



Early bilingualism, language attainment, and brain development



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ARTICLE INFO

Keywords:

Bilingualism
Magnetic resonance imaging
Brain development
Language attainment
Brain function
Brain structure
Neural connectivity

ABSTRACT

The brain demonstrates a remarkable capacity to undergo structural and functional change in response to experience throughout the lifespan. Evidence suggests that, in many domains of skill acquisition, the manifestation of this neuroplasticity depends on the age at which learning begins. The fact that most skills are acquired late in childhood or in adulthood has proven to be a limitation in studies aimed at determining the relationship between age of acquisition and brain plasticity. Bilingualism, however, provides an optimal model for discerning differences in how the brain wires when a skill is acquired from birth, when the brain circuitry for language is being constructed, versus later in life, when the pathways subserving the first language are already well developed. This review examines some of the existing knowledge about optimal periods in language development, with particular attention to the attainment of native-like phonology. It focuses on the differences in brain structure and function between simultaneous and sequential bilinguals and the compensatory mechanisms employed when bilingualism is achieved later in life, based on evidence from studies using a variety of neuroimaging modalities, including positron emission tomography (PET), task-based and resting-state functional magnetic resonance imaging (fMRI), and structural MRI. The discussion concludes with the presentation of recent neuroimaging studies that explore the concept of nested optimal periods in language development and the different neural paths to language proficiency taken by simultaneous and sequential bilinguals, with extrapolation to general notions of the relationship between age of acquisition and ultimate skill performance.

1. Introduction

The trophic effect of experience on neural development is reflected in demonstrable changes in brain function and structure. Neural reconfiguration in response to environmental exigencies, whether triggered by the requirement for specific motor behaviors or cognitive skills is referred to as neuroplasticity. Once established, these changes influence the development of subsequent competencies. Such experience-dependent brain modifications, likely the result of alterations in gene expression in neuronal substrates (Flavell and Greenberg, 2008), appear limited by the age at which a given skill is learned and the domain in which that ability is acquired. While most skills appear to be maximally attained during an *optimal* or *sensitive* period of development, recent observations have demonstrated that neuroplastic changes take place throughout the lifespan, even into senescence (Boyke et al., 2008). Identifying the mechanisms of neuroplasticity and the factors that influence its trajectory is essential in order to sort out the complexities of the learning process and the compensatory changes in the brain that promote near peak performance despite

suboptimal circumstances for skill acquisition.

Neuroplasticity has been investigated from the biochemical and neuronal perspectives to the level of the intact human brain (For a review see Zatorre et al., 2012). Over the past several decades, neuroimaging has become central to the study of neuroplasticity at the macrostructural and functional levels, with an initial focus on the skills of specialized experts, whose abilities developed late in childhood, adolescence, or adulthood (Münste et al., 2002). Professional musicians were among the earliest groups studied using a variety of applications of magnetic resonance imaging (MRI) to determine the size and gray matter density (GMD) of auditory and motor brain regions (Bermudez et al., 2009; Amunts et al., 1997; Schlaug et al., 1995a, 1995b). However, while a vast majority of published reports have revealed brain alterations in children and mature adults resulting from skill attainment, inferences based on such studies cannot be fully extrapolated to brain models of native acquisition.

A comparison of how the brain wires both in infancy and later in life provides immeasurable insight into how age of acquisition (AoA)

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influences brain structure and function and how the brain maximizes the efficiency of information processing (Butz et al., 2014; Achard and Bullmore, 2007; Watts and Strogatz, 1998). It appears that during the first few years of life, when the brain is in an active phase of being built, early sensory experience has the greatest capacity to strengthen neural circuitry. Understanding how the timing of language experience shapes brain structure and function is the objective of this review, and bilingualism will serve as the model to make sense of how this early versus late experience affects brain organization.

2. Development of the language network: optimal periods in language acquisition

Language is a cardinal human ability that lends itself to the study of how age of experience differentially influences brain development. The capacity to distinguish spoken language from other sounds, in fact, appears to begin in utero, with newborns demonstrating a preference for their mother's speech (Decasper and Fifer, 1980). There is debate, however, as to how the neural systems that develop for language are affected by biological maturation and experience (Elman et al., 1997). Penfield and Roberts (1959) proposed that language acquisition is tied to and restricted by age-dependent plasticity, basing their hypothesis on the more successful recovery of language function in children than in adults following surgery, and positing that young children had the facility to learn multiple languages. Lenneberg (1967) popularized Penfield and Roberts' (1959) observation that the acquisition of a fully native-like language capacity was constrained by age, becoming progressively more difficult to attain after a *critical period* that he believed ended at puberty, reflecting a significant degree of brain maturation.

Neuroimaging studies of language development in neonates and young children have provided considerable data about when fetuses and newborns can discriminate sounds and frequency changes. Discriminative ability of the auditory system is a prerequisite for the development of language. Draganova et al. (2007), using magnetoencephalography (MEG), demonstrated that two-thirds of fetuses as young as 28 weeks gestation and 89% of neonates responded to a change in tone-burst frequency. Perani et al. (2011) used fMRI and diffusion tensor imaging (DTI) to study the neuroanatomic basis for the discrimination of different speech sounds and prosodies by newborns, and observed that two-day-old infants activated language regions bilaterally, with dominance in the right auditory cortex. Moreover, three-month-olds were found to process speech in the inferior frontal gyrus (IFG) and temporal regions, similar to adults. Activation in the superior temporal gyrus (STG) and in the primary and secondary auditory cortices was also observed in response to normal speech. In addition, DTI has revealed a dorsal axonal pathway connecting the temporal and premotor cortices, providing a route for sensory-to-motor mapping, thus facilitating the processing of phonological feedback, a necessity during the babbling phase of language development (Goldstein and Schwade, 2008). The early presence of this pathway strengthens the connection between language perception and language production required for the subsequent acquisition of speech (Perani et al., 2011). Although evidence suggests that connectivity between the IFG and the temporal cortex (i.e., the arcuate fasciculus) has not yet formed in the 1–4 month postnatal period, one might speculate that early language input might have an organizing effect on this developing connection (Dubois et al., 2008).

An fMRI study by Dehaene-Lambertz et al. (2002) provided further evidence that the cortical language substrate was significantly developed in infants at 3 months of age, demonstrating that there was increased activity in response to speech, especially in the superior

temporal gyrus, with lateralization of activity to the left STG at the level of the planum temporale (Wernicke's area). Of note, similar levels of activity were induced in the temporal lobe with both forward and backward speech, suggesting that, although this structure is functional in 3-month-olds, it has not yet acquired an adult-type preference for native language at this juncture (Dehaene-Lambertz et al., 2002).

The maturation of speech production ability correlates with a remarkable increase in overall brain size as the child transitions from babbling to one- and two- word utterances, to full sentences, reaching adult size before age 6, and 80% of its ultimate volume at the time of sentence production (Sakai, 2005). The greatest increase in cortical surface area occurs during the first and second years of life (1.80 times and 1.20 times respectively; Li et al., 2013), with considerable tertiary folding occurring postnatally, driven by specific patterns of cortical connectivity (Nie et al., 2012; Van Essen, 1997). The variability in the folding observed in the adult brain, however, is thought to be established by the time of birth (Hill et al., 2010). Of note, the most significant growth of the STG occurs during the first year of life, an observation consistent with the functional evidence of the very early development of the infant's ability to discriminate speech sounds. An anatomical sequence study of cortical development in young children demonstrated that the earliest parts of the brain to mature are the motor and sensory brain areas, followed by regions involved in spatial orientation and speech and language, including parts of the temporal lobe and the IFG. Other parts of the temporal lobe, however, have a more protracted course of development into adulthood (Gogtay et al., 2004). This pattern of early maturation of language-related brain areas may account for a potential loss of the brain's capacity for cortical and subcortical reorganization in later childhood, although dynamic changes in the brain continue during development, with significant restructuring possible due to the growth of new synapses, progressive myelination, and the pruning of superfluous connections within networks (Homaie et al., 2010; Gogtay et al., 2004).

3. Optimal period in bilingual language development

Since language develops from birth, the acquisition of a second language (L2), studied with the tools of neuroimaging, permits researchers to observe the attainment of a complex skill in a naturalistic environment. The structural and functional brain alterations associated with learning two languages concurrently from birth (simultaneous bilinguals) can be compared with observed changes related to learning a second language after the first language (L1) has already been established (sequential bilinguals). More broadly, understanding the patterns of L2-related neuroplasticity will likely help disentangle what are believed to be the two most important variables influencing the capacity for experience-dependent skill learning and brain development, namely, age of acquisition and proficiency (Perani and Abutalebi, 2005).

Evidence suggests that language acquisition is influenced from the beginning by both endogenous and experiential factors. For example, neonates prefer listening to speech over other sounds (Vouloumanos and Werker, 2004; Moon et al., 1993). In this regard, infants exposed to language from birth demonstrate, at first, a universal capacity to perceive the phonemes of all spoken languages (Kuhl, 2010; Werker and Tees, 1984; Eimas et al., 1971). By the age of 6 months, however, the child's ability to discriminate non-native phonemic contrasts begins to wane, initially for vowels and later for consonants (Kuhl, 2004; Kuhl et al., 1992; Werker and Tees, 1984). By 9–10 months of age, the pre-linguistic vocalizations of an infant in the conversational stage of babbling closely resemble the phonetics of their native language

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