aging and memory research also indicate older adults show more robust bilateral activation during working memory tasks relative to younger adults (Grady, McIntosh & Craik, 2005; Reuter-Lorenz et al., 2001; Schulze et al., 2011; Vallesi, McIntosh & Stuss, 2011; Weis et al., 2011). Vallesi et al. (2011) examined the effects of increasing cognitive demands on the normal aging brain using fMRI neuroimaging during an attention task in younger and older adults. Participants completed a go/no-go task that required that participants make a response to “go” stimuli, but not to “no-go” stimuli. Stimuli included coloured letters and numbers and participants were asked to respond (go condition) to a red O and blue X, but not to a blue O or...
red X (high-conflict/no-go condition) nor red and blue numbers (low-conflict/no-go condition). A more complex version of the task asked participants to respond (go condition) to red vowels, but not to blue vowels. Thus, the task complexity (simple: X and O; complex: vowels and consonants), and cognitive conflict (high conflict: red O and blue X versus blue O or red X; low conflict: red O and blue X versus red and blue numbers) were systematically varied in this study. Both younger and older adults showed greater activation in regions associated with cognitive control including bilateral fronto-parietal regions and superior medial prefrontal cortex for high conflict versus low conflict conditions. However, age-related differences emerged. As task difficulty increased (simple X/O versus complex vowels/consonants), older participants over-recruited these brain regions, including homologous sites. Thus, the aging brain might meet greater memory demands by recruiting additional resources in the right hemisphere (Grady, McIntosh & Craik, 2005; Vallesi, McIntosh & Stuss, 2011).

4 Bilingual Advantage

Similarly, the bilingual brain may also meet greater demands by recruiting additional resources in the right hemisphere. A bilingual speaker is not simply the sum of two monolingual speakers; instead, bilinguals have representations of two separate linguistic systems that are linked in theoretically important ways (de Groot, 1993; Francis, 1999; Kroll & Stewart, 1994). There is considerable evidence that bilingual’s two languages are both activated to some degree at all times (Dijkstra & Van Heuven, 1998; Haigh & Jared, 2007; Kerkhofs, Dijkstra, Chwilla & de Bruijn, 2006). Bilinguals must selectively activate the target language and while inhibiting or minimizing interference from the non-target language (Green 1986, 1998). Under this view, bilingualism is an inherently competitive process as bilingual speakers have to maintain phonological, lexical-semantic, and syntactic representations for two languages instead of one, and these representations may compete for selection (Abutalebi & Green, 2007).

Bilingualism ostensibly places additional demands on attentional resources that control interference. Moreover, a bilingual has to maintain dual language systems that may place additional demands on linguistic resources. These additional demands require additional neural resources that would otherwise not be utilized by a monolingual. There is evidence to suggest that competition between lexical items in each of a bilingual’s two languages compete for
selection when bilingual speakers are asked to name a picture in one language versus another (Costa & Caramazza, 1999). In their study, Costa and Caramazza (1999) presented English-Spanish bilingual participants with word and picture pairs and participants were instructed to name the picture in either English or Spanish. If the name of the picture and the accompanying word were the same, regardless of whether the pair was presented in the same language (e.g., mesa-mesa [table]) or different language (e.g., mesa-table), picture naming was facilitated as evidenced by faster naming latencies. However, if the word accompanying the picture was semantically related to the picture (e.g., mesa-chair), then naming latencies were slower, regardless of the language in which the word was presented. A semantically related word (e.g. table) can impede lexical access of the target word (e.g. chair); that this effect is present regardless of the language of presentation implies that a bilingual speaker indeed access both of their languages during lexical access, and this dual accessing can create competition for the selection of the correct target item (Costa & Caramazza, 1999).

By virtue of having to maintain and select between two linguistic systems, the bilingual thus has more experience in selecting among competing representations, in both linguistic and non-linguistic tasks (Bialystok, 2001; Bialystok, Craik, Klein & Viswanathan, 2004; Bialystok, Craik & Ryan, 2006; Bialystok & Martin, 2004; Poulin-Dubois, Blaye, Coutya & Bialystok; 2011). Researchers have reported a cognitive advantage of bilingualism (Bialystok, Craik & Luk, 2012), for instance, faster behavioural performance on conflict tasks requiring cognitive control (Bialystok, 2001; Bialystok et al., 2004; Poulin-Dubois, Blaye, Coutya & Bialystok; 2011) and task-switching paradigm requiring an enhanced ability to shift between different mental sets (Prior & MacWhinney, 2010). For example, Bialystok et al. (2004) demonstrated a bilingual cognitive advantage among older adults while performing a task tapping cognitive control. Participants were instructed to press a left key when a blue square appeared on the screen, and a right key when a red square appeared. In the experiment, half of the trials presented the stimulus on the same side of the screen as the associated response key, and the other half of the trials presented the stimulus on the opposite side. This design measured attentional processes such as response inhibition; participants had to monitor for the stimulus and produce the target response (i.e., blue square required a left key press), but inhibit their response if the stimulus was presented on the side of the screen incongruent with the response (i.e. blue square presented on the right side of the screen). Bilinguals showed better response inhibition relative to
monolinguals. Bialystok et al. (2004) interpret their findings as indicating that more effective attentional processing is exhibited by bilinguals as a direct consequence of bilinguals having “more practice” with inhibition by having to inhibit a non-target language. This advantage in cognitive control over the lifespan serves to offset aging-related declines in aspects of attention and executive function.

By contrast, that bilinguals demonstrate enhanced linguistic and cognitive performance relative to their monolingual peers does not support the view that bilingualism presents a challenge to the developing brain. Bilingual experience affords children an advantage in phonological awareness, that is, the awareness of and ability to manipulate the sound units of one’s language (Kovelman, Baker & Petitto, 2008b; Eviatar & Ibrahim, 2000). Kovelman, Baker and Petitto (2008b) found that bilingual English-Spanish school-aged children outperformed monolingual English children on a complex phonological task requiring participants to articulate each phoneme in a word (e.g., “boat” = /b/ /ow/ /t/), indicating a linguistic advantage of bilingualism. Moreover, bilingual exposure in early life affords infants a linguistic advantage over monolinguals without any cost to their language development (Petitto, Berens, Kovelman, Dubins, Jasińska & Shalinsky, 2012). Bilingual infants demonstrate greater and longer neural sensitivity to universal phonetic distinctions when monolingual infants can no longer make such discriminations. Remarkably, bilinguals’ resilient neural sensitivity to universal phonetic distinctions is not at the expense of their sensitivity to phonetic contrasts in their native language (Jasińska & Petitto, 2011). Both monolinguals and bilinguals showed similar neural activation in the left inferior frontal gyrus (LIFG) for native language phonetic contrasts indicating that dual language exposure in infancy does not delay nor disrupt typical language development. Bilinguals also showed more robust neural activation in the superior temporal gyrus (STG) for non-native language phonetic contrasts relative to monolinguals, demonstrating a linguistic phonological processing advantage. Early bilingual exposure may provide a linguistic “Perceptual Wedge” that extends infants’ sensitivity to universal phonetic contrast and may later aid language and reading development in childhood (Petitto, Berens, Kovelman, Dubins, Jasińska & Shalinsky, 2012; Jasińska & Petitto; 2011).

These studies suggest the possibility that bilinguals’ greater hemispheric symmetry may contribute to their increased performance on linguistic and cognitive tasks alike. In fact, bilateral
activation for language has been associated with verbal ability (Catani et al., 2007). Catani et al.’s (2007) study examined whether the degree of lateralization of language pathways related to possible language benefits for monolingual participants. Catani et al. (2007) used diffusion tensor MRI tractography to investigate correlations between perisylvian white matter language pathways and behaviour performance on a verbal recall task requiring participants to form semantic associations between words. Their findings indicate that bilateral representation of the perisylvian language pathways was correlated with enhanced behaviour performance (Catani et al., 2007).

5 Research Questions and Hypotheses

The research question of this study asks why bilinguals show more robust recruitment of right hemisphere classic language homologues relative to monolinguals. Does bilingualism present a greater demand to the developing brain, which in turn, requires additional neural resources for language processing? Said another way, is bilateral recruitment a compensatory measure to deal with the demands accrued by two, not one, language systems? There are two underlying assumptions here; first, more difficult tasks require more bilateral activation. Second, bilingual processing is more difficult than monolingual processing, such that a bilingual requires additional neural systems in order to “keep par” with a monolingual. This implies that monolingual processing is “normal” and that bilingualism is atypical and disrupts normal development.

Alternatively, bilinguals’ greater bilateral recruitment may be activity-dependent; dual language experience results in more symmetrical activation patterns, irrespective of the processing demands of two languages. Bilingualism does not delay nor disrupt the brain’s typical development and language learning; rather, exposure to two (or more) languages from birth provides an enriching environment for the young infant that fosters the development of neural pathways supporting language. That is, without bilingual exposure, the monolingual does not recruit bilateral IFG and STG for language processing. In summary, two hypotheses were tested as potential explanations for bilinguals’ greater bilateral neural recruitment.
Hypothesis (1) states that bilingualism poses a challenge to the developing brain such that bilinguals require additional neural resources to meet the demands of dual language processing.

Hypothesis (2) states that bilingual exposure provides enriching neural experiences that potentiate enhanced language processing in both hemispheres.

The study examined the time course of neural activation in left and right hemispheres during language processing in monolingual, early-exposed (birth to age 3) and later-exposed (age 4 to 6) bilingual children in two experiments. Direct comparisons of the brains of early-exposed bilinguals, later-exposed bilinguals, and monolinguals were performed while participants complete linguistic tasks during functional Near Infrared Spectroscopy (fNIRS) neuroimaging. fNIRS has significantly enhanced the ability to image human language and higher cognition. The fNIRS technology provides good anatomical localization, excellent temporal resolution, is quiet and “child-friendly”, and thus exceptionally suited for the study of language (see methods below for a more detailed description; see also Quaresima, Bisconti & Ferrari, 2012 for a review).

The two experiments in this study consisted of different language tasks including word processing and sentence processing that measure different aspects of linguistic function and differentially engage the right hemisphere. In the word processing task, a single word reading paradigm was used, whereas in the sentence processing task, a semantic plausibility judgment task was used. Lexical processing robustly engages the left hemisphere language network, including the LIFG and STG. Sentence processing also robustly engages the left hemisphere language network. However, the key distinction between these tasks is that sentence processing additionally recruits homologous language areas in the right hemisphere, which have a critical role in the integration of semantic and syntactic information across a sentence.

The temporal dynamics of neural activation for language processing in monolinguals and bilinguals across the hemispheres can illuminate the neural mechanisms that contribute to the greater bilateral recruitment in bilingual brains and adjudicate between the two hypotheses. If bilingual language processing were linguistically more taxing, requiring more neural resources, this would predict asynchronous temporal activation patterns in the left and right hemisphere. For example, initial robust recruitment of the left hemisphere classic language areas, which if not sufficient to meet the demands of bilingual language processing, were followed by additional right hemisphere recruitment. If bilingual language processing is enriching and allows language
pathways more equal development in both hemispheres, this would predict synchronous temporal activation patterns in the left and right hemispheres. For example, simultaneous left and right hemisphere recruitment will occur.

Furthermore, the temporal dynamics of hemispheric recruitment may differ during word versus sentence processing. All participants are predicted to show greater right hemisphere engagement for sentence processing as compared with word processing. The nature of the aspects of language structure that are measured by the respective tasks yields different predictions for temporal synchrony across the two hemispheres. Greater synchrony is predicted for sentence processing versus word processing because the semantic relations between words have to be integrated into the forming syntactic structure of the sentence.
Chapter 2: Research Design and Methods

6 Participants

10 early-exposed bilingual children (4 females), 10 later-exposed bilingual children (6 females) and 10 English monolingual children (6 females) were included in the study. Bilingual participants were divided into two groups: early- and later-exposed. Early-exposed bilinguals received simultaneous exposure to their two languages from birth whereas later-exposed bilinguals received exposure to their second language between the ages of 4-6 (see Table 1).

6.1 Assessment of Bilingual Language Background and Use

Participants were grouped based on language background reported in a previously validated and published questionnaire called the “Bilingual Language Background and Use Questionnaire” (“BLBUQ;” see Holowka, Brosseau-Lapré & Petitto, 2002; Kovelman, Baker & Petitto, 2008a; 2008b; Penhune, Cismaru, Dorisaint-Pierre, Petitto & Zatorre, 2003; Petitto et al., 2012; 2001; Petitto, Zatorre, Gauna, Nikelski, Dostie & Evans, 2000 for more details on this extensive bilingual language questionnaire). Parents filled in the BLBU Questionnaire. Participants were grouped as monolinguals, early-exposed or later-exposed bilinguals based on the age of first bilingual exposure. All parents of child participants reported high language proficiency and language use in English and in their second language. Proficiency and use was based on reported input languages of parents, the languages used in the home and at school, and the relative amount of exposure in each language throughout their lives on the Bilingual Language Background and Use Questionnaire. This questionnaire asked (a) detailed questions about parents’ language use and attitudes (language background, educational history, employment facts, social contexts across which each parent uses his or her languages, personal language preference containing standardized questions to assess language dominance and language preference, personal attitudes about language/s, language use with the child and participant’s other siblings, parents’ linguistic expectations for their child, parents’ attitudes towards bilingualism, parents’ self-assessment about “balanced” bilingual input, and (b) detailed questions about the nature of language input
and use with the child languages used with the child, questions about child rearing, questions about who cares for the child and number of hours, caretaker’s language/s, child’s exposure patterns to television/radio). All participants received exposure to English in the home from birth.

As a specific design feature of this study, the other language of the bilingual participants came from a varied linguistic pool. We specifically selected bilingual participants that would yield language pairs from typologically distinct languages covering analytical languages (e.g., English), morphologically rich languages (e.g., Russian, Spanish, Urdu), different writing systems (e.g., Cyrillic), and word orders (e.g., SVO (German), VSO (Arabic)). This study design controlled for potential confounds that could arise from comparing only one language pairing (e.g. English and French). Previously, our laboratory has observed differences in neural recruitment for aspects of language processing that were predicted from typological differences between a bilingual’s two languages. Kovelman, Baker and Petitto (2008a) compared patterns of neural activation among monolingual English speakers and Spanish-English bilingual speakers in each of their two languages during a syntactic processing task. Important differences in patterns of neural activation were observed between English and Spanish language processing that corresponded to grammatical distinctions between the two languages. English is an analytical language, that is, there are comparatively fewer morphological markers on words to indicate, for example, whether a noun serves as the subject or object of a sentence. In English, this information (subject versus object) is informed by the word order in the sentences. Spanish, on the other hand, is a more morphologically rich language, whereby whether a noun is a subject or an object is informed by morphological markers. Morphological processing recruits anterior regions of the LIFG (Price, 2010; Fiez, 1997), and Kovelman, Baker and Petitto (2008a) observed greater activation in the anterior LIFG in bilingual participants while processing Spanish as compared with English. In this study, we aimed to control for these types of typological influences on patterns of neural activation in the bilingual brain. By including a diverse linguistic sample, potential group difference, therefore, could not be attributable to the linguistic features of a specific language pairing, but rather to early life bilingual language experience. Here, the research question is fundamentally biological in nature and pertaining to the impact of experiential differences on language representation across the hemispheres as opposed to a research question fundamentally linguistic in nature and pertaining to the impact of
features of different grammars on language representation across the hemispheres. Thus, the
design of this study specific to a biological research question.

6.2  Inclusion and Exclusion Criteria

Only participants who did not have speech/language disorders, reading disabilities,
developmental delays, any other neurological condition, or vision and/or hearing problems that
would interfere with their ability to participate were included in the study. All participants were
right-handed.

6.2.1  Participant Socioeconomic Status

Participants from all socioeconomic, cultural, language backgrounds were included in the study.
Socioeconomic status (SES) was calculated from maternal education and occupation (SéAguin,
Potvin, St-Denis & Loiselle, 1999; Vekiri, 2010). SES was coded on a scale of one through four
based on the following grouping: 4 upper-SES = professionals with “college graduate”, 3 upper-
middle-SES = service sector workers with “college graduate”, 2 middle-SES = service sector
with “high school/GED” and “blue-collar workers” with “college graduate”, and 1 lower-SES =
blue collar workers with “high school/GED”. Mean SES rank for monolingual children was 3.4,
mean SES rank for early-exposed bilingual children was 3.4 and mean SES rank for later-
exposed bilingual children was 3.0 ($F(1,26) = .185, p > .05, n.s.$)

Participants were selected from a database of language and reading neuroimaging research led by
Prof. Laura-Ann Petitto. The participant data in this database has been collected by Jasińska and
Petitto. Participants were selected for this study from the larger database based on the inclusion
criteria and in order to meet monolingual, early-exposed bilingual and later-exposed bilingual
group requirements as outlined above.

7  Tasks

As a specific design feature, participants completed two experiments. In Experiment 1, a single
word reading task was used. In Experiment 2, a sentence judgment task was used. These tasks
tested lexical and syntactic aspects of language structure, and yield different neuroanatomical predictions of left and right hemisphere involvement (Beeman et al., 2000; Beeman & Bowden, 2000; Berl et al., 2010; Caplan, 2001; Caplan et al., 2002; Caplan, Alpert & Waters, 1998; Caplan, Alpert, Waters & Olivieri, 2000; Caplan, Chen & Waters, 2008; Caplan, Stanczak & Waters, 2008; Caplan, Waters & Alpert, 2003; Damasio, Grabowski, Tranel & Hichwa, 1996; Fernandez, 2003; Foundas et al., 2018; Jasińska & Petitto, 2013a,b; 2011; 2010; Kovelman, Baker & Petitto, 2008a; Luke et al., 2002; Petitto, Zatorre et al., 2000; Price, 2000; Stromswold, Caplan, Alpert & Raunch, 1996; Vigneau et al., 2011; Woodcock, 1991; Zatorre & Belin, 2001; Zatorre et al., 1996).

8 Procedure

The hemodynamic response was measured with a Hitachi ETG-4000 Near Infrared Spectroscopy system with 46 channels, acquiring data at 10 Hz (Shalinsky, Kovelman, Berens & Petitto, 2009). The 18 lasers and 15 detectors were segregated into one 3 x 5 array and two 3 x 3 arrays (see Figure 2). Once the participant was comfortably seated, one array was placed on each side of the participant’s head and one array was placed over top. Positioning of the array was accomplished using the 10–20 system (Jasper, 1958) to maximally overlay regions classically involved in language areas in the left hemisphere as well as their homologues in the right hemisphere, and attentional and executive functioning areas in the frontal lobe (Shalinsky, Kovelman, Berens & Petitto, 2009).

While undergoing fNIRS neuroimaging, participants were presented with a word processing task and a sentence processing task.

8.1 Word Processing Task

Participants were presented with 72 word stimuli (e.g., cold, debt, bark) from widely used Woodcock Johnson Language Proficiency Battery-Revised (Woodcock, 1991). 48 items were English words and 24 items were pronounceable but non-existent words (e.g. dask). Participants were asked to read words that appeared on a computer aloud into a microphone placed directly in
front of them. The word frequencies for all stimuli were controlled and words varied from 3-7 letters in length. The selection of 2/3 of the stimuli as real words and the remaining 1/3 as nonsense words ensured that participants did not anticipate the order of stimulus presentation. Moreover, the inclusion of nonsense words is linguistically motivated. The nonsense word stimuli have one-to-one grapheme-to-phoneme correspondence, meaning that these words can be sounded out letter by letter in order to yield the correct pronunciation. These stimuli involve phonological and morphological processing; while no corresponding semantic content is accessed when the child reads the nonsense word. Words and nonsense words predict differential neural recruitment. For example, kotz et al. (2010) found increased activation for words as compared with nonsense words in the left pars orbitalis and pars triangularis. Fiebach, et al. (2002) found increased activation in the posterior temporal lobe and temporoparietal regions for words as compared with nonsense words.

The experiment was organized into three runs. Runs begin with an initial 30 seconds during which a fixation cross appeared in the middle of the screen. Runs consisted of 6 blocks of 4 words each separated by 15-second rest periods of fixation. The duration of stimulus presentation depended on participant’s response time, followed by a 2 second inter-stimulus interval during which a fixation cross appeared on the monitor.

8.2 Sentence Processing Task

Participants were presented with 64 English sentences. Sentences were either plausible or implausible. For example, a plausible sentence would be *The light-house guided the sailor that piloted the boat*, whereas an implausible sentence would be *The sailor guided the light-house that piloted the boat* (Stromswold, Caplan, Alpert & Raunch, 1996). The sentences varied in syntactic construction: the head of the relative clause (*the light-house*) was the object of the main clause and the subject of the verb of the relative clause, or alternatively, the head of the relative clause (*the sailor*) was the subject of the main clause and the object of the verb of the relative clause (Chen, West, Waters & Caplan, 2006). Participants were asked to read the sentence silently and decide whether the sentence was semantically plausible by pressing a button.
The set of sentences has previously been used by Kovelman, Baker and Petitto (2008a), which were provided directly to this research team by David Caplan (Caplan et al., 2008; 2003; 2000; 1998; Stromswold et al., 1996). Several considerations were taken under account when this set of stimuli were designed (Stromswold et al., 1996). The sentences are based on scenarios, with each scenario appearing equally often across each condition. As a result, differences in hemodynamic response could not be attributed to differences in semantics, word frequency, or word choice. Participants could not use the sequence of animacy of subject and object noun phrases (e.g., the light-house, the sailor) in order to make plausibility judgements because the animacy of subject and object noun phrases varied orthogonally. Moreover, all noun phrases were singular, common and definite. Participants had to read the entire sentence before making a judgment because the syntactic location at which the sentence became implausible varied.

Runs begin with 30 seconds of fixation, and 15-second rest periods. Runs were organized into 8 blocks of 8 sentences/block. The duration of stimulus presentation depended on participant’s response time, followed by a 2 second inter-stimulus interval during which a fixation cross appeared on the monitor. Data analysis and results (below) apply only to the plausible sentence types.

8.3 fNIRS Brain Imaging

8.3.1 Theory

fNIRS is an optical neuroimaging method that measures changes in blood oxygenation levels, measuring both average tissue hemoglobin oxygen saturation and total hemoglobin concentration. This technique is based on differential absorption of light at different wavelengths proportional to concentrations of oxygenated hemoglobin and deoxygenated hemoglobin. A series of light-emitting optodes and light-measuring detectors are segregated into arrays. The optodes emit near infrared light at two wavelengths (780 and 830 nm). Oxygenated hemoglobin and deoxygenated hemoglobin have distinct absorption spectra, thus using wavelengths of 780 and 830 nm allows for the possibility to determine concentration changes in both oxygenated and deoxygenated hemoglobin. The detector measure the amount of light absorbed. This combination yields optical density values, or the ratio of the light falling upon a material to the light transmitted through the material. Optical density values relate to oxygenated
and deoxygenated hemoglobin concentration changes according to the modified Beer-Lambert Law (Cope & Delpy, 1988):

\[ \Delta \phi(r,s;\lambda,t) = -\ln \left( \frac{U(r,s;\lambda,t)}{U_0(r,s;\lambda,t)} \right) \]  

(1)

Where \( \Delta \phi(r,s;\lambda,t) \) is the optical density at time \( t \) due to concentration changes in oxygenated and deoxygenated hemoglobin at detector position \( r \) and source position \( s \). \( \lambda \) is the wavelength at the laser source. \( U(r,s;\lambda,t) \) is the initial photon flux, or the number of photos emitted by the laser source that reach the tissue. \( U_0(r,s;\lambda,t) \) is the measured photo flux at time \( t \), or the number of photos that reach the detector. Thus, the ratio of the amount of light emitted at the source to the amount of light reflected back to the detector indicates the amount of light absorbed at the tissue, which is directly related to oxygenated and deoxygenated hemoglobin concentrations (Boas et al., 2001).

### 8.3.2 Advantages over fMRI

fNIRS is similar to fMRI, however fNIRS has important advantages over fMRI (Shalinsky, Kovelman, Berens & Petitto, 2009). Participants in an fNIRS neuroimaging experiment can remain comfortably seated. This is a particularly useful feature for research with pediatric populations as it obviates the need to “train” or expose children to a mock fMRI scanner prior to testing. The fNIRS tolerates movement better than fMRI, which confers a notable advantage for pediatric neuroimaging. The system does not need to be housed in a special facility whereby a shield from electrical potentials (EEG/ERP) or protection for the magnet of the MRI needs to be put in place. This also means that participants can enter the fNIRS testing room without having to take under consideration whether their clothing includes any metal components. Moreover, for those participants who use glasses, or may wear braces, these metal items will not obstruct the neuroimaging study. The fNIRS system is also virtually silent, and thus well-suited for language research as it permits the researcher to present auditory stimuli or record a participants’ vocal response without interference.

fNIRS yields separate measures of deoxygenated and oxygenated hemoglobin, compared to fMRI, which yields a combined blood oxygen level density (BOLD) measure (a ratio between oxygenated and deoxygenated hemoglobin). fNIRS has good spatial resolution and it has better
temporal resolution than fMRI (10 Hz). fNIRS’ depth of recording in the human cortex is less than fMRI, measuring about ~3 to 4 cm deep, but this is well-suited for studying the brain’s higher cortical functions, such as language. Most importantly, fNIRS’ faster sampling rate of neural activity at 10 Hz, as compared to fMRIs sampling rate of approximately once every 2 seconds makes this neuroimaging technology best suited to address the research question of this proposed study. Thus, fNIRS provides both the spatial information and the temporal information that can inform the proposed hypotheses in ways not possible with fMRI.
Chapter 3: Data Analysis

9 Behavioural Analysis: Response Times and Accuracy Rates

Analysis of covariance (ANCOVAs) was performed to assess whether monolinguals, early-exposed bilinguals, and later-exposed bilinguals show different or similar response times and accuracy rates across word processing and sentence processing tasks. The dependent variables were Word Reading Response Time, Sentence Judgment Response Time, Word Reading Accuracy and Sentence Judgment Accuracy. The independent variable was Group (Monolinguals, Early-exposed Bilinguals, and Later-exposed Bilinguals) with Age as a covariate.

10 Neuroimaging Analysis

One important advance of this study was to provide a new system of statistical analysis techniques to answer a previously unanswerable, novel question. The methodological contribution here is the use of advanced statistical techniques, in a novel combination, to fNIRS neuroimaging data, thereby advancing fNIRS data analysis, the central theoretical question about brain laterality under investigation at the heart of the present study, as well as the fNIRS neuroimaging field.

Variability in approaches to fNIRS data analysis still exists (Hoshi, 2011; Huppert, Diamond, Franceschini & Boas; 2009; Schelkanova & Toronov, 2012). Thus, one methodological goal of this study was to advance a system of analysis that will corroborate findings across multiple statistical approaches, render the results in a manner interpretable to the larger neuroimaging field, and enhance the statistical insights afforded by fNIRS. One of the main advantages of fNIRS relative to fMRI is its’ superior temporal resolution. In order to optimize this advantage of fNIRS, statistical methods that make possible inferences about both the neuroanatomical location and time-course of changes in oxygenated hemoglobin, deoxygenated hemoglobin and total hemoglobin are advanced here for the first time.
This novel data analysis system incorporated four distinct statistical techniques, which, in combination with one another, yielded insights into both spatial and temporal information about neural activation: (i) calculation of laterality index, (ii) statistical parametric mapping, (iii) partial least squares analysis, and (iv) functional connectivity as indicated by a coherence index and cross-correlation time lag index of synchrony. This approach revealed insights into the specific research questions of the study and the nature of human laterality and its function while simultaneously advancing fNIRS neuroimaging.

10.1 Laterality Index

The laterality index is a widely used measure of cerebral asymmetry in neuroimaging (Chaudhary, Hall, DeCerce, Rey & Godavarty, 2011; Petitto et al., 2001; Powell et al., 2006; Shibuya-Tayoshi et al., 2007; Shimoda, Takeda, Imai, Kaneko & Kato, 2008; Szalfræski et al., 2012). Laterality indices are calculated by computing the difference between left and right hemisphere activation as a ratio of combined left and right hemisphere activation. In fNIRS neuroimaging, the laterality index can be calculated from the peak changes in oxygenated haemoglobin concentrations at a given channel with respect to time and stimulus (Chaudhary et al., 2011), as in Eq. (2):

$$ L(t) = \frac{(HbO_{left}(t) - HbO_{right}(t))}{(HbO_{left}(t) + HbO_{right}(t))} $$

A near-zero laterality index value indicates no hemispheric asymmetry, or bilateral activation, whereas a laterality index value of 1 indicates left hemisphere dominance and a laterality value of -1 indicates right hemisphere dominance. A laterality index calculation was performed for each left hemisphere fNIRS channel and its corresponding right hemisphere homologue channel. Next, a Group with Age ANCOVA was performed to assess whether monolinguals, early-exposed bilinguals, and later-exposed bilinguals show different or similar laterality indices across word reading and sentence judgment tasks.
10.2 Statistical Parametric Mapping

Data were analyzed using a Matlab-based statistical software package: Statistical Parametric Mapping for NIRS (NIRS-SPM, Version 3.1; Jang et al., 2009; Ye et al., 2009). SPM results indicate whether the spatial patterns of neural activation are similar or different among monolinguals, early- and later-exposed bilinguals. Thus, SPM provided a whole-brain analysis that can indicate if the degree of bilateral activation varies among the experimental groups and tasks.

10.2.1 Theory of Statistical Parametric Mapping

The central tenet of experimental and model design for SPM is that task-related neural activation can be quantified by a subtraction of the hemodynamic response evoked by two different tasks (Friston, 2003; 2007; Horwitz, Tagamets & McIntosh, 1999). SPM involves the construction of continuous statistical processes to test hypotheses about brain activation related to aspects of experimental manipulation encoded in the design matrix. SPMs are images (“maps”) with values that are distributed according to known probability distributions (e.g., t- or F-distributions) as t- or F-maps. In the SPM analysis, each measurement space (i.e., fNIRS channel) is analyzed using a standard univariate tests such as a t-test. This approach tests whether neural activation, as indicated by changes in hemodynamic response at the particular channel, is significantly different from zero. Thus, each t-test represents a test of the null hypothesis that no difference in neural activation occurs.

Hypotheses about regionally specific effects are tested and the resulting p-values are displayed as images in the form of statistical parametric maps (SPMs). The GLM approach focuses on modeling and fitting a time-series signal and residual noise at the individual subject level (Friston, 2007). In an fNIRS neuroimaging experiment with N subjects, for each subject, k, the preprocessed data are represented as a vector of T time points in $Y_k$, the design matrix is $X_k$ and parameter estimates are $\beta_k$ (for $k = 1,\ldots, N$).

$$Y_k = X_k\beta_k + e_k \quad (3)$$

Time-series are modeled as a weighted sum of a predictor variable(s) and residual noise. The goal is to estimate each predictor’s contribution to the observed variation in the time-series. The parameter, $\beta$, is estimated to scale predictor variables while minimizing the sum of squared
residuals. The size of the scaling parameter and whether it is significantly greater than zero is used to determine the contribution of each predictor variable, $X$, to the signal, $Y$. $\beta$ is a matrix of parameters to be estimated the defined the contribution of each component of the design matrix $X$ to the value of $Y$. $\beta$ can be thought of as how much of $X$ is needed to approximate $Y$? $Y$ is the matrix of observed data (changes in HbO and HbR concentration over time and at different spatial locations). $X$ is the design matrix, which encodes aspects of the experimental manipulation such as groups and task condition. Lastly, $e$ is the unknown error or noise in the data (Friston, 2007; Ye et al., 2009; Jasińska & Petitto, 2013c).

The parameter $\beta$ and its variance is estimated as follows (Monti, 2011):

$$\beta = (X^TX)^{-1}X^TY$$

$$\text{var}(\beta) = \sigma^2(X^TX)^{-1}$$

(4)

The parameters are best estimated when the following assumptions from the Gauss-Markov theorem regarding the residual are satisfied:

1. Assumption of Independence: All errors for different time points are uncorrelated and the expected value of the error term is zero.

$$\text{cov}(e_i,e_j) = 0$$

$$E(e_i) = 0$$

(5)

2. Assumption of Homoscedasticity: All errors have the same variance.

$$\text{var}(e_i) = \sigma^2 < \infty$$

(6)

3. Absence of Multicollinearity: No regressor is a linear transformation of one (or more) other regressors.

The assumption that all residuals have the same variance (i.e., across all time-points) can produce incorrect statistics when violated (Luo & Nichols, 2003). fNIRS, like fMRI, data represents a correlated time-series signal, which violates assumptions of the Gauss-Markov theorem. The GLM approach in SPM estimates and removes the correlation before the model parameters are estimated (Bullmore et al., 1996; Della-Maggiore, Chau, Peres-Neto & McIntosh,
2001; Monti, 2011). This correlation is often modeled with an Auto-Regressive model of order 1 [AR(1)], whereby the error at a time-point is predicted from the error at the previous time-point (Harrison, Penny & Friston, 2003; Friston, 2007; Monti, 2011; see Lenoski et al., 2008 for comparison of several strategies). Further, none of the predictor variables that comprise the design matrix, $X$, can be perfectly correlated with another predictor variable. As two predictor variables become more correlated (multicollinearity), their unique contribution to the outcome variable becomes impossible to compute.

Providing these assumptions are satisfied, the individual-level hemodynamic time-series can be modeled as a function of the experimental design matrix, scaling parameter and residual. Group level analysis can be approached by combining parameters of interest at both the group and individual levels, such a model can be written as follows (Friston, 2007; Ye et al., 2009; Jasińska & Petitto, 2013c):

$$Y_G = XX_G \beta_G + e$$  \hspace{1cm} (7)

where $Y_G$ is composed of all individuals’ timeseries, $X$ is the individual-level design matrix, $X_G$ is the group-level design matrix and $e$ is the residual error. This approach can be summarized as a hierarchical two-level model where group level analysis is carried out using the results of subject level analyses, referred to as the “summary statistics” approach (Holmes & Friston, 1998; Worsley et al., 2002), as follows:

$$Y = X\beta + e$$

$$\beta = XX_G\beta_G + e$$  \hspace{1cm} (8)

The SPM approach is predicated on a series of univariate statistics testing whether a subtraction between experimental conditions is significantly greater than zero for each individual participant. These univariate comparisons are performed for each fMRI voxel or for each fNIRS channel, and can lead to incorrect inferences if corrections for multiple comparisons are not applied (Bennett et al., 2010; Poldrack, 2012). These subject level analyses are then used for group level analyses. However, they can be highly susceptible to the influence of outlier participants if such outliers are not modeled correctly (Poldrack, 2012; Woolrich, 2008).
10.2.2 Data Pre-processing and Analysis

Using the modified Beer–Lambert equation (Cope & Delpy, 1988; and adapted and advanced by Boas, Gaudette, Strangman, Cheng, Marota & Mandeville, 2001 and our laboratory; Kovelman, Shalinsky, Berens & Petitto, 2008a; Kovelman, Shalinsky, White, Schmitt, Berens, Paymer & Petitto, 2009; Petitto, Berens, Kovelman, Dubins, Jasińska & Shalinsky, 2012; Shalinsky, Kovelman, Berens & Petitto, 2009), NIRS-SPM converts optical density values into concentration changes in oxygenated and deoxygenated haemoglobin response (HbO and HbR, respectively). Changes in HbO and HbR concentrations were filtered with a Gaussian filter and decomposed using a Wavelet-Minimum Description Length (MDL) detrending algorithm in order to remove global trends resulting from breathing, blood pressure variation, vasomotion, or participant movement artifacts and improve the signal-to-noise ratio (Jang et al., 2009). NIRS-SPM allows the spatial registration of NIRS channels to MNI space without structural MRI (Singh et al., 2005) by using a three dimensional digitizer (Polhemus Corp.) and provides activation maps of HbO, HbR and THb based on the general linear model and Sun’s tube formula correction (Sun, 1993; Sun & Loader, 1994).

10.2.3 Statistical Testing

Significance contrasts were performed between monolinguals and early-exposed bilinguals, and between early-exposed bilinguals and later-exposed bilinguals at left hemisphere, right hemisphere and frontal lobe sites for word processing and sentence processing tasks, respectively. Group differences in HbO activations were thresholded at $p = .05$ and significant results are plotted as HbO activation maps with left hemisphere, right hemisphere and frontal views.

10.3 Partial Least Squares

Partial least squares (PLS) analysis was performed across the three groups, monolinguals, early-exposed bilinguals and later-exposed bilinguals, and across word processing and sentence processing tasks. PLS is a multivariate data analysis technique that allows for the simultaneous analysis of spatial and temporal neuroimaging data (Krishnan, Williams, McIntosh & Abdi, 2010; Lobaugh, West & McIntosh, 2001; McIntosh, Bookstein, Haxby & Grady, 1996; McIntosh
This approach is ideal for highly correlated dependent measures, as is the case for neuroimaging data sets. Individual data points in fNIRS data matrices are both temporally and spatially correlated, that is, data points are partially dependent on the values of adjacent data points in time, as well as, data points belonging to the same channel and adjacent brain regions. In PLS, the optimal least-squares fit to a part of a covariance matrix is calculated. That is, PLS calculates the covariance of two or more matrices (e.g., a neuroimaging data matrix and a design matrix) with the goal of obtaining a new set of variables that best related the two matrices using the fewest dimensions (McIntosh et al., 1996).

PLS analysis uses data matrix composed of rows of data representing changes in oxygen concentrations at 20 time points following stimulus presentation (corresponding to 2 seconds), at each channel, for each subject. Individual data matrices were constructed per group. Each matrix is made of a priori sub-matrices that code for different aspects of the experimental design. Mean-centered task PLS approach was used to analyze group differences (Krishnan et al., 2010). In the mean-centered approach, the average for each group is calculated, and the mean of each column in the resulting matrix is subtracted from each value.

The covariance of each time point for each channel is calculated and the resulting covariance matrix is subjected to singular value decomposition (SVD). The decomposition yields a set of mutually orthogonal latent variables (LVs), each consisting of a Brain Score indicating the location and timing of the task effects across conditions and subjects, and a Design Score indicating the group contrast (Krishnan et al., 2010; Lobaugh et al., 2001). Each LV expresses a symmetrical relationship between the components of the experimental design that relate to the measures of changes in oxygen concentrations, and the optimal spatiotemporal pattern of changes in oxygen concentrations related to the design components. Channel saliencies, which are the numerical weights at each time point and channel location, identify the time points that are most related to the task effects expressed in the LV. Design saliences indicate the extent to which each contrast is related to the pattern of changes in oxygen concentrations. Brain scores are the dot product of a subject’s measured changes in oxygen concentrations and the channel saliences for a given LV, and indicate how strongly individual subjects expressed the patterns on the LV.
Statistical inferences regarding the number of LVs to retain were implemented using permutation tests and bootstrapping. 1000 permutation tests of the LVs were performed to address whether the effect represented by the given LV is statistically different from noise. 1000 bootstrap samples were performed to estimate the standard errors of the saliences. The ratio of the salience to the bootstrap standard error was used to determine what portion of the NIRS signal shows the experimental effect across subjects. Bootstrap ratios correspond to z-scores and were used to assess statistical significance.

10.4 Functional Connectivity

Functional connectivity between different brain regions was calculated using a measure of coherence and cross-correlation applied to HbO concentration changes.

10.4.1 Coherence

Coherence is a measure of the relative amplitude and phase between two time series (Friston, 1994; Sasai, Homae, Watanabe & Taga, 2011). This measure reflects the degree of linear association, or synchrony, represented by two fNIRS measurement channels, and can be used to define the temporal properties of the hemodynamic response across brain regions (Marchini & Ripley, 2000; Muller, Lohmann, Bosch & Cramon, 2001; Rho, McIntosh & Jirsa; 2011; Wiener, 1949). This measure provides an index of functional connectivity and has been used across various functional neuroimaging data, such as fMRI (Sun, Miller & D’Esposito, 2004), electroencephalography (EEG; Weiss & Rappelsberger, 2000), magnetoencephalography (MEG; Srinivasan, Winter, Ding & Nunez, 2007), and recently, fNIRS (Sasai, Homae, Watanabe & Taga, 2011). Two brain regions that have the same underlying neural activity will be highly coherent. If two fNIRS measurement channels have high coherence, this indicates that the relationship between the channels can be well approximated by a linear time-invariant transformation, thereby providing a measure of synchrony between two signals (Marchini & Ripley, 2000; Muller et al., 2001; Wiener, 1949). The coherence measure is a correlation coefficient squared that estimates the consistence of a pair of signals (i.e. the time series at a given fNIRS measurement channel) at a given frequency. This can be interpreted as the proportion of the power in one of the two fNIRS measurement channels, which can be explained
by its linear regression to the second channel (Muller et al., 2001). Coherence is a positive function, between 0 and 1, where 0 indicates that two fNIRS measurement channels have no linear relationship, and 1 indicates that one fNIRS measurement channel can be predicted from the other (Muller et al., 2001).

Squared coherence values between all channel pairs for each participant were calculated by applying Welch’s averaged modified periodogram (using a 1024-point Fourier transform, Hanning window, and 512-point overlap). A Group with Age ANCOVA was performed on average z-scored (using Fischer’s z transformation) coherence values at 0-0.1 Hz frequency bands for 5 connectivity groups: (1) homologous IFG, (2) STG, (3) DLPFC, and (4) long-range frontal-posterior sites for both word and sentence processing tasks (Sasai, Homae, Watanabe & Taga, 2011).

10.4.2 Cross Correlation
Cross-correlation quantifies the relationship between two different time-series signals representing changes in HbO concentration over time and across brain areas (as measured by fNIRS channels). While coherence analyses are operational on frequency-domain data, cross-correlation provides the complementary analysis of time-domain data. Cross-correlation measures the dependence of the values of one time-series on the other time-series, and thereby provides an index of the synchrony between two time-series as a function of a time lag applied to one of the two time-series signals. (Hyde & Jesmanowicz, 2012; Taghizadeh, 2000). Formally, the cross-correlation function can be defined as follows:

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} x(t) y(t + \tau) dt$$

(9)

where $T$ is time, $\tau$ is the time lag, $x(t)$ is the time-series from the first fNIRS channel, $y(t + \tau)$ is the time-series from the second fNIRS channel as a function of the time lag between the two time-series. This measure of functional connectivity and synchrony between two brain areas has been used across different functional neuroimaging data, such as fMRI (Bandettini, Jesmanowicz, Wong & Hyde, 1993; Golestani & Goodyear, 2011; Kanasaku, Kitazawa & Kawano, 1998), electroencephalography (EEG; Abdullah, Maddage, Cosic & Cvetkovic, 2010), event-related optical signal imaging (EROS; Rykhlevskaia, Fabiani & Gratton, 2006), and fNIRS (Sasai et al., 2012). If time-series from two fNIRS measurement channels have a zero-lag
dependence, this indicates that the two signals occur synchronously, and reflect synchronized neural activation across the respective brain areas (Bandettini et al., 1993; Hyde & Jesmanowicz, 2012). If there is a time-lagged dependence between the two channels, this can indicate that x leads y (or y leads x). In this case, neural activation as measured by the first fNIRS channel leads neural activation as measured by the second fNIRS channel. That is, the neural activation across the respective brain areas is asynchronous.

The result of the cross-correlation calculation can be plotted to reveal when maximum (and minimum) cross-correlation values occur over the time-series. Peak values (maximum and minimum) near the zero time point indicate a zero-lag between the two time-series, and represent synchronous neural activation. Whereas, peak values at later, non-zero, time-points represent more asynchronous neural activation.

Cross-correlations values between all channel pairs for each participant were calculated (using normalized time-series whereby autocorrelations at zero lag are identically 1, and range of lags equal to the length of the time series: \(-T\) to \(T\)). A Group with Age ANCOVA was performed on time-lags corresponding to maximum cross-correlations for 4 connectivity groups: (1) homologous IFG, (2) STG, (3) DLPFC, and (4) long-range frontal-posterior sites for both word and sentence processing tasks (Sasai, Homae, Watanabe & Taga, 2011).

10.4.3 Functional Connectivity and Behaviour

Partial correlations were performed in order to assess whether functional connectivity, as indicated by coherence and cross-correlation values, were significantly related to behavior, as indicated by response times and accuracy rates across word and sentence processing tasks.

Experiment 1 (Word Processing): The variables were Word Reading Response Time and Word Reading Accuracy, Functional Connectivity across Brain Areas (STG, IFG, DLPFC, Fronto-posterior; as indicated by coherence and cross-correlation values), while controlling for the effects of Group (Monolinguals, Early-exposed Bilinguals, and Later-exposed Bilinguals) and Age.

Experiment 2 (Sentence Processing): The variables were Sentence Judgment Response Time and Sentence Judgment Accuracy, Functional Connectivity across Brain Areas (STG, IFG, DLPFC, Fronto-posterior; as indicated by coherence and cross-correlation values), while controlling for
the effects of Group (Monolinguals, Early-exposed Bilinguals, and Later-exposed Bilinguals) and Age.
Chapter 4: Results

11 Experiment 1: Word Processing

11.1 Behavioural Results

11.1.1 Response Time
This analysis revealed a significant effect of Age ($F(1,26) = 7.923, p < .01$, partial $\eta^2 = .234$). There was no main effect of Group ($F(2,26) = 1.447, p = .254$, n.s.; see Table 2).

11.1.2 Accuracy
This analysis revealed a significant effect of Age ($F(1,26) = 24.690, p < .001$, partial $\eta^2 = .487$). There was no main effect of Group ($F(2,26) = .991, p = .385$, n.s.; see Table 2).

11.2 Neuroimaging Results

11.2.1 Laterality Index
All participants showed overall left hemisphere lateralization during the word reading task (mean laterality index = 0.20). The analysis revealed a significant effect of Group at fNIRS channels corresponding to the STG (Monolingual LI: .36, Early-exposed bilingual LI: -.04, Later-exposed bilingual LI: -.32; $F(1,26) = 3.59, p < .05$) and the pre-central gyrus (Monolingual LI: .18, Early-exposed bilingual LI: -.21, Later-exposed bilingual LI: -.33; $F(1,26) = 3.46, p < .05$; see Table 3).

11.2.2 Statistical Parametric Mapping
HbO activation maps revealed a significant difference in neural activation patterns among monolingual and early-exposed bilingual participants. Early-exposed bilinguals showed greater
neural activation in left and right hemisphere classic language areas and the prefrontal cortex including the left IFG, left MTG, left DLPFC, right RLPFC, right STG and right IPL while reading words as compared with monolinguals (see Figure 3). Monolinguals did not show any significantly greater neural activation as compared with bilinguals.

HbO activation maps also revealed a significant difference in neural activation patterns among early-exposed and later-exposed bilinguals. Greater neural activation was observed for later-exposed bilinguals as compared with early-exposed bilinguals in left and right hemisphere classic language areas and the prefrontal cortex including the left MTG, right IPL, right STG and left DLPFC, right RLPFC (see Figure 4) and for later-exposed bilingual as compared with monolinguals in left and right hemisphere classic language areas and the prefrontal cortex including the left MTG, right IPL, right STG and left RLPFC (see Figure 5).

11.2.3 Partial Least Squares

One LV was significant by permutation test ($p = .022$) and accounted for 82% of the cross-block covariance matrix. The remaining LVs accounted for the remaining variance and were not significant. Plots of the brain scores by design scores and task saliences for LV1 indicate that later-exposed bilinguals demonstrated greater decreases in oxygenated hemoglobin as compared with monolinguals and early-exposed bilinguals (see Figure 6). Channels maximally overlaying the left STG (BA 22; bootstrap ratio of 1.88 corresponding to a z-score with probability that approaches significance at .06), right Pre-Central and Post-Central Gyrii (BA 6 and BA 43; bootstrap ratio of 2.40 corresponding to a z-score with probability of .02), right STG (BA 22; bootstrap ratio of 1.87 corresponding to a z-score with probability that approaches significance .06), right IPL (BA 40; bootstrap ratio of 2.35 corresponding to a z-score with probability of .02), left prefrontal cortex (BA 10; bootstrap ratio of 2.06 corresponding to a z-score with probability of .04), and bilateral frontal eye fields (BA 8; bootstrap ratio of 1.95 corresponding to a z-score with probability of .05). Over two seconds of stimulus presentation (corresponding to 20 time points), maximal differences among groups were found at the onset of word reading. Bootstrap ratios were found to decrease in the right STG (Bootstrap ratios of initial 10 time points vs. final 10 time points; $F(1,19) = 43.13, p < .001$).
11.2.4 Functional Connectivity

11.2.4.1 Coherence

Overall, plots of coherence values among all 46 channels revealed differences between monolinguals, early-exposed bilinguals and later-exposed bilinguals during word reading (see Figure 7). Statistical analyses revealed a significant effect of Group on coherence values at fNIRS channels corresponding to homologous IFG connectivity (Monolingual: .45, Early-exposed bilingual: .95, Later-exposed bilingual: .57; $F(2,26) = 5.76, p < .01$) and homologous STG connectivity (Monolingual: .41, Early-exposed bilingual: .69, Later-exposed bilingual: .61; $F(2,26) = 4.1, p < .05$). No significant effect of Age was observed on coherence values at fNIRS channels corresponding to homologous IFG connectivity ($F(1,26) = .38, p > .05$, n.s.) or homologous STG connectivity ($F(1,26) = 2.2, p > .05$, n.s.). No significant effect of Group or Age was observed on coherence values at fNIRS channels corresponding to homologous DLPFC connectivity (Group: Monolingual: .62, Early-exposed bilingual: .83, Later-exposed bilingual: .53; $F(2,26) = 1.69, p > .05$, n.s.; Age: $F(1,26) = 1.31, p > .05$, n.s.). This analysis also revealed an effect of Age on coherence values at fNIRS channels corresponding to fronto-posterior connectivity that approached significance, but did not reveal a significant effect of Group at the same location (Group: Monolingual: .58, Early-exposed bilingual: .70, Later-exposed bilingual: .48; $F(2,26) = 2.1, p > .05$, n.s.; Age: $F(1,26) = 3.66, p = .07$; see Figure 8).

11.2.4.1.1 Coherence and Behavioural Indices of Word Processing

Partial correlations revealed a significant relationship between coherence values across brain areas and behavioural measures of word processing. Word reading response time was significantly correlated with functional connectivity in the DLPFC ($r(26) = -.26, p < .01$), across fronto-posterior sites ($r(26) = -.29, p < .01$), and with approaching significance in homologous IFG ($r(26) = -.30, p = .06$). Negative correlation values indicate that faster word reading response times are related with higher coherence values, indicating greater functional connectivity and synchronization of neural activity across brain areas.

11.2.4.2 Cross-Correlation

Statistical analyses revealed a significant effect of Group and Age on cross-correlation time-lag values at fNIRS channels corresponding to homologous STG connectivity (Group: Monolingual:
129.9, Early-exposed bilingual: 104.24, Later-exposed bilingual: 103.57; \( F(2,26) = 3.87, p < .05 \); see Figure 9; Age: \( F(1,26) = 4.46, p < .05 \). No significant effect of Group or Age was observed on cross-correlation time-lag values at fNIRS channels corresponding to homologous IFG connectivity (Group: Monolingual: 131.49, Early-exposed bilingual: 110.40, Later-exposed bilingual: 118.76; \( F(2,26) = .934, p > .05, n.s. \); Age: \( F(1,26) = 1.299, p > .05, n.s. \). DLPFC connectivity (Group: Monolingual: 141.29, Early-exposed bilingual: 113.29, Later-exposed bilingual: 114.49; \( F(2,26) = .837, p > .05, n.s. \); Age: \( F(1,26) = 3.268, p = .082, n.s. \)), nor fronto-posterior connectivity (Group: Monolingual: 136.90, Early-exposed bilingual: 117.55, Later-exposed bilingual: 112.43; \( F(2,26) = .972, p > .05, n.s. \); Age: \( F(1,26) = 1.455, p > .05, n.s. \)).

11.2.4.2.1 Cross-Correlation and Behavioural Indices of Word Processing

Partial correlations revealed a significant relationship between cross-correlation values across brain areas and behavioural measures of word processing. Word reading accuracy was correlated with functional connectivity in the STG with approaching significance (\( r(26) = -0.27, p = .08 \)). Negative correlation values indicate that higher word reading accuracy rates are related with lower cross-correlation values, indicating greater functional connectivity and synchronization of neural activity across brain areas.
12  Experiment 2: Sentence Processing

12.2  Behavioural Results

12.2.4  Response Time

This analysis revealed a significant effect of Age ($F(1,26) = 8.484, p < .01$, partial $\eta^2 = .246$). There was no main effect of Group ($F(2,26) = .499, p = .613, n.s.$; see Table 2).

12.2.5  Accuracy

This analysis revealed a significant effect of Age ($F(1,26) = 4.374, p < .05$, partial $\eta^2 = .144$) and a significant effect of Group ($F(2,26) = 5.089, p < .05$, partial $\eta^2 = .281$; see Table 2).

12.3  Neuroimaging Results

12.3.4  Laterality Index

All participants showed overall left hemisphere lateralization during the sentence judgement task (mean laterality index = 0.30). This analysis revealed a significant effect of Group at fNIRS channels corresponding to the IFG (Monolingual LI: .52, Early-exposed bilingual LI: .39, Later-exposed bilingual LI: -.24; $F(1,26) = 6.57, p < .01$) and the STG (Monolingual LI: .10, Early-exposed bilingual LI: -.03, Later-exposed bilingual LI: -.45; $F(1,26) = 3.38, p < .05$; see Table 3).

12.3.5  Statistical Parametric Mapping

HbO activation maps revealed a significant difference in neural activation patterns between monolinguals and early-exposed bilinguals. Early-exposed bilinguals showed greater neural activation in left and right hemisphere classic language areas and the prefrontal cortex including the left STG, bilateral IPL, and left DLPFC while making plausibility judgments about sentences as compared with monolinguals (see Figure 10). Monolinguals did not show any significantly greater neural activation as compared with bilinguals.
HbO activation maps also revealed a significant difference in neural activation patterns among early-exposed and later-exposed bilinguals. Greater neural activation was observed for later-exposed bilinguals as compared with early-exposed bilinguals in left and right hemisphere classic language areas and the prefrontal cortex including the bilateral STG, bilateral IPL, and bilateral DLPFC and bilateral RLPFC (see Figure 11) and for later-exposed bilingual as compared with monolinguals in left and right hemisphere classic language areas and the prefrontal cortex including the bilateral STG, bilateral DLPFC and bilateral RLPFC (see Figure 12).

12.3.6 Partial Least Squares
One LV approached significance by permutation test ($p = .090$) and accounted for 88% of the cross-block covariance matrix. The remaining LVs accounted for the remaining variance and were not significant. Plots of the brain scores by design scores and task saliences for LV1 indicate that later-exposed bilinguals demonstrated greater increases in oxygenated hemoglobin as compared with monolinguals and early-exposed bilinguals (see Figure 13). Channels maximally overlaying the left IFG (BA 44/46; bootstrap ratio of 2.16 corresponding to a z-score with probability of .03), left STG (BA 22; bootstrap ratio of 1.93 corresponding to a z-score with probability of .05), right Pre-Central and Post-Central Gyrii (BA 6; bootstrap ratio of 1.93 corresponding to a z-score with probability of .05), right DLPFC (BA 9; bootstrap ratio of 1.88 corresponding to a z-score with probability that approaches significance at .06), and bilateral frontal eye fields (BA 8; bootstrap ratio of 2.76 corresponding to a z-score with probability of .006). Over two seconds of stimulus presentation (corresponding to 20 time points), maximal differences among groups were found at the onset of sentence judgment. Bootstrap ratios were found to decrease in the left IFG (Bootstrap ratios of initial 10 time points vs. final 10 time points; $F(1,19) = 25.6$, $p < .001$).

12.3.7 Functional Connectivity
12.3.7.1 Coherence
Overall, plots of coherence values among all 46 channels revealed differences between monolinguals, early-exposed bilinguals and later-exposed bilinguals during sentence judgment (see Figure 14). Statistical analyses revealed a significant effect of Group and Age on coherence values at fNIRS channels corresponding to homologous STG connectivity (Group: Monolingual:
.32, Early-exposed bilingual: .40, Later-exposed bilingual: .59; \( F(2,26) = 4.31, p < .05 \); Age: \( F(1,26) = 4.09, p = .05 \). Statistical analyses revealed an effect of Age that approached significance, but no significant effect of Group was observed on coherence values at fNIRS channels corresponding to homologous IFG connectivity (Group: Monolingual: .43, Early-exposed bilingual: .52, Later-exposed bilingual: .56; \( F(2,26) = .91, p > .05, n.s. \); Age: \( F(1,26) = 3.19, p = .09 \)), homologous DLPFC connectivity (Group: Monolingual: .51, Early-exposed bilingual: .51, Later-exposed bilingual: .52; \( F(2,26) = .01, p > .05, n.s. \); Age: \( F(1,26) = .46, p > .05, n.s. \)), or fronto-posterior connectivity (Group: Monolingual: .49, Early-exposed bilingual: .48, Later-exposed bilingual: .47; \( F(2,26) = .15, p > .05, n.s. \); Age: \( F(1,26) = 1.39, p > .05, n.s. \); see Figure 15).

12.3.7.1.1 Coherence and Behavioural Indices of Sentence Processing

Partial correlations did not reveal any significant relationship between coherence values across brain areas and behavioural measures of sentence processing.

12.3.7.2 Cross-Correlation

Statistical analyses revealed a significant effect of Age on cross-correlation time-lag values at fNIRS channels corresponding to homologous STG connectivity (\( F(1,26) = 7.13, p < .05 \)), homologous IFG connectivity (\( F(1,26) = 5.23, p < .05 \)), and fronto-posterior connectivity with approaching significance (\( F(1,26) = 4.14, p = .052 \)). No significant main effect of Age was observed on cross-correlation time-lag values at fNIRS channels corresponding to DLPFC connectivity (\( F(1,26) = 2.01, p > .05, n.s. \)).

No significant main effect of Group was observed on cross-correlation time-lag values at fNIRS channels corresponding to homologous STG connectivity (Monolingual: 76.68, Early-exposed bilingual: 69.13, Later-exposed bilingual: 67.83; \( F(2,26) = 1.105, p > .05, n.s. \)), homologous IFG connectivity (Monolingual: 79.71, Early-exposed bilingual: 71.72, Later-exposed bilingual: 66.30; \( F(2,26) = 1.40, p > .05, n.s. \)), DLPFC connectivity (Monolingual: 77.74, Early-exposed bilingual: 71.94, Later-exposed bilingual: 71.09; \( F(2,26) = .361, p > .05, n.s. \)), nor fronto-posterior connectivity (Monolingual: 77.05, Early-exposed bilingual: 70.16, Later-exposed bilingual: 65.97; \( F(2,26) = .986, p > .05, n.s. \)).
However, statistical analyses revealed a Group by Age interaction on cross-correlation time-lag values that approached significance at fNIRS channels corresponding to homologous STG connectivity (Monolingual: 78.89, Early-exposed bilingual: 67.67, Later-exposed bilingual: 66.78; $F(3,26) = 2.87, p = .056$) and homologous IFG connectivity (Monolingual: 81.51, Early-exposed bilingual: 70.48, Later-exposed bilingual: 65.40; $F(3,26) = 2.37, p = .093$).

12.3.7.2.1 Cross-Correlation and Behavioural Indices of Sentence Processing

Partial correlations revealed a significant relationship between cross-correlation values across brain areas and behavioural measures of sentence processing. Sentence judgment accuracy rates were significantly correlated with functional connectivity in homologous STG ($r(26) = .34, p < .05$), homologous IFG ($r(26) = .33, p < .05$), DLPFC ($r(26) = .38, p < .05$), and across fronto-posterior sites ($r(26) = .38, p < .05$). Positive correlation values indicate that higher accuracy rates on sentence judgment are related with higher cross-correlation values, indicating lower synchronization of neural activity across brain areas.

13 Functional Connectivity Differences: Word Processing versus Sentence Processing

Functional connectivity analyses, namely coherence and cross-correlation, revealed different results across word processing (Experiment 1) and sentence processing (Experiment 2) tasks. Task-related differences in functional connectivity among monolingual, early-exposed and later-exposed bilingual children were examined using a Group (Monolingual, Early-exposed Bilingual, Later-Exposed Bilingual) x Task (Word Processing, Sentence Processing) x Brain Area (STG, IFG, DLPFC, Fronto-posterior) with Age repeated-measures analysis of covariance (ANCOVA) of coherence and cross-correlation values.

13.2.4.1 Coherence

Statistical analyses revealed a significant Group x Brain Area interaction ($F(6,75) = 2.44, p < .05$). Higher coherence values were found for IFG and STG, but this was dependent on Group.
13.2.4.2 Cross-Correlation

Statistical analyses revealed significant Task x Brain Area ($F(3,75) = 4.18, p < .01$) and Task x Brain Area x Age ($F(3,75) = 4.06, p < .05$) interactions. Lower cross-correlation values were found for sentence processing as compared with word processing; indicating that greater synchronization among the hemispheres is present for sentence processing. Functional synchronization was dependent on brain areas and increased with age.
Chapter 5: Discussion

14 Hemispheric Lateralization: Monolingual versus Early-Exposed and Later-Exposed Bilingual Language Processing

The central question of this study is what conditions drive human brain lateralization. While human language is strongly left hemisphere lateralized this has also been observed to vary with language experience. Bilinguals not only demonstrate left hemisphere lateralization, but greater right hemisphere involvement for language processing as compared to monolinguals. Here, bilingualism is used as a new view into brain’s potential for bilaterality and the neural origins of human brain lateralization. Why does bilingual language processing produce greater bilateral hemispheric recruitment relative to monolingual language processing? Does bilingual experience place increased cognitive ‘dual-task’ demands on the developing brain that require the recruitment of additional neural resources from the right hemisphere? Said another way, is bilateral recruitment a compensatory measure to deal with the demands accrued by two, not one, language systems? Alternatively, does early bilingual language experience potentiate the right hemisphere’s enhanced language processing capacity and make possible more efficient and enhanced processing in both the left and right hemispheres? Importantly, what insights could answering these questions yield into the neural origins of hemispheric laterality?

Indeed, questions about the origins of left-hemisphere specialization for language in ontogeny have persisted in neuroscience, with both genetic inheritance models of cerebral asymmetry (Annett, 2002) and experience-based models of cerebral asymmetry (Plaut & Behrmann, 2011) providing partial accounts of this phenomenon. The Petitto team has found that early-exposed bilinguals show greater extent and variability of neural recruitment within the brain’s left hemisphere (e.g., Left Inferior Frontal Gyrus; LIFG, Superior Temporal Gyrus; STG) and greater neural recruitment of their right hemisphere homologue regions called “the neural signature of bilingualism” (Kovelman, Baker & Petitto, 2008a; Jasińska & Petitto, 2013a;b).
Thus, bilingual language experience in early life can change the functional organization of the brain that supports language and aspects of higher cognitive processing. Moreover, this neural change is, at least partially, dependent on the age of first bilingual language exposure: early, simultaneous exposure to two languages from birth as compared with first bilingual exposure at age five. Here, new insights are provided into the nature of language processing across the developing brain’s two hemispheres and the developing brain’s propensity for expanded neural recruitment of classic language tissue in both hemispheres.

Bilateral activation may be associated with experience-dependent cortical organization in early life. Early life experiences such as exposure to two languages from birth can provide enriching stimulation to the developing brain, making possible greater development of bilateral language pathways during a time when the brain’s capacity for language learning is greatest. Alternatively, the functional significance of bilateral activation may be to meet increased processing demands resulting from the challenges bilingualism poses for the developing brain. Here, bilingual language processing may be more difficult and more taxing on the brain. These competing hypotheses were tested in this study. Hypothesis 1: The human brain is strongly left hemisphere lateralized for language, but, when faced with the demands of two languages, additional right hemisphere neural resources are recruited. Hypothesis 2: The human brain has the potential for enhanced dual hemispheric language processing that can be either potentiated or not based on early life bilingual versus monolingual language experience.

In order to provide new insights into the research questions raised in this study, direct comparisons of the brains of early-exposed bilinguals, later-exposed bilinguals, and monolinguals were performed while participants completed linguistic tasks during functional Near Infrared Spectroscopy (fNIRS) neuroimaging. The recruitment of neural resources in the brain’s two hemisphere supporting word and sentence processing (as measured by word processing and sentence processing tasks) among young monolinguals and bilinguals was compared. The temporal dynamics of hemispheric recruitment in the monolingual and bilingual brain permit new insights into nature of language processing across the hemispheres by providing a test of competing hypotheses at the heart of contemporary scientific investigation into the nature and plasticity of the bilingual brain. If bilingual language processing is linguistically more taxing, requiring more neural resources, this would predict asynchronous temporal activation patterns in the left and right hemisphere. For example, initial robust
recruitment of the left hemisphere classic language areas, which if not sufficient to meet the demands of bilingual language processing, will be followed by additional right hemisphere recruitment. If bilingual language processing is enriching and allows language pathways more equal development in both hemispheres, this would predict synchronous temporal activation patterns in the left and right hemispheres. For example, simultaneous left and right hemisphere recruitment will occur.

Thus, to test these predictions, the following questions needed to be answered: Are brain areas recruited synchronously across the left and right hemispheres across monolingual and bilingual children? Or, does a temporal asynchrony exist in the recruitment of the left and right hemispheres? If so, do differences in the temporal dynamics of neural recruitment of the hemispheres depend on the age of bilingual exposure (early versus later)?

15 Novel Approach

A comprehensive analytical approach was required to illuminate the neural mechanisms that contribute to the greater bilateral recruitment in bilingual brains and adjudicate between the two hypotheses. While neuroscience has pursued answers to questions about the nature of language laterality using, for example, neuroimaging studies of language processing across the hemispheres (Bottini et al., 1994; Catani et al., 2007; Dorsaint-Pierre et al., 2006; Holland et al., 2007; Molfese, 1978; Penhune et al., 1996; Petitto, Zatorre et al., 2000; Powell et al., 2006), the field has largely offered observations of variations in laterality across various paradigms and populations, with little explanatory adequacy. A crucial piece of information, in addition to the functional localization of brain areas in each hemisphere underlying language processing, is the temporal dynamics of how these brain areas across hemispheres are functionally integrated.

Thus, multiple novel statistical analysis approaches were advanced here for the first time to investigate neural activation in left and right hemispheres. Here, four distinct statistical techniques were applied to neuroimaging data of changes in oxygenated haemoglobin over time while participants performed language tasks: (i) calculation of laterality index, (ii) statistical parametric mapping, (iii) partial least squares analysis, and (iv) functional connectivity as indicated by a coherence index and cross-correlation time lag index of synchrony. This unique
A combination of statistical analyses was designed to evaluate differences in hemispheric lateralization, spatiotemporal patterns of neural activation in brain areas associated with language (e.g., left hemisphere IFG, STG, IPL and their right hemisphere homologues) and aspects of higher cognition (e.g., DLPFC), as well as, the temporal dynamics of the recruitment of these brain areas across the brain’s two hemispheres. Thus, this approach represents an advancement in the analysis of neuroimaging data, while shedding new light onto the early life experiences that drive hemispheric lateralization and, in turn, the very nature of laterality in our species.

This statistical approach was applied to the analysis of neural activation patterns among monolingual children and bilingual children with varying ages of first bilingual language exposure while they completed language tasks, which differentially recruit the left and right hemispheres. The specific language tasks, a single word reading task and a sentence judgment task, tested lexical and syntactic aspects of language structure, and revealed differences in left and right hemisphere involvement. While both language tasks robustly engage classic left hemisphere language areas, a distinction exists among word and sentence processing. Sentence processing tasks require the integration of both semantic and syntactic content of the sentence and, thus, involve the processing of context, which is largely processed in the right hemisphere. These aspects of linguistic function found at the sentence-level involve the right hemisphere to a greater degree than aspects of linguistic function at the word-level only (Beeman et al., 2000; Beeman & Bowden, 2000; Berl et al., 2010; Luke et al., 2002; Petitto, Zatorre et al., 2000; Vigneau et al., 2011). Thus, the selection of both a word and sentence processing task represented a specific design feature of this study.

Another novel design feature of this study is that young early-exposed bilingual children (first bilingual exposure between ages birth to age 3 years) were examined in comparison with later-exposed bilingual children (first bilingual exposure between ages 4 to 6 years)—with particular attention given to the nature of language processing in their first/earliest exposed language (in this case, English). While it is understood that language proficiency can impact neural processing (Chee et al., 2004; Hahne & Friederici, 2001; Marian et al., 2003; Nauchi & Sakai, 2009; Perani et al., 2003; Wartenburger et al., 2003), language proficiency was held constant by comparing all bilingual groups’ earliest exposed language (English) with English monolingual controls. Previous research has found differences in behavioural and neural activation for early-exposed bilinguals and later-exposed bilinguals in their second language (Chee et al., 2004; Hahne &
Friederici, 2001; Marian et al., 2003; Nauchi & Sakai, 2009; Perani et al., 2003; Wartenburger et al., 2003). The field has attributed these differences to the later age of acquisition and/or to the lower proficiency levels in the second language. However, the bilinguals in the present study performed the task in their earliest exposed language, which they had all acquired from birth, used regularly, and were highly proficient in. Thus, whether the age of bilingual language exposure would modify the temporal dynamics of hemispheric recruitment supporting language processing in the first language of all participants was directly assessed.

The design of this study, namely, (1) the selection of specific language tasks designed to differentially recruit the left and right hemispheres, (2) the comparison of monolinguals, early-exposed bilinguals and later-exposed bilinguals, that is, populations that differ in the degree of hemispheric language laterality, and most notably, (3) the advancement of a novel combination of neuroimaging statistical approaches permitted new answers to the previously unanswerable research questions raised in this study.

16 Neural Activation in the Bilingual Brain

As predicted, bilinguals showed greater bilateral recruitment than monolinguals. Results revealed greater neural activation in both left and right hemispheres in early-exposed and later-exposed bilinguals as compared with monolinguals, specifically in bilateral IFG and STG. Moreover, early-exposed bilingual children showed a different pattern of neural activation as compared to later-exposed bilingual children. Later-exposed bilingual children showed greater neural recruitment of classic language areas (LIFG, Broca’s Area, STG) and cognitive-general areas (e.g. DLPFC) as compared to early-exposed bilinguals. This observation implies that the age of first bilingual language exposure has the potential to modify the brain’s developmental trajectory supporting language processing. Importantly, although bilingual participants showed greater recruitment of the right hemisphere during language tasks relative to monolingual participants, both monolingual and bilingual participants showed robust left hemisphere recruitment for language. That is, *bilinguals demonstrate left hemisphere language lateralization, but with greater right hemisphere involvement relative to their monolingual peers.*
16.2 Monolingual, Early- and Later-Exposed Bilingual Processing

Behavioural data largely revealed similar response times and accuracy rates across the three groups (monolinguals, early-exposed bilinguals, later-exposed bilinguals) during word reading and sentence judgment tasks. Although bilinguals demonstrated better performance on the word reading task relative to their monolingual peers, this effect was not statistically significant. Regarding the sentence judgment task, bilinguals demonstrated significantly better accuracy rates as compared with monolinguals. Although bilinguals also demonstrated faster response times on the sentence judgment task, this effect was also not statistically significant.

While the behavioural data did not reveal significant group differences in response times and accuracy rates during word reading, and no significant group differences in response times during sentence judgment, the neuroimaging data revealed differences in neural recruitment among monolinguals, early-exposed bilinguals and later-exposed bilinguals—those that carry important theoretical implications regarding contemporary questions about the nature of the bilingual brain. It is clear that this fascinating finding warrants more formal study.

All participants (monolinguals, early-exposed bilinguals and later-exposed bilinguals) showed overall left hemisphere lateralization for language. Positive laterality index values and left hemisphere HbO activation maps indicate robust left hemisphere recruitment during word and syntactic processing. However, important group differences emerged. Bilinguals demonstrated greater bilateral activation as compared with monolinguals, with later-exposed bilinguals demonstrating greater right hemisphere recruitment as compared with early-exposed bilinguals. The results corroborate lateralization differences among monolinguals, and bilinguals with varying ages of first bilingual exposure. The degree of language lateralization varies as a function of language experience, with bilinguals demonstrating a greater extent and variability of right hemisphere involvement for language processing relative to monolinguals.

Results of statistical parametric mapping also revealed differences in right hemisphere recruitment among monolinguals, early-exposed bilinguals and later-exposed bilinguals. Relative to monolinguals, early-exposed and later-exposed bilinguals showed a greater extent and variability of neural activation in left hemisphere language areas and their right hemisphere homologues (IFG, STG, IPL) and areas in the frontal cortex. Moreover, results of partial least squares analyses corroborated the statistical parametric maps and also revealed differences in
neural recruitment among the groups, with later-exposed bilinguals showing the most significantly different patterns of neural activation. Furthermore, bilinguals showed more variability in neural activation throughout the prefrontal cortex including the RLPFC and DLPFC. The RLPFC is involved in reasoning and integrating information (Baker et al., 1996; Elliott, Frith & Dolan, 1997; Gilbert et al., 2006) and the DLPFC is involved in working memory and attention (Fuster, 2008), which is consistent with monitoring and selecting between two language systems and the demands of complex tasks such as word reading and sentence judgment. That bilinguals, both early-exposed and later-exposed, show increased activation in the STG is consistent with the demands of processing two linguistic systems over one, that is, bilinguals may recruit a greater extent and variability of the left STG and additional right hemisphere homologues for word and sentence processing.

16.3 Word and Sentence Processing

The word reading and the sentence judgments task robustly engaged left hemisphere language areas, their right hemisphere homologues and areas in the frontal cortex, important differences in patterns of neural activation were observed. Group differences in neural activation from statistical parametric mapping during the sentence judgment task revealed differential recruitment of brain areas in the frontal cortex (DLPFC, RLPFC; frontopolar area) as compared with the word reading task. While both tasks tested aspects of language processing, the sentence processing task asked participants to make a decision whereas the word reading task only required participants to passively read a word as it appeared on a computer screen. Thus, this added cognitive component of decision-making would ostensibly produce the differences in neural recruitment observed between word reading and sentence judgment.

17 Temporal Dynamics of Bilateral Neural Activation in the Bilingual Brain

Most notably, significant differences in the temporal dynamics of hemispheric recruitment were observed among monolinguals, early-exposed bilinguals and later-exposed bilinguals,
differences that yielded specific answers to the central theoretical question of this study: why do bilinguals show greater bilateral recruitment relative to monolinguals?

Difference between monolingual, early-exposed bilinguals and later-exposed bilinguals in temporal dynamics of hemispheric recruitment were revealed by partial least squares analysis and functional connectivity (coherence) analyses. Results of partial least squares analyses showed that differences in patterns of neural activation between groups varied over the time course of stimulus presentation (words, or sentences). Thus, two distinct findings emerge: monolinguals, early-exposed bilinguals and later-exposed bilinguals show differences in the extent and variability of neural activation in brain areas associated with language and aspects of higher cognition, and more so, monolinguals, early-exposed bilinguals and later-exposed bilinguals show differences in the time course of recruitment of these brain areas.

During word processing, coherences analyses showed difference between monolinguals, early-exposed bilinguals and later-exposed bilinguals in functional connectivity across the hemispheres while reading words. Monolinguals showed lower coherence between homologous IFG and STG sites during word reading. By contrast, early-exposed bilinguals showed greater coherence between homologous IFG and STG sites. Differences in functional connectivity also emerged between early-exposed and later-exposed bilinguals. Later-exposed bilinguals showed lower coherence between homologous IFG sites during word reading.

Cross-correlations analyses also showed difference between monolinguals, early-exposed bilinguals and later-exposed bilinguals in functional connectivity across homologous STG sites while reading words. Monolinguals showed longer time lag values, indicating greater asynchrony in neural recruitment of the left and right STG. By contrast, early-exposed and later-exposed bilinguals showed time lag values between homologous STG sites, with later-exposed bilinguals showing longer time lag values between homologous STG sites during word reading.

Why would later-exposed bilinguals show more right hemisphere recruitment than early-exposed bilinguals, yet reveal less functional connectivity between the hemispheres? As was hypothesized, functional connectivity (i.e. synchrony) differences between the hemispheres may be driven by early life language experiences. Thus, early-exposed bilinguals would reveal greater functional connectivity, whereas later-exposed bilinguals would not. This is exactly what was observed in the present study. Yet, both bilingual groups (early and later exposed) show
greater right hemisphere recruitment. Increased bilateral recruitment in the later-exposed bilingual brain is congruent with the demands of processing two languages, which has previously been found to engage the right hemisphere to a greater extent. Crucially, this observation would have not been possible with only one statistical analysis approach. That is, while laterality index and statistical parametric mapping analyses did reveal increased bilateral recruitment among early and later-exposed bilinguals relative to their monolingual peers, this finding alone does not provide a test of the hypotheses in this study, and in turn does not answer the research question raised here. Indeed, it is the innovative combination of analyses presented in this study that permitted the novel insight that early (as opposed to later) bilingual exposure results in greater synchrony in hemispheric recruitment.

In contrast, during sentence processing, a different pattern emerged. Coherences analyses showed a difference between monolinguals, early-exposed bilinguals and later-exposed bilinguals in functional connectivity across the left and right STG while judging sentences, but only later-exposed bilinguals showed significantly greater functional connectivity in the STG as compared with both monolinguals and early-exposed bilinguals. No significant differences among monolinguals and early-exposed bilinguals were observed. Moreover, cross-correlation analyses corroborated this result: no significant differences among monolinguals, early-exposed and later-exposed bilinguals were observed across.

Indeed, differences in functional connectivity, which indicate the degree of synchronicity among various brain areas, were statistically different among word and sentence processing. All participants generally showed greater functional connectivity for sentence processing as compared with word processing, though this was dependent on the specific brain areas.

Why might word processing and sentence processing produce different observations of left and right hemisphere IFG and STG functional connectivity? Recall that word and sentence processing tasks differentially recruit the right hemisphere, word processing largely involves a network of left hemisphere language areas, while sentence processing is known to engage more sites in the right hemisphere which serve to integrate syntactic and semantic content.

Together, these findings indicate more synchronous hemispheric recruitment among early-exposed bilinguals relative to both later-exposed bilinguals and monolinguals. Most notably, differences in synchronous hemispheric recruitment among the three groups were correlated with
behavioural performance across word and sentence processing tasks. Increased functional connectivity (as indexed by coherence and cross-correlation values) in classic language areas was correlated with faster word reading response times and higher accuracy rates. More, increased functional connectivity (as indexed by cross-correlation values) in the STG, DLPFC and across fronto-posterior sites was correlated with higher sentence judgment accuracy rates. This observation suggests that increased functional connectivity is related to improved language processing. Indeed, greater functional connectivity may very well be the mechanism that underlies the language advantages conferred upon a bilingual child should she have been fortunate enough to be exposed to two languages in early life.

Of interest, differences between monolinguals and bilinguals in functional connectivity across frontal and posterior brain regions were not observed, which would have indicated strong cognitive engagement associated with the working memory and attentional resources required for processing a ‘dual-language task’. That increased homologous language area connectivity in bilinguals as compared to monolinguals was observed indicated strong linguistic engagement.

Additionally, the observed increase in functional connectivity in the DLPFC and between frontal and posterior brain regions with age among all children indicated maturational changes in the higher cognitive systems. Early language experiences contribute to developmental changes that have the potential to yield more equal, and potentially enhanced, neural development and equally efficient connections between the hemispheres. Experience, and importantly, the timing of that experience in development, can result in changes in the patterns of neural activation, specifically reflecting more bilateral neural recruitment. Importantly, the temporal dynamics of neural activation are altered as a result of early life language experience.

Compelling evidence was observed in support of the hypothesis that bilingualism imparts fundamental changes classic language areas in the right hemisphere. However, the age of first bilingual exposure is important. These results reveal new information about the potential extent and variability of language-dedicated neural tissue and its functional integration, and how this may be modified through experience when a child is exposed to one or two languages at different points in development. Dual language exposure appears to have an impact on how the bilingual brain engages the regions and areas that underlie human language, the degree of activation in these areas, and the time course of their recruitment.
Across all ages, an overall pattern emerged; bilinguals showed more robust recruitment of the left IFG, left STG and left IPL and the right hemisphere homologues of these classic left hemisphere language areas, as well as, the DLPFC and RLPFC relative to monolinguals. Early bilingual exposure can yield different lateralization patterns across the brain’s two hemispheres. Monolingual and bilingual brains with varying ages of first bilingual exposure do differ in the extent and variability with which the right hemisphere is recruited, and the time course of its recruitment, suggesting that language experience can modify the neurodevelopmental changes that support aspects of language processing, namely word and sentence processing, in both hemispheres.

18 Insights into Bilingual Language Organization

Comparing monolingual and bilingual brains provides an examination of how dual language exposure can change language organization in the brain. Bilinguals do recruit the same language-dedicated brain regions as monolinguals (Abutalebi et al., 2001), but bilinguals recruit these brain regions to a greater extent and variability as monolinguals (Kovelman, Baker & Petitto, 2008a).

18.2 Support for Neural Signature Hypothesis

The finding that monolingual and bilingual brains differ specifically in the recruitment of brain areas classically associated with aspects of language function lends support to the “Neural Signature” hypothesis of bilingualism (Kovelman, Baker & Petitto, 2008a). Despite the fact that the young brain has yet to undergo substantial maturational changes that will facilitate language processing, early life bilingual experience has modified the extent to which classic language tissue (LIFG, Broca’s, STG, and their right hemisphere homologues) is recruited for aspects of word and sentence processing.

Is greater extent and variability of neural activation, particularly in the right hemisphere, necessarily advantageous for the young bilingual child? Controversy abounds as to whether greater or less neural activation reflects learning and an increase in ability. Indeed, changes to neural organization occur as an individual acquires a new skill such as reading (Brown et al., 2005; Jasinska & Petitto, 2013b; Sandak et al., 2004; Schlaggar et al., 2002). For example,
Sandak et al (2004) found that as reading skill increased, activation in temporoparietal, frontal and right hemisphere posterior areas diminished while activation in the left hemisphere increased. Similarly, Brown et al (2005) observed increased activation in left frontal and left parietal regions, and diminishing activation in bilateral extrastriate cortex with increase in age and reading ability. Our laboratory also observed age-related increase in neural activation of the left inferior frontal gyrus during reading accompanied by decrease in left superior temporal gyrus activation (Jasinska and Petitto, 2013b). In scientific research on language and reading impairment, greater right hemisphere recruitment has also been observed among children with dyslexia as compared with typical readers (Breier et al., 2003; Shaywitz et al., 2002; Simos et al., 2000; 2002; 2011). In light of these findings, could bilinguals’ greater activation in the right hemisphere indicate delayed language and reading development? If this were the case, we would expect to find behavioural evidence of language and reading delay among bilingual participants. To our knowledge, no robust indication of a bilingual delay exists. In contrast, studies from our laboratory and others have repeatedly observed healthy, typical language and reading development patterns among bilinguals, and indeed, language and reading advantages for bilinguals relative to their monolingual peers (Petitto et al., 2001; Kovelman, Baker & Petitto, 2008a;b, Petitto et al., 2012; Jasinska & Petitto, 2013a;b; Berens, Kovelman & Petitto, 2013; Bialystok et al., 2003; Eviatar & Ibrahim, 2000; Laurent & Martinot, 2010). The behavioural results of the present study support a language and reading advantage for bilinguals: we observed faster response times and higher accuracy rates among bilingual participants as compared with monolingual participants. Moreover, though greater right hemisphere activation has been observed among children with dyslexia (Breier et al., 2003; Shaywitz et al., 2002; Simos et al., 2000; 2002; 2011), the right hemisphere activation in this population is less well-defined to specific brain regions known to support aspects of language and reading in left frontal and left temporoparietal regions. Children with dyslexia show more equivalent bilateral neural activation or right-hemisphere lateralization for language and reading (Breier et al., 2003; Shaywitz et al., 2002; Simos et al., 2000; 2002; 2011). Bilinguals show a greater extent and variability of neural activation to left hemisphere “classic” language architecture including the left inferior frontal gyrus and left superior temporal gyrus, and their right hemisphere homologues. In contrast to the neural profile of a dyslexic brain, the bilingual brain remains left-hemisphere lateralized for language and shows a well-defined neural profile of classic language area recruitment. Together, the behavioural advantage language and reading and the underlying patterns of neural activation
in classic language architecture among bilinguals does not provide any support for delay or deviance in language and reading development.

Comparing early-exposed bilingual and later-exposed bilingual brains provides additional insights into how the age of dual language can impact the neural organization for language in the bilingual brain. Should patterns of neural activation for language in the monolingual brain be similar to those of a later-exposed bilingual in their first language? Introducing a second language in childhood indeed changes how the brain processes the first language (Jasińska & Petitto, 2013a).

Much of language acquisition has already occurred by the age of five, at which point the later-exposed bilingual children in this study were first exposed to their other language (bilingual exposure between 4-6 years of age). Beyond a difference in the age of bilingual exposure between early exposed and later exposed bilinguals, other meaningful differences between the two groups exist.

First, if a child is acquiring two languages simultaneously from birth, these two languages are both considered the first language. The implication here is that a fully formed language system is not already in place during acquisition. On the other hand, if a child acquires one language from birth, and another language later in childhood, the acquisition of this other language occurs in a brain that already has a fully formed language system in place for the first language. Thus, one critical distinction between early exposed and later exposed bilinguals is whether language acquisition occurs with an established language system in place or not. In support of this, the neural representations of a later-learned language indeed do differ as a function of the age of first exposure to the other language (Abutalebi et al., 2005). The underlying factor being that later language learners do not typically achieve the same level of proficiency as native speakers, particularly in domains of phonology, morphology and syntax (Johnson & Newport, 1989; Lardiere, 1998; Lenneberg, 1967; Montrul, 2009a;b).

Second, a later-exposed bilingual has less bilingual experience as an early-exposed bilingual. Across children of the same age, the early-exposed bilingual will have had more years of experience processing dual languages as compared with her later-exposed peer. In this study, for example, a 10-year-old bilingual may have had 10 years of bilingual exposure if in the early-exposed group, or only 5 years of bilingual exposure if in the later-exposed group. Early-exposed
bilinguals can have twice the bilingual experience that a later-exposed bilingual has. Could this difference in “time on task” in each language impact language lateralization and the temporal dynamics of hemispheric recruitment during language processing? We think not. First, language acquisition naturally occurs when the child has systematic exposure to quality language input. The quality of language exposure, and its systematicity across situations and contexts that the child finds herself, rather than the quantity of language exposure or the “time-on-task” in each language, is conducive to natural language development (Genesee, 2009; Petitto et al., 2001). Second, numerous studies have revealed that the amount of experience one may have in their other language does not predict native-like proficiency attainment, particularly in phonology, morphology and syntax (Cebrian, 2006; Lardiere, 1998; Moyer, 1999; Montrul, 2002; 2006; Oyama, 1976). When language attainment levels are compared across individuals exposed to their other language early versus later in life, while holding constant the number of years of experience in that language, early exposed bilinguals are found to outperform their later-exposed peers. For example, a 25-year-old adult with first bilingual language exposure at age 5 will demonstrate higher language proficiency levels as compared with a 35-year-old adult with first bilingual language exposure at age 15, regardless of the fact that they share 10 years of bilingual experience. Moreover, when language attainment levels are compared across individuals exposed to their other language at the same age, while varying the number of years of experience in that language, notable differences in language proficiency are not observed. For example, a 30-year-old adult and a 35-year-old adult with first bilingual language exposure at age 25 will comparable language proficiency levels (Cebrian, 2006; Lardiere, 1998; Moyer, 1999; Montrul, 2002; 2006; Oyama, 1976).

What patterns of language lateralization and temporal dynamics of hemispheric recruitment during language processing can we expect among bilingual individuals who did fully acquire their earliest-exposed language (i.e., incomplete acquisition)? The phenomenon of incomplete acquisition in language development occurs among individuals who relocated during early childhood. Under these conditions, the child begins to acquire a language, but ceases to continue to acquire this language upon being exposed to a new community language. Consequently, language proficiency in the earliest exposed language is decreased, even such that the individual has little working knowledge of the language. Nevertheless, could early exposure to two languages, even under circumstances where the acquisition of one of the two languages is
discontinued in early childhood, still drive right hemisphere activation for language? We predict
that this would indeed be the case. Our laboratory previously observed differences in neural
recruitment during phonological processing among bilingual infants relative to their monolingual
peers (Petitto et al., 2012). Bilingual infants showed more robust neural activation in the superior
temporal gyrus (STG) for phonetic contrasts they were not previously exposed to relative to
monolinguals, demonstrating a linguistic phonological processing advantage. Early bilingual
exposure, even as early as the first year of life, extends infants’ neural recruitment and yielding
changes to the patterns of neural activation underlying language processing. Based on this
evidence, we expect that bilingual exposure, even in cases of incomplete acquisition, will have a
persistent impact on neural organization for language. Indeed, there is evidence to indicate that
exposure to another language affords the individual “neural savings” when acquiring a third
language (c.f. Petitto). Knowledge of multiple languages enhances overall attainment in a new
language (Abu-Rabia & Sanitsky, 2010).

19 Role of Experience in Maintaining Dual Language Systems

One possible explanation that can provide a partial account of the observed differences between
monolinguals, early-exposed bilinguals and later-exposed bilinguals in the temporal dynamics of
hemispheric recruitment during language processing remains. The bilingual child exposed to two
languages from birth has considerable experience in maintaining dual language representations.
Much evidence exists in support of the view that a bilingual’s two languages are accessed to
some degree at all times, which has functional consequences to attentional and linguistic
processes, conferring upon the bilingual child both a cognitive and language advantage
(Abutalebi & Green, 2007; Bialystok et al., 2006; Kovelman, Baker & Petitto, 2008b; Petitto et
al., 2012). It may hold true that the bilingual child simply has more practice with accessing the
right hemisphere as a way to compensate for the demands of processing two languages
(Hypothesis 1), and this experience has made the recruitment of the right hemisphere a more
efficient processes. Under this view, the synchronous accessing of the two hemispheres in the
bilingual brain is not related to an enriched early life experience that potentiates dual
hemispheric representations for language (Hypothesis 2), but instead is a result of extra practice
in accessing the right hemisphere in order to meet the increased demands associated with being a
bilingual speaker (Hypothesis 1). Thus, the bilingual speaker becomes so effective at accessing the right hemisphere, that the two hemispheres are indeed recruited synchronously.

Though this view warrants further investigation, we do not believe that this explanation is sufficient. This possible explanation has distinct predictions that we did not find evidence in support of. If synchronous accessing of the brain’s two hemispheres among bilinguals is indeed a direct consequence of bilinguals having more practice recruiting extra resources in the right hemisphere as a way to compensate for the demands of processing two versus one language, then this view would predict that synchronous activation across the hemisphere would increase as the bilingual speaker accrued “more practice”. If this were indeed the case, then we would not expect developing populations (here, children ages 6-10) to show such practice-based efficiency in dual hemispheric recruitment given that the brain at this age still has considerable maturation to undergo, including myelination of white matter tracts that contribute to more efficient processing. However, in order to fully examine this alternative hypothesis, namely, that synchronous accessing of the two hemispheres in the bilingual brain emerges as a result of increased practice recruiting extra right hemisphere resources as a compensatory measure for the demands of dual language processing, instead of as a result of an enriched early life language experience, further research is required. One proposal would be to track changes in laterality (and bilaterality) in monolinguals and bilingual and examine the degree of synchronicity between the two hemispheres from infancy through to adulthood. Should synchrony in the recruitment of the two hemispheres for language processing be invariant over development (while the bilingual is presumably gaining more practice in recruiting neural resources to maintain the increased demands associated with being a bilingual), this would lend further support to the hypothesis we have presented here: bilingualism is an enriched early life language experience that potentiates dual hemispheric representations for language.

Is any type of early life experience sufficient to produce differences in neural activation and connectivity between the two hemispheres? Is the increase in synchrony in the recruitment of the two hemispheres for language processing specifically related to enriched language experience (i.e., bilingualism), or would other types of early life enrichments produce similar neural profiles? Changes in neural organization do occur as an individual becomes an expert versus a novice in a specific domain (e.g., novel objects; Gauthier et al., 1999; birds; Gauthier, Skudlarski, Gore & Anderson, 2000; art; Pang, Nadal, Muller-Paul, Rosenberg & Klein, 2013;
music; Kuchenbuch, Paraskevopoulos, Herholz & Pantev, 2012). For example, musical training impacts hemispheric lateralization for tonal processing (Kuchenbuch et al., 2012; Ono et al., 2011). The human child, however, is born ready to acquire language, unlike other domains of knowledge and expertise; the young infant requires systematic exposure to linguistic patterns during key maturational periods in order for the biological predisposition for language to be potentiated. This is a fundamentally different process from the acquisition of expertise in other domains such as learning to identify various bird species, play chess, or a musical instrument. Gaining familiarity and subsequent expertise in, for example, bird species would presumably not potentiate an inherent capacity to individuate birds with expert precision. Unlike language, such expertise can also be acquired at any stage in the lifespan, with individuals continuing to build expertise (e.g., learning the features of more bird species) without critical or sensitive periods in brain maturation having a strong impact on the overall expert outcomes (Gautheir et al., 2000). Though this is a fascinating potential area of study, one that warrants further investigation, we nevertheless predict that the findings of this study, namely, increased synchrony between the hemispheres and the potentiation of bilateral activation by rich early life language experiences, would not be replicated by other non-linguistic early life experiences.

20 Significance

Through the novel lens of the bilingual brain, we were able to address questions about hemispheric lateralization and its origins in development. The lateralization of certain functions, most notably language, to one hemisphere versus the other has been one of the earliest and most consistent findings in cognitive neuroscience and cognitive psychology.

Left hemisphere language lateralization is present in the majority of the adult population, as well as infant and child populations (Dehaene-Lambertz, Dehaene & Hertz-Pannier, 2002; Hiscock & Kinsbourne, 1987; Holowka & Petitto, 2002; Molfese & Molfese 1985; Molfese, 1978a;b; Szaflarski et al., 2012; Wada et al., 1975). Moreover, there are cerebral asymmetries in cortical structure and handedness in utero (Amunts et al., 1996; Falzi, Perrone & Vignolo, 1982; Grimshaw, Bryden & Finegan, 1995; Penhune, Zatorre, MacDonald & Evans, 1996; Rademacher, Caviness, Steinmetz & Galaburda, 1993). There are also genetic influences on handedness and lateralization (Annett, 1972; 2002; Corballis, 1997; McManus, 1999). Together, this evidence suggests an innate predisposition to left-hemisphere specialization for language
from birth, and perhaps even earlier. Thus, one theoretical position regarding human language lateralization holds that language is lateralized to the left hemisphere from birth, and remains constant throughout the life span.

Yet, there is also evidence of increasing lateralization over development that may be driven by maturation and/or experience. Lenneberg (1967) highlighted the importance of maturation processes over development. Under this view, both hemispheres may begin with the capacity to represent language, but a progressive loss in this equipotentiality occurs over development, coupled with an increasing specialization in the left hemisphere for language. Why would a loss of equipotentiality occur? One plausible explanation for such a phenomenon is based on brain maturation. The degree of brain maturation in the left hemisphere may inhibit the maintenance and continuous development and right hemisphere language homologous. If the left hemisphere circuitry for language is dominant to the right, for instance, more white matter tracts are myelinated in the left hemisphere language areas, then this process may exert inhibition over the right hemisphere (Szaflarski et al., 2012; Vigneau et al., 2011). Indeed, white matter tract integrity does increase with age, and thus may contribute to a decline in right hemisphere language function (Fields, 2005; Szaflarski et al., 2012; Yakovlev & Lecours, 1967).

The experience-based “competition model of lateralization” and a biologically-based “genetic model of lateralization” each provide only a partial explanation of hemispheric lateralization. Thus, there remained questions about the origins of left-hemisphere specialization for language in ontogeny, which the present study informs. The discovery of synchronous bilateral activation in bilinguals suggests that early life bilingual language experience may potentiate more equal development of the brain’s language processing in the two hemispheres. Hemispheric language lateralization may not originate from an innate, biological predisposition for language to “reside” in the left hemisphere; rather, our species may possess an innate capacity to represent language bilaterally. The role of early life language experience may be to potentiate this capacity. That early life bilingual experience may potentiate language representation in both hemispheres provides new insights into the mechanism that makes possible the linguistic advantages widely observed in bilinguals relative to their monolingual peers: greater facility noted in word reading (Kovelman, Baker & Petitto, 2008b), sentence processing (Kovelman, Baker & Petitto, 2008a) and phonology (Holland et al., 2007). Rather than bilingualism presenting a demanding ‘dual-
task’ for a child requiring additional neural resources (Bialystok, 2001), instead, bilingualism may provide enrichment for the developing brain.

21 Limitations

The present study is only one of few studies to investigate the nature of laterality and the conditions that drive hemispheric lateralization for language by comparing the temporal dynamics of monolingual and bilingual language processing across the hemispheres. Thus, as a first-time investigation of its kind into the complex nature of hemispheric lateralization, it has limitations that warrant further investigation. The key limitation of the present study is that only one language was investigated. While it is known typological differences among languages can produce some differences in the degree of language laterality (e.g., tonal languages such as Chinese engage more of the right hemisphere), only English was examined. To compensate for this limitation, this study offered a unique advantage: bilingual participants spoke languages from a varied linguistic pool covering analytical languages (e.g., English), morphologically rich languages (e.g., Russian, Spanish, Urdu), different writing systems (e.g., Cyrillic), and word orders (e.g., SVO (German), VSO (Arabic)). In doing so, we could directly compare monolingual versus bilingual brains, irrespective of typological variations that could drive lateralization differences. Thus, the study design controlled for potential confounds that would have been introduced if only one language pair was studied.

In this study, participants were presented with a word processing and a sentence processing task. In both tasks, the stimuli were presented visually: words and sentences were printed on a computer screen. One limitation of the present research is that auditory language presentation was not used, and the tasks not only engaged language processes, but reading processes as well. While both visual- and auditory-based language processing produces similar neural responses associated with language processing (Chee, O’Craven, Bergida, Rosen & Savoy, 1999), reading processing produces neural responses in brain areas associated with processing written language such as the visual word form area of the fusiform gyrus, the angular gyrus, and the supramarginal gyrus (Pugh, Mencl, Jenner, Katz, Frost, Lee, Shaywitz & Shaywitz, 2001; Pugh, Shaywitz, Shaywitz, Constable, Skudlarski, Fulbright, Bronen, Shankweiler, Katz, Fletcher & Gore, 1996). Conversely, auditory-based language processing produces neural responses in brain areas...
associated with acoustic analysis such as the superior temporal gyrus, the primary auditory cortex, and the planum temporale (Binder, Frost, Hammmeke, Bellgowan, Springer & Possing, 2000; Petitto, Zatorre et al., 2000). Thus, the temporal dynamics of hemispheric recruitment in the monolingual, early-exposed bilingual and later-exposed bilingual brain need further examination across the auditory modality of language processing. This particularly warrants further investigation given that temporal and spectral acoustic analysis of the human auditory speech signal show lateralization to the left and right hemispheres, respectively (Zatorre & Belin, 2001).

However, the core brain areas at the heart of the research question of the present study, namely, the inferior frontal gyrus and superior temporal gyrus are robustly engaged by both auditory and visual language tasks (Chee et al., 1999; Petitto, Zatorre et al., 2001) The neuroanatomical areas under investigation here are not specific to visual or auditory processing, but rather reflect language processing. Thus, the conclusions drawn from the findings of the present study are not specific to the modality of language processing and provide a compelling account of the temporal dynamics of language processing, be it auditory or visual.

22 Future Directions

We hope to study changes in lateralization among monolingual and bilingual children earlier in their development, even before children utter their first word. Critical periods of brain maturation that serve language function occur during the first year. Thus, examining the lateralization of language function during this time, as it is guided by biological/maturational process, yet remains malleable to experience-driven changes such as bilingual language exposure will permit us to gain greater insight into the mechanisms (be they innate, or experiential) of hemispheric lateralization.

Further, as noted above as one of our study’s limitations. It is important to pursue an investigation of auditory language processing, in addition to visually-presented language processing. Acoustic speech processing demonstrates a lateralization of function: temporal feature are more robustly processed in the left hemisphere whereas spectral features are more robustly processed in the right hemisphere (Zatorre & Belin, 2001). Are the hemispheres
recruited for these same functions, and in a synchronous manner, among monolinguals and bilinguals? Beyond our observations of synchronous temporal accessing of the two hemispheres for word and sentence processing in the bilingual brain using a visual task, a future research direction is to ask whether our observations hold true for other aspects of language function (i.e., acoustic analysis of the speech signal)?

We also seek to continue our advancements in quantitative methods for functional neuroimaging, and specifically fNIRS brain imaging. Theoretical advancements must be coupled with innovations in methodology. Together, this will permits us to ask and answer novel questions at the cusp of neuroscience and advance our understanding of the human brain, its functional organization and development.

23 Conclusions

New insights into neural change and neural plasticity in development as a function of early monolingual versus dual language experience are provided, which address the neural recruitment of human language processing tissue. This neural difference may provide the bilinguals with a language advantage. Indeed, experience with two language systems (bilingual), specifically two languages, instead of one (monolingual), has been shown to result in a phonological processing advantage (Petitto et al., 2012) and a reading advantage (Kovelman, Baker & Petitto, 2008a). Thus, the study illuminates how early bilingual exposure supports language development in both hemispheres and offers linguistic advantages to the bilingual child.

Most notably, the bilingual's synchronous accessing of classic language areas in the brain’s two hemispheres may constitute the underlying neural systems that give rise to the language and reading advantages observed among bilingual children relative to their monolingual peers (Kovelman, Baker & Petitto, 2008b). The findings have vital educational benefits regarding the age at which young bilinguals are best to receive early dual language exposure. How much can bilingual exposure modify the neural organization for language, whether multilingualism, relative to bilingualism, yields more variable neural recruitment, and at what point in language development is the brain most susceptible to experience-based changes, all demand further investigation.
Bilinguals provide a powerful new window into the human language processing potential that is not fully recruited (engaged) in monolinguals. The findings from the bilingual brain present a new view on the synergy between early life experience and the full biological extent of the neural tissue underlying language across the hemispheres, the functional integration, and its origins.
Footnote

The author wishes to acknowledge that aspects of this research are submitted for publication as the following co-authored manuscripts:

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10.1037/0894-4105.13.1.111


10.1093/cercor/bhg079


Appendices

Appendix 1. Language Background & Use Questionnaire


1. HISTORY

Age: Date of Birth: Place of Birth:

Mother’s Highest degree completed (circle one): High School/GED College Graduate

Mother’s Occupation:

Father’s Highest degree completed (circle one): High School/GED College Graduate

Father’s Occupation:

When and where did your child start learning English? (i.e., from birth, age 3; at home, at daycare, at school, from a caretaker, from a family member)

When and where did your child start learning French? (i.e., from birth, age 3; at home, at daycare, at school from a caretaker, from a family member)

What other languages does your child know? At what age and where did he/she learn them?

What is child’s father’s native language?

What is child’s mother’s native language?

2. PATTERNS OF LANGUAGE BACKGROUND AND USE
From Birth to age 5:

What percent of the time did your child’s father speak to him/her in

<table>
<thead>
<tr>
<th>Language</th>
<th>Frequency</th>
<th>1-20%</th>
<th>20-50%</th>
<th>50-80%</th>
<th>80-100%</th>
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<tbody>
<tr>
<td>English</td>
<td>Never</td>
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<td>French</td>
<td>Never</td>
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<tr>
<td>Other</td>
<td>Never</td>
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</table>

What percent of the time did your child’s mother speak to him/her in

<table>
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<tr>
<th>Language</th>
<th>Frequency</th>
<th>1-20%</th>
<th>20-50%</th>
<th>50-80%</th>
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<tr>
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<td>French</td>
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<tr>
<td>Other</td>
<td>Never</td>
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What language(s) does your child use with their siblings?

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<tr>
<th>Language</th>
<th>Frequency</th>
<th>1-20%</th>
<th>20-50%</th>
<th>50-80%</th>
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<tbody>
<tr>
<td>English</td>
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<td>Other</td>
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What language(s) does your child use with their friends?

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<tr>
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<td>French</td>
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<td>Other</td>
<td>Never</td>
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From age 5 to now:

What percent of the time did your child’s father speak to him/her in

<table>
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<tr>
<th>Language</th>
<th>Frequency</th>
<th>1-20%</th>
<th>20-50%</th>
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<td>Other</td>
<td>Never</td>
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</tbody>
</table>
What percent of the time did your child’s mother speak to him/her in:

<table>
<thead>
<tr>
<th>Language</th>
<th>Never</th>
<th>1-20%</th>
<th>20-50%</th>
<th>50-80%</th>
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What language(s) does your child use with their siblings?

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<tr>
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<th>20-50%</th>
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<th>20-50%</th>
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<th>80-100%</th>
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<td>French</td>
<td>Never</td>
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<tr>
<td>Other</td>
<td>Never</td>
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</table>

3. EDUCATION AND LITERACY

When did your child learn to read in English?

- Age 5 or earlier
- Age 6-7
- Age 8-12

Where did your child learn to read in English?

- School
- Home
- Self-taught
- Other

When did your child learn to read in French?

- Age 5 or earlier
- Age 6-7
- Age 8-12
Where did your child learn to read in French?

School    Home    Self-taught    Other ________________

Between the ages of birth and 7 years, did you read books to your child in

English    French    Both

During preschool or daycare:

What language(s) was your child educated in?    English    French    Both

Did your child read books at school in    English    French    Both

Did your child read on their own for pleasure in English    French    Both

During elementary school:

What language(s) was your child educated in?    English    French    Both

Did your child read books at school in    English    French    Both

Did your child read on their own for pleasure in English    French    Both

4. LANGUAGE PREFERENCE

If a book was available in both languages, which one would your child be most likely to select?

English    French    Equally comfortable in both

If it were vital for your child to understand all of a particular text and it was available in both languages, which one would he/she select?

English    French    Equally comfortable in both

Which language does your child feel most comfortable speaking?

English    French    Equally comfortable in both
Which language does your child feel most comfortable writing?

English  French  Equally comfortable in both

5. LANGUAGE PROFICIENCY AND DOMINANCE

How do others in your social community perceive your child? (circle any that apply)

English speaker  French speaker  Bilingual person

Does your child view him/herself as

More English proficient  More French proficient  Equally proficient in both

6. LANGUAGE MAINTAINANCE/CULTURE

Which of the following does your child do at least once in a typical week? (check any that apply)

In English  In French  Neither

Listen to music  ___  ___  ___  ___
Watch TV  ___  ___  ___  ___
Read magazines  ___  ___  ___  ___
Watch movies or films  ___  ___  ___  ___
Surf the internet  ___  ___  ___  ___
Converse with friends  ___  ___  ___  ___

With which culture does your child identify more?

English-speaking  French-speaking  Identify equally with both

As a member of a cultural group, does your child view him/herself as
<table>
<thead>
<tr>
<th>Bicultural/Multicultural</th>
<th>Somewhat bicultural</th>
<th>Mono-cultural</th>
</tr>
</thead>
</table>

Additional comments
Appendix 2. Word Reading Task


1. away
2. key
3. paid
4. hog
5. ewe
6. gone
7. debt
8. your
9. rox
10. grawl
11. dask
12. tupa
13. market
14. horn
15. sofa
16. ring
17. busy
18. owe
19. acid
20. ballet
21. zoop
22. quantric
23. yosh
24. nan
25. bark
26. feet
27. robot
28. compete
29. says
30. loser
31. cent
32. calf
33. tadlen
34. tayed
35. wint
36. gusp
37. tape
38. stop
39. depend
40. cold
41. cafe
42. echo
43. island
44. suit
45. mibgus
46. hatu
47. plew
48. coge
49. lazy
50. start
51. sank
52. down
53. son
54. caution
55. two
56. range
57. zudo
58. jox
59. fod
60. nopy
61. neon
62. few
63. zero
64. cat
65. rice
66. iron
67. knee
68. sign
69. feap
70. lish
71. telp
72. vomo
Appendix 3. Sentence Judgment Task


1. The legend that the knight described rescued the king
2. The butcher that the knife cut summoned the doctor
3. The man installed the fan that bothered the heat
4. The bow adorned the dress that altered the tailor
5. The fire repelled the wolf that threatened the child
6. The lighthouse guided the sailor that piloted the boat
7. The school that the teacher employed taught the class
8. The patient that the drug cured thanked the doctor
9. The juice stained the rug that spilled the child
10. The millionaire donated the money that aided the orphan
11. The school employed the teacher that taught the class
12. The knight described the king that rescued the legend
13. The man that the salt sprinkled melted the ice
14. The magician that the trick performed entertained the girl
15. The woman that the crime alarmed hired the bodyguard
16. The fence that the carpenter built surrounded the yard
17. The sailor that the lighthouse guided piloted the boat
18. The man hammered the nail that pierced the pipe
19. The person recovered the jewelry that rewarded the store
20. The heater that the woman warmed hemmed the skirt
21. The fire that the wolf repelled threatened the child
22. The rosebush that the bee attracted stung the gardener
23. The chef added the spice that flavored the soup
24. The baby sucked the pacifier that comforted the lullaby
25. The boy tipped the barber that pleased the haircut
26. The coin that the man sold interested the collector
27. The teenager wore the miniskirt that horrified the mother
28. The child ate the popcorn that excited the toy
29. The armor that the knight protected killed the opponent
30. The toothache annoyed the woman that saw the dentist
31. The janitor that the snow shoveled coated the sidewalk
32. The person that the store rewarded recovered the jewelry
33. The haircut that the boy pleased tipped the barber
34. The food prepared the heiress that displeased the cook
35. The wood that the man chopped heated the cabin
36. The heat that the man bothered installed the fan
37. The woman that the toothache annoyed saw the dentist
38. The mother read the book that fascinated the child
39. The wood heated the cabin that chopped the man
40. The girl applied the bandaid that pricked the thorn
41. The doctor discovered the drug that prevented the disease
42. The mother that the book read fascinated the child
43. The fence surrounded the yard that built the carpenter
44. The food that the cook prepared displeased the heiress
45. The well that the man dug supplied the water
46. The tailor that the bow altered adorned the dress
47. The woman hemmed the skirt that warmed the heater
48. The father hummed the song that soothed the child
49. The nail that the man hammered pierced the pipe
50. The spice that the chef added flavored the soup
51. The millionaire that the money donated aided the orphan
52. The novel satisfied the editor that submitted the writer
53. The child that the juice spilled stained the rug
54. The trick entertained the girl that performed the magician
55. The cowboy cracked the whip that terrified the horse
56. The book bored the child that pestered the mother
57. The pilot flew the plane that transported the king
58. The plane that the pilot flew transported the king
59. The man sprinkled the salt that melted the ice
60. The coin interested the collector that sold the man
61. The child that the toy excited ate the popcorn
62. The song that the father hummed soothed the child
63. The envelope contained the check that sealed the woman
64. The cowboy that the whip cracked terrified the horse
Table 1

*Participant Demographics.*

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean Age (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolinguals</td>
<td>8.1 (0.5)</td>
</tr>
<tr>
<td>Early-Exposed Bilinguals</td>
<td>9.2 (1)</td>
</tr>
<tr>
<td>Later-Exposed Bilinguals</td>
<td>8.6 (1.2)</td>
</tr>
</tbody>
</table>
Table 2

Response times and accuracy rates for word reading and sentence judgment tasks across monolinguals, early-exposed bilinguals and later-exposed bilinguals.

<table>
<thead>
<tr>
<th>Group</th>
<th>Word Reading</th>
<th>Sentence Judgment</th>
<th>Word Reading</th>
<th>Sentence Judgment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Response Time (msec)</td>
<td></td>
<td>Accuracy (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean (SD)</td>
<td></td>
<td>Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Monolinguals</td>
<td>1182 (68)</td>
<td>6740 (527)</td>
<td>78.5 (3.2)</td>
<td>52.6 (3.6)</td>
</tr>
<tr>
<td>Early-Exposed Bilinguals</td>
<td>1020 (68)</td>
<td>6055 (524)</td>
<td>84.0 (3.2)</td>
<td>66.9 (3.6)</td>
</tr>
<tr>
<td>Later-Exposed Bilinguals</td>
<td>1124 (68)</td>
<td>6136 (522)</td>
<td>84.0 (3.2)</td>
<td>66.8 (3.6)</td>
</tr>
</tbody>
</table>
Table 3

Significant laterality indices at the Superior Temporal Gyrus and Inferior Frontal Gyrus during Word Reading and Sentence Judgment tasks across monolinguals, early-exposed bilinguals and later-exposed bilinguals.

<table>
<thead>
<tr>
<th>Group</th>
<th>Superior Temporal Gyrus</th>
<th>Inferior Frontal Gyrus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Word Reading</td>
<td>Sentence Judgment</td>
</tr>
<tr>
<td>Monolinguals</td>
<td>.36 (.18)</td>
<td>.52 (.16)</td>
</tr>
<tr>
<td>Early-Exposed Bilinguals</td>
<td>-.04 (.18)</td>
<td>.39 (.16)</td>
</tr>
<tr>
<td>Later-Exposed Bilinguals</td>
<td>-.32 (.18)</td>
<td>-.24 (.16)</td>
</tr>
</tbody>
</table>
Figure 1. The language network. Brain sites and pathways underlying human language processing.
Figure 2. fNIRS placement (a) Key locations in Jasper (1958) 10–20 system. The detector in the lowest row of optodes was placed over T3/T4; (b) Probe arrays were placed over left-hemisphere language areas and their right-hemisphere homologues as well as the frontal cortex. (c) Location of 46 channels.
Figure 3. Word Processing: Neural activation of early-exposed bilingual children relative to monolingual children during word processing (t-statistic map from HbO, $p = .05$, corrected). Early-exposed bilingual children show robust (a) left MTG, left IFG, (b) right STG, right IPL, and (c) DLPFC and RLPFC activation while reading words relative to monolingual children.
Figure 4. Word Processing: Neural activation of early-exposed bilingual children relative to later-exposed bilingual children during word processing (t-statistic map from HbO, p = .05, corrected). Early-exposed bilingual children show robust (a) left MTG, (b) right STG, right IPL, and (c) DLPFC and RLPFC activation while reading words relative to later-exposed bilingual children.
Figure 5. Word Processing: Neural activation of later-exposed bilingual children relative to monolingual children during word reading (t-statistic map from HbO, $p = .05$, corrected). Later-exposed bilingual children show robust (a) left MTG, (b) right STG, right IPL, and (c) frontopolar activation while reading words relative to monolingual children.
Figure 6. Word Processing: (a) Task saliencies for LV1 and (b) plot of brain scores by design scores for monolingual, early-exposed bilingual and later-exposed bilingual children while reading words.
Figure 7. Word Processing: Brain Coherence Scores by Group. Coherence values between all 46 fNIRS measurement channels for monolingual children, early-exposed bilingual children and later-exposed bilingual children while reading words.
Figure 8. Word Processing: Functional Connectivity (Coherence) by Brain Region and Group. Bilateral IFG, bilateral STG, DLPFC, and fronto-posterior functional connectivity for monolingual children, early-exposed bilingual children and later-exposed bilingual children while reading words.
Figure 9. Word Processing: Cross-Correlation by Group at Superior Temporal Gyrus.

Average cross-correlation values between homologous STG sites for monolingual children, early-exposed bilingual children and later-exposed bilingual children while reading words. Peak cross-correlation values are observed earlier for early-exposed bilingual as compared with later-exposed bilinguals. Peak cross-correlation values are observed latest for monolinguals as compared with early- and later-exposed bilinguals.
Figure 10. Sentence Processing: Neural activation of early-exposed bilingual children as compared to monolingual children (t-statistic map from HbO, \( p = .05 \), corrected). Early-exposed bilingual children show more robust neural activation in (a) the left and (b) the right hemispheres (bilateral Inferior Parietal Lobule, STG), and (c) frontal lobes (DLPFC) while reading sentences relative to monolingual children.
Figure 11. Sentence Processing: Neural activation of later-exposed bilingual children as compared to early-exposed bilingual children (t-statistic map from HbO, $p = .05$, corrected). Later-exposed bilingual children show more robust neural activation in (a) the left and (b) the right hemispheres (bilateral STG, right Inferior Parietal Lobule) and (c) frontal lobes (DLPFC, Frontopolar area) while reading sentences relative to early-exposed bilingual children.
Figure 12. Sentence Processing: Neural activation of later-exposed bilingual children as compared to monolingual children (t-statistic map from HbO, $p = .05$, corrected). Later-exposed bilingual children show more robust neural activation in (a) the left and (b) the right hemispheres (bilateral STG), and (c) frontal lobes (DLPFC, Frontopolar area) while reading sentences relative to monolingual children.
Figure 13. Sentence Processing (a) Task saliencies for LV1 and (b) plot of brain scores by design scores for monolingual, early-exposed bilingual and later-exposed bilingual children while reading sentences.
Figure 14. Sentence Processing: Brain Coherence Scores by Group. Coherence values between all 46 fNIRS measurement channels for monolingual children, early-exposed bilingual children and later-exposed bilingual children while reading sentences.
Figure 15. Sentence Processing: Functional Connectivity by Brain Region and Group. Bilateral IFG, bilateral STG, DLPFC, and fronto-posterior functional connectivity for monolingual children, early-exposed bilingual children and later-exposed bilingual children while reading sentences.