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Review

Neuroplasticity as a function of second language learning: Anatomical changes in the human brain

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ABSTRACT

The brain has an extraordinary ability to functionally and physically change or reconfigure its structure in response to environmental stimulus, cognitive demand, or behavioral experience. This property, known as neuroplasticity, has been examined extensively in many domains. But how does neuroplasticity occur in the brain as a function of an individual's experience with a second language? It is not until recently that we have gained some understanding of this question by examining the anatomical changes as well as functional neural patterns that are induced by the learning and use of multiple languages. In this article we review emerging evidence regarding how structural neuroplasticity occurs in the brain as a result of one's bilingual experience. Our review aims at identifying the processes and mechanisms that drive experience-dependent anatomical changes, and integrating structural imaging data with current knowledge of functional neural plasticity of language and other cognitive skills. The evidence reviewed so far portrays a picture that is highly consistent with structural neuroplasticity observed for other domains: second language experience-induced brain changes, including increased gray matter (GM) density and white matter (WM) integrity, can be found in children, young adults, and the elderly; can occur rapidly with short-term language learning or training; and are sensitive to age, age of acquisition, proficiency or performance level, language-specific characteristics, and individual differences. We conclude with a theoretical perspective on neuroplasticity in language and bilingualism, and point to future directions for research.

1. Introduction

More than half of the world's population are actively learning or speaking a second language in addition to their native tongue (Grosjean & Li, 2013). What impact does experience with a second language have on the human brain? Traditionally, both folk wisdom and scientific evidence point to the decreasing plasticity of the adult brain in acquiring a new language, especially given the arguments of the so-called "critical period hypothesis" (Kennedy & Norman, 2005;

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Lenneberg, 1967). Recent scientific evidence, however, has challenged this view. In particular, cognitive and brain studies of bilingual language acquisition, along with studies of memory, attention, and perception, have demonstrated continued neuroplasticity for language learning in the adult brain that has never been previously imagined (see Abutalebi & Green, 2007; Hernandez, 2013; Li, 2014, for reviews). The study of neuroplasticity of language learning in adulthood, along with the understanding of neural correlates of language processing and representation, has made significant progress in the last decade thanks to rapid advances in neuroimaging technologies (see reviews in Hickok, 2009; Poeppel, Emmorey, Hickok, & Pylkkänen, 2012; Price, 2000, 2010; Richardson & Price, 2009; Rodriguez-Fornells Cunillera, Mestres-Misse, & de Diego-Balaguer, 2009).

Experience-dependent neural changes can result from many aspects of environmental input, cognitive demand, or behavioral experience, but the intensity and frequency of language use may be particularly powerful in bringing about such changes in the brain (see Bates, 1999 for an earlier synthesis). Many people are born bilingual in our increasingly more connected and multilingual world, while many others are learning a new language later in life due to travel, business, or immigration. Globalization, widespread use of digital technology, and increased cross-cultural communication provide further impetus to the rapid rise of bilingualism and multilingual societies. The study of the bilingual brain originally arose from neuroscientists' interest in understanding how the same brain supports and represents two or more languages. Since the mid-to-late 1990s, a large number of neurocognitive studies, using neuroimaging methods such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography/event-related potential (EEG/ERP), have revealed specific functional brain patterns in the learning of a second language (L2) (see reviews in Abutalebi, Cappa, & Perani, 2005; Costa & Sebastian-Galles, 2014; Hernandez, 2013; Indefrey, 2006; Li & Tokowicz, 2012; van Hell & Tokowicz, 2010). These studies indicate that in contrast to predictions of the critical period hypothesis, L2 learning, even if it occurs late in adulthood, lead to both behavioral and neural changes that can approximate the patterns of native or first language (L1).

Even more surprising is that the neural patterns of L2 experience are often, if not always, accompanied by anatomical changes in brain structure. Such anatomical changes can occur in the form of, for example, increased gray matter (GM) density, increased cortical thickness (CT), or enhanced white matter (WM) integrity. A number of recent studies have thus begun to examine the structural or anatomical changes induced by L2 experience on the brain. Given the significant anatomical changes that have been reported for memory, attention, and other cognitive domains (see Section 3.2), it is important that we consider the anatomical substrates of second language learning. In this article, we provide an overview and synthesis of the relevant studies, and identify key variables and mechanisms underlying language experience related structural neuroplasticity. We aim at not only reviewing the emerging literature, but also identifying the common principles that drive brain changes and integrating our knowledge of structure-function-behavior relationships.

2. Anatomical correlates of second language learning

Research in bilingualism and second language[1] has generated much enthusiasm lately in the study of the mind and the brain (see Diamond, 2010). What has brought bilingualism to the spotlight? There may be several reasons but one key line of research behind the current enthusiasm is the neurocognitive impact that the learning and use of multiple languages may have on the brain (see reviews in Bialystok, 2009; Costa & Sebastian-Galles, 2014; Hernandez, 2013; Li, 2014). The bilingual brain is a highly adaptive system, and it responds to multiple language experiences flexibly and reflects the adaptive dynamics as both functional and anatomical brain changes. In this section we review the major evidence that has accumulated in the last decade on how the learning of L2, or bilingual experience more generally, may bring about anatomical changes in the brain.

Functional neuroimaging methods, especially fMRI, have played a key role in the study of bilingualism and second language acquisition (see Grosjean & Li, 2013, Chapter 10; Hernandez, 2013; Indefrey, 2006; Li & Tokowicz, 2012; for reviews). While functional neuroimaging has led to a significant understanding of the bilingual brain, the use of structural imaging techniques has only begun recently in the study of bilingualism and second language. As we will discuss below, structural imaging methods allow us to measure brain changes in anatomical structure and may offer broader implications for understanding the bilingual brain, particularly with regard to their ability to identify causal links between experience and neuroplasticity through training. Let us first briefly review the three major measures and the methodologies with which we can identify learning-induced or experience-dependent changes in the brain's anatomical structures.

2.1. *Measures of anatomical changes*

Neurons are organized within the brain to form GM and WM. GM consists primarily of neuronal cell bodies, whereas WM consists of axons and support cells (e.g., glia cells). Bundles of axons form the so-called fiber tracts that connect different cortical regions within the same hemisphere (through association tracts), between hemispheres (through commissures, e.g., the corpus callosum (CC)), or between cortical and subcortical structures (projection tracts). The brain is filled with cerebrospinal fluid (CSF), which also runs through the ventricles of the brain. Measures of anatomical changes focus mainly on changes in GM and WM.

[1] Many people learn or speak a third or fourth language. Here we use “bilingualism” or “second language” as a generic and inclusive term to cover situations of two or *more than* two languages.