



HAL
open science

Neuroplasticity of second language vocabulary acquisition

Frédéric Isel

► **To cite this version:**

Frédéric Isel. Neuroplasticity of second language vocabulary acquisition: The role of linguistic experience in individual learning. *Langage, Interaction et Acquisition / Language, Interaction and Acquisition*, 2021, 12 (1), pp.54-81. 10.1075/lia.20023.ise . hal-04073245

HAL Id: hal-04073245

<https://hal.science/hal-04073245>

Submitted on 5 May 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Neuroplasticity of second language vocabulary acquisition

The role of linguistic experience in individual learning

Frédéric Isel

Université Paris Nanterre, CNRS, UMR Modèles, Dynamiques, Corpus

The present article reviews a series of selected functional and structural magnetic resonance imaging (MRI) studies focusing on the neuroplasticity of second language vocabulary acquisition as a function of linguistic experience. A clear-cut picture emerging from the review is that brain changes induced by second language vocabulary acquisition are observed at both functional and structural levels. Importantly, second language experience is even able to shape brain structures in short-term training of a few weeks. The evidence that linguistic experience can sculpt the brain in late second language learners, and even solely after a short-term laboratory training, constitutes a strong argument against theoretical approaches postulating that environmental factors are relatively unimportant for language development. Rather, combined neuroimaging data lend support to the determining role of linguistic experience in linguistic knowledge emergence during second language acquisition, at least at the lexical level.

Keywords: bilingualism, vocabulary acquisition, linguistic experience, neuroplasticity, Magnetic Resonance Imaging (MRI)

This review focuses on the neuroplastic changes induced by second language vocabulary acquisition. Particular emphasis is placed on structural MRI (sMRI) data as they provide comprehensive evidence of real neuroanatomical changes. This article comprises five sections. Section 1 is a short introduction, followed by Section 2, presenting the issue of brain changes induced by second language acquisition (SLA) experiences. Then, Section 3 proposes a short overview of selected studies using functional imaging, while Section 4 is devoted to a more detailed presentation of selected structural imaging data. Finally, the last section is dedicated to conclusions and perspectives. Throughout the article, we will endeavor to show that both linguistic experience and learning context lead to different learning performances, evaluated by behavioral word recognition tests. We will also underline the role of

individual variations in the ability to learn new words, differences which could be partly explained by the variation of activity in certain brain regions before any training.

1. Introduction

The human brain is unique, especially because it underlies the faculty of language, i.e. the ability to express thoughts symbolically and share them with others. The reasons for this uniqueness are both genetic and epigenetic (Schumann, 2004). Neuroanatomically, the brain continues to change and adapt throughout the lifespan, which impacts the different cognitive functions and in particular language. This plasticity means that within anatomic, physiological, and genetic limits, skills and behavior can change. It also indicates that a person's actions/ experiences/learning affect the shape and connections in that person's brain (Dewaele, 2009). This plastic change of the brain is called neuroplasticity. Neuro-plasticity is a property of the brain that gives it the ability to achieve functional and structural changes or reconfigurations in response to environmental stimuli, cognitive demands, or behavioral experience (Li, Legault, & Litcofsky, 2014).

In this article, we will show, through a series of selected neuroimaging studies, that the bilingual brain is a highly adaptive system which responds to multiple language experiences flexibly and reflects the adaptive dynamics as both functional and anatomical brain changes. Language experiences can be operationalized in different ways by systematically manipulating various psycholinguistic factors: age of acquisition (AoA) of the second language (L2), proficiency in L2, frequency of L2 use, and type of bilingualism (unimodal vs. bimodal). Moreover, linguistic experience can be simulated by means of different learning contexts, such as the traditional classroom, immersion learning in a realistic language context, or in a virtual context (laboratory).

We focus particularly on functional and structural MRI studies, which are the most numerous in this field for examining the neural effect of different short term L2 trainings. We do not claim to make an exhaustive presentation of all the work in this area of research. We only wish to provide an overview of current knowledge on the question of the relationship between neuroplastic changes and L2 vocabulary learning. We have deliberately limited our review to studies testing young adults, that is, at an age when it is reasonably certain that changes in brain structures as a result of L2 language experience, if such changes do exist, can be captured, due to the high malleability and adaptability of the brain in this age group. In order to help readers locate some of the cortical areas which will often be mentioned in most of the neuroimaging studies referred to in this review, a synthetic view of anatomical and cytoarchitectonic details of the left hemisphere is displayed in Figure 1 (in

the online appendix; image adapted from Friederici, 2011).

2. Second language experience-dependent neuroplasticity

Language experience constitutes an intensive experience occurring on a daily basis and across the lifespan. As such, it provides a powerful environmental input to the nervous system to induce anatomical changes in the human brain. Among language experiences, one is particularly rich, namely second language acquisition (SLA); the related question is to what extent functional and structural changes may be shaped during SLA.

A singularity of the human species is that humans have a unique ability to learn more than one language. Bilingualism is not a marginal case in our increasingly connected and multilingual world. Note that historically, forms of bilingualism have already existed, especially when national languages and regional languages (dialects, for example) coexisted. Many people are born bilingual, while many others learn a new language later in life for a variety of reasons, such as travel, business, or immigration. It is therefore crucial to study the neurodynamics of the cognitive mechanisms underlying second language learning. In addition, applied research is faced with a major challenge, to improve learning methods and to develop suitable didactic tools.

Since the 1990s, neuroplasticity has been examined extensively in different domains of the cognitive neuroscience of language (for examples with event related brain potentials (ERP), see Weber-Fox & Neville, 1996, 1999). In particular, the psycholinguistic literature of bilingualism and SLA has investigated how the same brain can support and represent two or more languages (word level: Isel, Baumgaertner, Thrän, Meisel, & Büchel, 2010; sentence level: Wartenburger et al., 2003), but also which brain areas might support the mechanism of language switching in bilinguals (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001, among others). 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 (EEG) with ERP, have revealed specific functional brain patterns in the learning of an L2 (for reviews, see Costa & Sebastián-Gallés, 2014; Hernandez, 2013). These studies have consistently shown, in contrast to predictions of the critical period hypothesis (CPH; Lenneberg, 1967; Penfeld & Roberts, 1959), that L2 learning, even if it occurs late in adulthood, leads to both behavioral and neural changes that may approximate the patterns of the native or first language (L1). Although learning an L2 is a skill thought to be mediated by functional rather than structural brain changes, structural imaging studies have provided evidence that learning a second language

can also cause changes in the anatomy of the brain. Such anatomical changes can occur in the form of, for example, increased grey¹ matter volume (GMV), increased cortical thickness (CT)², or enhanced white matter (WM) integrity³ (for a detailed presentation of these different measures, see Li et al., 2014; Legault, Fang, Lan, & Li, 2019a).

However, the question of how neuroplasticity occurs in the brain as a function of an individual's linguistic experience during SLA is far from answered. In the last few years, many studies have contributed to a better understanding of the bilingual brain, especially using neuroimaging techniques such as fMRI (for a review of 100 fMRI studies, see Price, 2010; for a review and synthesis of PET and fMRI studies of heard speech, spoken language and reading, see Price, 2012). MRI studies usually examine the anatomical changes (structural imaging) and the functional neural patterns (functional imaging) that are induced by the learning and use of multiple languages. More recently, effective connectivity analyses⁴ of fMRI data (for an example in second language vocabulary acquisition, see Yang, Gates, Molenaar, & Li, 2015) have complemented functional and structural approaches. Effective connectivity analyses consist of examining at a given time (contemporaneously) both the activation of brain regions and their connection, as well as across different times (sequentially) the direction of influences between these regions and the strength of connections. Currently, effective analyses are run through methods such as unified structural equation modeling (uSEM; Gates, Molenaar, Hillary, Ram, &

¹ The term grey matter designates nerve tissue composed of nerve cell bodies, unmyelinated nerve fibers and supportive tissue found in the brain and spinal cord. It is differentiated from white matter by the color of the tissues and the presence of more myelinated nerve cells in white matter. Grey matter is mainly located on the surface of the brain, while white matter is found buried in the inner layer of the brain cortex. Grey matter serves to process information in the brain (Purves et al., 2008). Cross-sectional studies have established that differences in regional grey matter are associated with performance abilities (Mechelli et al., 2004; Milad et al., 2005), suggesting that an increase in grey matter corresponds to improved functioning in the relevant area.

² CT, also based on structural MRI scans, measures the thickness of GM (Fischl & Dale, 2000). Unlike GM volume, CT is a direct measure of cortical morphology. Structurally there may be an inverse relationship between CT and GM due to the cortical folding patterns: thicker cortical regions are less convoluted and therefore have a lower GM density (see Chung, Dalton, Shen, Evans, & Davidson, 2006).

³ WM integrity refers to a measure based on data from diffusion tensor imaging (DTI), a technique that examines the diffusion of water molecules in the brain. DTI is also called quantitative MRI (qMRI). Specifically, DTI compares the degree of diffusivity of neurons along the axon, referred to as axial diffusivity (AD) along with the radial diffusivity (RD) that is perpendicular to the axon diameter (Filler, 2009). By far the most commonly used value to calculate the magnitude of diffusion is fractional anisotropy (FA), a normalized standard diffusivity value between 0 and 1 (Assaf & Pasternak, 2008). The higher the FA value, the more integrity the WM has.

⁴ For reasons of space, we decided not to present fMRI studies which have used this method of data analysis. Moreover, as this method is recent, in particular in the field of second language vocabulary acquisition, it is difficult to come to coherent conclusions for the time being.

Rovine, 2010; Kim, Zhu, Chang, Bentler, & Ernst, 2007). These analyses have made it possible to study the brain networks – collections of regions jointly engaged by some mental process – underlying second language learning, especially word learning, i.e. the level of linguistic analysis on which we focus in the present review.

Critically, connectivity analyses allow researchers to identify effective connectivity changes associated with individual differences in L2 sound-to-word mapping while learning new words. Moreover, these analyses offer the opportunity to gradually relate connectivity changes with success in second language word learning. While MRI remains one of the most widely used tools for studying second language experience-induced brain changes using a brain network approach, a small number of recent studies used another method to examine how these changes are manifested, namely in EEG, by dynamic brain oscillations and synchronization patterns that subserve the language networks (see for example, Reiterer, Pereda, & Bhattacharya, 2011). Neurophysiologically, functional connectivity can be defined as the synchronization between spatially remote neurophysiological events. It reveals temporal correlational relationships between different brain regions. Thus, EEG coherence can be used to measure the functional connectivity of specific frequency bands between pairs of cortical regions (Friston, Frith, Liddle, & Frackowiak, 1993).

The study of the relation between an individual's linguistic experience during SLA and the induced brain changes requires adopting a definition of what one means by linguistic experience. In the laboratory, one way to simulate the concept of linguistic experience through experimental designs consists of systematically manipulating short-term L2 training (viewed as a learning context). Usually, for L2 vocabulary learning, different methods of training are proposed such as word word, word-picture, virtual reality (VR), or even immersive virtual reality (iVR). Comparative neuroimaging studies have set themselves the goal of assessing the efficiency of these different training methods in well-controlled pre- and post training experimental designs (Legault et al., 2019a among others). In this article we review emerging evidence regarding how functional and structural neuroplasticity occurs in the brain as a result of one's bilingual experience during L2 vocabulary learning. L2 vocabulary learning constitutes a major step when individuals begin to learn a second language. Linguistically, vocabulary learning involves mapping a new L2 lexicon onto pre-existing mental concepts, which are already connected to words in the L1 (see Kroll & Stewart, 1994 for the seminal version of the *Revised Hierarchical Model*).

In lexicology, learning a new lexical unit is viewed as creating an arbitrary relationship between form and meaning, and encoding it, one way or another, into the learner's permanent semantic memory. According to Saussure (1916; see posthumous work by Godel, 1957), the linguistic sign unites not a thing and a name, but a concept and an

acoustic image (i.e. a mental representation, in the terminology of cognitive psychology). In psycholinguistics, the expression “mental lexicon” is commonly used to refer to the body of knowledge that a subject has about words in their language (Segui, 1992). This knowledge concerns the semantic, syntactic, morphological, phonological and orthographic properties of words. As claimed by Segui (1992, 2015), any model of language processing (perception or interpretation) or production must necessarily incorporate a lexical component. Indeed, the lexicon constitutes the fundamental interface which links the formal level to the interpretive level of language (Segui, 2015). Several fMRI studies have investigated the structural architecture of the mental lexicon as it has been formulated in previous behavioral studies. For example, Fiebach, Friederici, Müller, and von Cramon (2002) reported fMRI evidence that lends support to a dual-route model for visual word recognition involving in parallel a fast pathway to the mental lexicon (i.e. a direct map of orthographic percepts onto stored word form representations), and a slower “assembled” or nonlexical route which translates graphemic input into phonological information. Other dual-route models have also been proposed based on behavioral and neurophysiological data to describe the processing of morphologically complex words (for a review, see Isel, Gunter, & Friederici, 2003; Isel & Shen, 2020).

Next, we discuss how learning new L2 words may induce brain changes. For this purpose, we will rely on results reported by functional neuroimaging studies.

3. Functional imaging data

Functional imaging studies have identified specific brain regions which are involved in second language vocabulary acquisition. Beyond these neuroanatomical localizations, progress has also been made in identifying possible spatial markers of individual differences in the ability to acquire new vocabularies (Breitenstein et al., 2005; Mei et al., 2008; Wong, Perrachione, & Parrish, 2007 among others). An overview of these different markers is presented below, and summarized in Table 1 (in the online appendix).

Word level

In an fMRI discrimination experiment, Wong et al. (2007) used a pitch-to-word learning program in which 17 native English speakers who had no previous exposure to any tone languages learned six English pseudosyllables superimposed with pitch (fundamental frequency) patterns resembling three Mandarin Chinese tones (high level, rising, falling). The 18 pseudowords were paired with pictures. Participants had to learn this vocabulary, using pitch in the words to differentiate them.

They were trained with feedback for three to four sessions per week until their individual ultimate attainment (i.e. asymptotic performance) was reached. Attainment level was defined by accuracy in word identification in the first session at which asymptotic performance was shown. Based on discrimination performances, Wong et al. (2007) created two subgroups of learners: one group, whose word recognition accuracy was 95% or above for two consecutive sessions, was classified as “successful learners”, and the other group, who failed to make a 5% improvement or better for four consecutive sessions, was classified as “less successful learners”. Data showed distinct neural responses in the two subgroups. While successful learners exhibited increased activation in the left posterior superior temporal gyrus (Brodmann Area, henceforth BA, 22; Brodmann, 1909), less successful learners showed increased activation in the homologous right superior temporal gyrus, as well as in the right inferior temporal gyrus. Moreover, compared to successful learners, in less successful learners brain activation was more diffuse in the fronto-temporal network. As noted by Yang et al. (2015), finding stronger left posterior superior temporal gyrus activation for successful learners is consistent with the function of phonological processing thought to be supported by this brain area (see Hickok, 2009; Hickok & Poeppel, 2007; Zhang et al., 2011). Interestingly, Wong et al.’s (2007) study also demonstrated that the successful learners’ neural patterns were distinct from those of the less successful learners even before the sound-to-word learning (i.e. before the behavioral training) began. The successful learners had greater brain activity in the posterior superior temporal gyrus in comparison with the less successful learners. This finding is decisive in the comprehension of SLA mechanisms, as it suggests that it may be possible to predict, based on neural signatures, who is likely to be a successful learner.

With the same objective of identifying neural predictors of auditory word learning in a new language, Mei et al. (2008) involved 24 native Chinese speakers in a 2-week training program to learn a logographic artificial language. Participants performed a passive listening task. Whole-brain analysis showed significant training-induced changes in the left frontal areas, superior parietal lobule, right supplementary motor area, insula/putamen, cerebellum, and bilateral temporal lobe.

More importantly, comparison of fMRI scans before and after training showed differentiated brain activation between successful and less successful learners, called by the authors “good learners” vs. “poor learners”. Note that in this study, participants were classified as “good learners” when their performance was above average during training, and as “poor performers” when the performance was below average. Critically, good learners displayed more activation in the left middle temporal gyrus/superior temporal sulcus and less activation in the right

inferior frontal gyrus during the pretraining scan. These findings lend support to the hypothesis that preexisting individual differences in neural activities may predict the ability to learn words in a new language. It is important to note that while Wong et al. (2007) showed that brain activity in the posterior superior temporal gyrus was found to be a possible neural predictor of auditory word learning before any training, Mei et al. (2008) reported differentiated activation between successful and less successful learners in the left middle temporal gyrus/ superior temporal sulcus and in the right inferior temporal gyrus. This difference might be attributable to the tasks used in the two studies (pitch discrimination versus passive listening).

Other brain markers of second language word learning have been identified. For example, Breitenstein et al. (2005) showed in an event-related fMRI study that the hippocampus, a cortical structure known to be critically involved in learning and memory processes (Squire, 1992), may also be a marker of individual differences in the ability to learn new vocabularies. In their study, native speakers of German performed 45 pseudo-word sound-picture associations in a 50-min training session. Using regression analyses, the authors found that over the 50-min training session the increase in novel word proficiency based on a test of lexical knowledge was accompanied by a linear decrease in Blood Oxygen Level Dependent (BOLD) signal changes in the left hippocampus. Based on these data, the authors concluded that learning-related hippocampal activity might be a stable marker of individual differences in the ability to acquire new vocabularies.

In the cognitive neuroscience of language community, there is a consensus that learning a second language, and in particular learning new vocabularies, leads to functional changes in the brain. However, learning an L2 can also induce changes in the anatomy of the brain, that is structural brain changes. These changes can take the form of increased grey matter volume, increased cortical thickness, or enhanced white matter integrity. We will now present selected structural MRI (sMRI) studies investigating this issue.

4. Structural imaging data

A summary of the core studies of structural brain variation selected for this review is displayed in Table 2 (in the online appendix). We will now present three examples of language experience that impacts brain neuroanatomy, namely, type of bilingualism, age of acquisition (AoA), and level of proficiency in the second language.

Long-term experiences with L2 and anatomical changes in the brain

Type of bilingualism

Zou, Ding, Abutalebi, Shu, and Peng (2012) reported that bimodal bilinguals (using both gestural and oral languages) have a greater GM volume in the left caudate nucleus than unimodal bilinguals (using two oral languages). To account for this structural variation as a function of the modality of bilingualism, the authors proposed that bimodal bilinguals may require greater cognitive control to manage the switching between their two languages in different modalities than bilinguals using two languages in the same modality. This could explain the increased GMV observed in the left caudate nucleus, a key brain area with the anterior cingulate gyrus and the middle frontal gyrus in a language control network (Abutalebi et al., 2012). However, this conclusion should be qualified in view of the results obtained in a recent magnetoencephalography (MEG) study. Using MEG, Blanco-Elorrieta, Emmorey, and Pylkkänen (2018) aimed to dissociate language engagement and disengagement in bilingualism. They showed in American Sign Language–English bimodal bilinguals who often sign and speak simultaneously that turning a language “off” (switching from simultaneous to single language production) led to increased activity in the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (dlPFC), while turning a language “on” (switching from one language to two simultaneously) did not. Blanco-Elorrieta et al. (2018) suggested that the burden of language switching lies in disengagement from the previous language as opposed to engaging a new language.

AoA and level of proficiency in the second language

More commonly, the degree of structural reorganization in bilinguals is often correlated with their second-language performance as assessed in L2 proficiency, a measure of how well a person performs in a second language across domains such as reading, writing, speaking, and listening. Another critical factor associated with neuroanatomical changes in the bilingual brain is the age of second language acquisition (AoA), i.e. the age at which a participant first learned a new language. An increasing amount of research has recently focused on examining how individual differences in performance might be associated with various aspects of L2 experience and neuroplasticity. The bilingual brain literature has so far focused on several factors in L2 experience that are key to modulating functional and structural brain responses (see Hernandez & Li, 2007; Hernandez, 2013 for reviews).

We will now discuss prominent brain structure changes associated with age of acquisition, proficiency or performance level, language-specific characteristics, and individual differences found in recent sMRI studies. Most of these studies were conducted in laboratory settings using a training paradigm, which varied in duration depending on the studies. In general, these studies have indicated that second

language experience-induced brain changes, including increased grey matter (GM) density and white matter (WM) integrity, can be found in individuals of various ages (children, young adults, and the elderly). Importantly, it was also demonstrated that these structural brain changes can occur rapidly, in only a few weeks, with short-term language learning or training. What few studies have so far established, however, is how long these changes last once training stops.

A first example of the reorganization of neural substrates induced by bilingual experience was attested by Mechelli et al. (2004) using voxel-based morphometry (VBM) to examine GM volume in early (AoA <5 yrs) or late (AoA 10–15 yrs) bilinguals of different ages who learned a second European language as L2. The authors showed that learning a second language increased the volume of grey matter in the left inferior parietal cortex, a particular region that becomes activated during verbal-fluency tasks, as shown by functional imaging (Poline, Vandenberghe, Holmes, Friston, & Frackowiak, 1996; Warburton et al., 1996). Crucially, the authors also reported that the degree of structural reorganization in this region was modulated by the proficiency attained and the age of acquisition. However, one qualification to the conclusions may be drawn from the Mechelli et al. study. Their experimental design was not longitudinal, and it is therefore difficult to decide to what extent pre-existing differences could also have played a role.

Previous imaging studies reported the involvement of the inferior parietal cortex in phonological working memory, lexical learning, and semantic integration (Baddeley, 2003; Della Rosa et al., 2013; Mechelli et al., 2004). Richardson and Price (2009) suggested that the expansion of this area in bilinguals might be particularly related to the bilingual's acquisition and processing of a larger vocabulary. Note that the inferior parietal cortex, and adjacent brain areas including the posterior supramarginal gyrus, have been found to play an important role in the knowledge of vocabulary in general, not only in L2 but also in L1 (see Yang et al., 2015 for a discussion). In L1, Lee et al. (2007) reported a significant positive correlation between monolingual vocabulary size and GM volume in the bilateral inferior parietal cortex and posterior supramarginal gyrus. Finally, and more importantly, in the results reported by Mechelli et al. (2004), a positive correlation between L2 proficiency and GM volume (the more proficient the learners, the greater the GM volume), and a negative correlation between the AoA and the GM volume (the earlier the AoA, the larger the GM volume) were found. These correlations indicate that the degree of bilingualism directly influences the structural characteristics of brain regions involved in L2 learning.

Hosoda, Tanaka, Nariai, Honda, and Hanakawa (2013) trained native Japanese university students to learn L2 English words in a laboratory setting for 16 weeks. In the trained group, the authors found an increased volume of grey matter and white matter in the right inferior gyrus.

Previous neuroimaging studies showed that the inferior gyrus plays a major role in semantic retrieval and in selecting relevant semantic information over distractors (Rodríguez-Fornells, Cunillera, Mestres-Missé, & de Diego-Balaguer, 2009; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Critically, the plastic changes observed by Hosoda et al. (2013) in the right inferior frontal gyrus were correlated with an improvement in L2 capacities (here, the knowledge of English vocabulary) in the trained group but were not observed in the control group. These structural imaging data provide stronger evidence for a causal relationship between linguistic experience and reorganization of the neural substrates as suggested by most current functional imaging data.

However, the changes in brain structure induced by L2 learning are not always observed in the intuitively expected direction. For example, a study conducted by Klein, Mok, Chen, and Watkins (2013) reported a negative correlation between L2 AoA and neuroanatomical changes such as cortical thickness (CT), that is, the earlier the learner's age of onset for L2 acquisition, the smaller the CT. This apparently contradictory finding in comparison with other studies that have, instead, reported a negative correlation between AoA and GM volume (i.e. the earlier the AoA, the larger the GM volume) may be explained structurally. Chung et al. (2006) argued that, at the structural level, there may be an inverse relationship between CT and GM due to cortical folding patterns. According to these authors, thicker cortical regions are less convoluted and therefore have less volume.

In addition to GM volume changes generally observed as a function of bilingual experience, WM integrity has also been found to differ between bilinguals and monolinguals. For example, using diffusion-weighted MRI (DW-MRI) tractography techniques and a network-based statistic (NBS) procedure, Garcia-Pentón, Pérez, Iturria-Medina, Gillon-Dowens, and Carreiras (2014) found two structural sub-networks that were more connected by white matter (WM) tracts in bilinguals than in monolinguals. This finding confirms WM brain plasticity in bilinguals. Importantly, the authors also showed that one of these sub-networks comprises left frontal and parietal/temporal regions, while the other comprises left occipital and parietal/temporal regions and also the right superior frontal gyrus. Most of these regions have been related to language processing and monitoring, suggesting that bilinguals develop specialized language sub-networks to deal with the two languages. Furthermore, Cummine and Boliek (2013) found higher fractional anisotropy (FA) values, i.e. an indicator of the magnitude of the diffusion of water molecules in the brain that is used to measure WM integrity (the higher the FA, the more integrity the WM has), for adult monolinguals over bilinguals in the right inferior fronto-occipital fasciculus and the anterior thalamic radiation. To account for the lower WM integrity in bilinguals found in their study, the authors proposed that bilinguals

(young adults in their early 20s) have an immature WM compared to monolinguals (older adults in their late 20s).

To compensate for this scarcity, Li et al. (2014) pointed out that future studies will need to use a longitudinal approach in order to trace anatomical changes in the same individuals. Moreover, it is also important to emphasize that the conclusions drawn regarding the effect of AoA on neuroplastic changes during L2 learning must be qualified until AoA and L2 proficiency have been strictly disentangled. Some researchers have indeed attempted to separate AoA from proficiency and to identify their independent contribution to the anatomical change in bilingual experience. For example, as we already saw, Mechelli et al. (2004) not only reported an effect of AoA but also an effect of L2 proficiency on GM volume, but in two opposite directions. While AoA correlated negatively with GM volume in both the left and right inferior parietal lobule, L2 proficiency correlated positively with GM volume in the left inferior parietal lobule. GM volume in the left inferior frontal gyrus pars opercularis was also found to correlate positively with performance levels in L2 lexical decision and verbal fluency tasks for young adult bilinguals (Grogan et al., 2012).

The studies using structural imaging presented above converge to show that long-term experiences with L2 lead to anatomical changes in the brain. We can then wonder to what extent short-term learning or intensive training may also be able to shape the cerebral structures of L2 learners' brains. From a didactic point of view, this question is of prime importance, especially with respect to the efficiency of L2 learning methods.

Structural brain changes induced by short-term L2 learning or training in laboratory settings

We will now present a brief overview of recent neuroimaging studies that have reported structural brain changes induced by short-term L2 learning or training in laboratory settings. It is important to note that in most of the L2 studies using a training paradigm, the training lasted for a few months to a year, and the shortest period within which a structural brain effect has been observed is 3 months. We even found a study reporting a change in GM volume after only two hours' training using a simplified language learning task (Kwok et al., 2011). Usually, the approach consisting in training participants in the lab, asking them to learn a simplified natural language (e.g. sounds or words) or even an artificial language (e.g. Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010; Wong et al., 2007; Yang & Li, 2012) is crucial to the analysis of neuroanatomical changes as a function of linguistic experience. The main advantage of the training paradigm is that the quantity of input delivered to the participants and the amount of time spent learning can be tightly controlled. Moreover, the results obtained in the trained group for which language background and motivation are measured are

compared to those in a control group. Another experimental strength of the training paradigm in neuroimaging studies is that it allows researchers to collect brain data at precisely designated times such as scanning before training, midway into training, right after training, or post-training with a time delay.

In a diffusion tensor imaging (DTI) study with American students, Schlegel, Rudelson and Tse (2012) demonstrated that an intensive nine-month Chinese language course of 7.5 hours a week was sufficient to lead to significant anatomical changes. Greater fractional anisotropy (FA) values were observed in learners in comparison to control participants who did not learn Chinese within the same period. Critically, FA slope changes correlated positively with the amount of Chinese learned by the trained group, which suggests that the structural changes were directly associated with language performance. These findings indicate that after only 9-months of training, and even in adult late learners of an L2, a WM reorganization can be observed in response to L2 learning, at least for vocabulary learning. However, a shortcoming in the Schlegel et al. (2012) study, but also more generally in most sMRI studies on induced neuroplasticity in L2 vocabulary learning, is that the study was cross-sectional. Unfortunately, only very few studies in the literature have investigated to what extent the longitudinal effects of L2 learning and individual differences in performance could be correlated with structural brain changes.

Recently, in order to address this gap in the literature, Legault et al. (2019a) examined the time course of brain changes as a result of individual differences across two semesters of L2 Spanish classroom learning. Using a longitudinal sMRI⁵ methodology, the authors showed that L2 lexical development is associated with functional and structural changes in brain regions that are important for cognitive control and semantic processing. Legault et al. (2019a) reported a post L2 learning CT increase in the left anterior cingulate cortex, a brain region known to be involved in bilingual language control, and in particular in conflict monitoring (see Abutalebi & Green, 2008; Bedoin, Abadie, Krzonowski, Ferragne, & Marcastel, 2019; Green & Abutalebi, 2013; Heidlmayr, Hemforth, Moutier, & Isel, 2015). Abutalebi et al. (2012) showed in an sMRI study that increased conflict monitoring ability is associated with decreased functional activity and increased GMV in the anterior cingulate cortex. Moreover, Legault et al. (2019a) also found a CT increase in the right middle temporal gyrus, a brain region posited to be a semantic processing 'hub' needed for processing lexical and conceptual semantic information (Binder & Desai, 2011; Hernandez, Woods, & Bradley, 2015; Rodríguez-Fornells et al., 2009).

Crucially, L2 learners who were better able to discriminate between native language and L2 words presented increased CT in the right middle

⁵ Longitudinal sMRI approaches are particularly relevant when inferring causal relationships between L2 experience and subsequent brain structure changes.

temporal gyrus. Finally, Legault et al. reported that CT in the left anterior cingulate cortex was correlated with functional connectivity between the anterior cingulate cortex and middle temporal gyrus. Consistently, in a previous fMRI connectivity study on the same L2 learning participants as in the Legault et al. (2019a) study, Grant, Fang, and Li (2015) reported changes in a functional network including the bilateral anterior cingulate cortex, caudate nucleus, inferior frontal gyrus, middle frontal gyrus, and middle temporal gyrus. Taken together, the sMRI data of Legault et al. (2019a) support the hypothesis that L2 learning induces structural brain changes corresponding to a functional connectivity network involved in L2 processing. Moreover, their data indicate that the observed structural changes are correlated with individual differences in L1 and L2 performance and experience.

All together, their findings provide considerable support for the idea that effective L2 learners' lexical development relies on the contribution of cognitive control and semantic networks. Previously, the dialogue between these two networks in the bilingual brain was captured in the Convergence Hypothesis (CH) model formulated by Green (2003), and Green, Crinion, and Price (2006).

This neurofunctional model was designed to account for L1 and L2 lexical processing in adult L2 learners. The CH model is particularly relevant to the issue of the contribution of cognitive control and semantic networks as it discusses not only the language networks activated in L2 processing but also the relationships between the separate brain areas thought to support lexical processing and executive functioning, respectively. The CH model predicts greater activation in cognitive control regions for L2 versus L1 lexical processing in the early L2 learning stage, with decreasing dependency on cognitive control and re-focused resources on a language network during proficient, late-stage L2 learning. A recent longitudinal functional connectivity study conducted by Grant et al. (2015) lends support to the CH model. The authors showed that adult L2 Spanish learners relied on language and cognitive control networks for the early stages of L2 learning, and switched to relying more on semantic processing regions during later learning stages. Previous fMRI studies in L1 already pointed out the important role of the executive control function in accounting for the lexical competition occurring during visual word recognition, in particular as illustrated by the orthographic neighborhood effect (Fiebach, Ricker, Friederici, & Jacobs, 2007).

We now return to recent neuroimaging studies that have reported structural brain changes induced by short-term L2 training. Mårtensson et al. (2012) found neuroplastic changes after only three months of an intensive ten-month language training program. The authors reported that training consisting of learning vocabulary and idioms (roughly 300 to 500

items weekly) in preparation for a career as a military interpreter led to increased CT in the left inferior frontal gyrus, left middle frontal gyrus, and left superior temporal gyrus, as well as increased right hippocampal volume in comparison with a control group matched for age and cognitive abilities. Interestingly, Xiang et al. (2012), in a structural connectivity study using diffusion tensor imaging (DTI), showed that WM microstructure in tracts that connect language regions such as the inferior temporal gyrus and superior temporal gyrus tended to increase with L2 experience or with AoA. However, Elmer, Hänggi, and Jäncke (2014) warned that the activity of interpreters is a peculiar form of bilingualism. They reported data suggesting that the linguistic experience acquired by interpreters is probably not comparable with that acquired by bilinguals. In a number of language and control brain regions and tracts, Elmer et al. (2014) counter-intuitively found a smaller GM volume and lower WM integrity in the professional simultaneous interpreters with a varying number of years of interpreting experience than in multilingual controls. In fact, GM volume in the right inferior frontal gyrus pars opercularis, left inferior frontal gyrus pars triangularis, middle anterior cingulate cortex, and bilateral caudate nucleus negatively correlated with the cumulative number of years interpreting. Elmer et al. (2014) speculated that the neuroanatomical differences observed between interpreters and multilinguals could be due to the mode of acquisition of the L2, as multilinguals usually have more time to learn, while interpreters undergo intensive training in classroom-based learning programs. The effect of the mode of acquisition on brain structures should be studied more thoroughly in future research. Another factor that may have played a role is the age at which participants started learning foreign languages. While interpreters started on average at the age of 29 (25 to 30), bilinguals were most often introduced to foreign languages between the ages of 8 and 14.

Impressively, with respect to the time of training able to produce neural changes, a study by Kwok et al. (2011) suggested that very rapid changes in GM volumes can be observed after only an intensive two-hour learning period of four monosyllabic color names (five study sessions, each lasting 20 minutes on average). Increased GM volume was found in the V 2/3 of the left visual cortex, a region known to mediate color vision. However, this finding must be contextualized before drawing from conclusions on the effect of short-term training when learning new words, as Kwok et al. (2011) used a simplified linguistic task that cannot be directly compared with a real language learning task. Nevertheless, one cannot ignore the fact that these results are perhaps the most rapidly produced structural change reported so far in the language domain.

In addition to the effect of training duration on neural changes, the study of L2 learning through a training paradigm raises another important question – whether there is direct correlation/relation between the duration of training and the duration of learning effects. In other words,

does short-term training yield only transient effects, and the shorter the training, the more quickly the effect wears off, and conversely, are more long-lasting effects due only to long-term experiences, such as years of language training? One way to answer this question in the laboratory is to systematically retest participants several months after the end of training to assess their L2 performances. Unfortunately, to the best of our knowledge, few studies have carried out such systematic retesting a few months later in order to determine the degree of entrenchment of the L2 vocabulary in long-term semantic memory.

These results suggest that even in a laboratory setting, L2 learning may shape neural structures, and that regular L2 use and practice is critical for the maintenance of these benefits. Another factor may partly explain the greater or lesser maintenance of training effects on brain structures, namely the type of learner (successful or less successful learners). Wong et al. (2008) provided some evidence that structural changes vary as a function of the type of learner. The authors studied data from adult monolingual English speakers learning pseudowords with pictures and reported that a larger GM volume was specifically observed in part of the primary auditory cortex, the left Heschl's Gyrus, when vocabulary training involved auditory variation of pitches conveying meaning, as in a tonal language like Chinese. The performance on the word-pitch mapping task correlated positively with GM and WM volume in the left Heschl's Gyrus. Importantly, the effects reported by Wong et al. (2007) were larger in "successful" (behavioral performance greater than a prefixed criterion of 95%) than in "less successful" learners. As mentioned earlier, Wong et al. (2007) already showed in a functional MRI study using the same performance criterion of 95%, that successful learners exhibited more focused activation in the left superior temporal gyrus, a brain area crucial for phonological processing, whereas the less successful learners were characterized by a more diffuse activation in the frontal and temporal cortical regions. Moreover, the authors reported that the two groups also showed differences in activation patterns even before learning, which directly questions the L2 learning aptitude issue.

In addition to the structural changes usually observed in the brain at the macrostructural level, Luo et al. (2019) recently investigated microstructural plasticity in the bilingual brain in a combined quantitative MRI (qMRI) and MRI (fMRI) approach. The authors aimed to quantify the microstructural properties of the brain and to test whether second language learning modulated the microstructure in the bilingual brain. They found significant microstructural variations related to age of L2 acquisition in the left inferior frontal region and the left fusiform gyrus. Interestingly, these two brain areas are known to be crucial for resolving lexical competition between bilinguals' two languages. Based on their data, Luo et al. (2019) concluded that early second language acquisition also contributes to enhancing cortical development at the microstructural level.

The role of learning context: Immersion learning, virtual environment, and the traditional classroom

In addition to the question of the duration of learning or the type of learners, as discussed above, another factor likely to play a determining role in L2 learning is the learning context. There are different types of learning context, such as immersion learning, a virtual environment, or a traditional classroom. Different learning contexts are likely to give rise to different outcomes of learning and memory, and the corresponding functional and structural changes. Recent neuroimaging studies addressed the impact of learning context on neuroanatomical changes and L2 learning performances, examining whether neuroanatomical changes would differ depending on whether individuals learn in a classroom setting, immersed in a realistic language context or in a virtual context.

In a structural MRI study, Stein et al. (2012) investigated the role of immersion by studying the brain structure characteristics of college students who spent five months in Switzerland learning German. The authors reported increased GM volume in the left inferior frontal gyrus and the left anterior temporal lobe, two areas that are implicated in lexical access and semantic integration. However, the absence of a non-immersed control group (classroom learning) is an important limitation of this study, and prevents one from drawing conclusions about the potential benefit of immersion learning compared to classroom learning. In addition to the fact that immersion learning enables the learners to interact with native speakers of the target language, it presents the benefit of providing a context involving a high degree of perceptual and sensorimotor integration, as discussed in embodied cognition theories (see Barsalou, 2008). Under the assumption that L2 learning is reinforced by embodied information, laboratory technology such as immersive virtual reality (iVR) would be expected to have significant implications for L2 learning (for a recent review, see Li, Legault, Klippel, & Zhao, 2020). Therefore, one can reasonably predict that more embodied experiences, such as immersion and virtual environments, should lead to longer lasting brain effects, as well as better learning outcomes.

In a recent study using virtual environment technology, Legault et al. (2019a) examined changes in CT and GM in relation to the context of training type. The study compared structural changes when learning with paired picture-word (PW) association to learning within virtual environments (VE) and to non-trained controls. The PW group were presented with black and white line drawings of the items to be learned, while the VE group was able to learn by moving their avatar through a 3D simulated space. Seven training sessions over approximately 20 days were administered to these two L2 training groups, during which the participants had to learn the same 90 Mandarin Chinese words

comprising items in three semantic categories, the zoo, the supermarket, or the kitchen. L2 training performance was assessed by accuracy and reaction time during a 4AFC (four alternative forced-choice) recognition task at the end of each training session. Retention tests (a 4AFC recognition task of all 90 L2 words) were administered three and six weeks after training was over. The results showed that CT and GMV increased in regions implicated in a language control network for both L2 training groups. Critically, the brain changes induced by the two learning contexts relied on different structures within this language control network. CT in the right inferior frontal gyrus was associated with L2 training performance for the PW group, whereas CT in the right inferior parietal lobule showed a positive correlation with L2 training performance for the VE group. Unfortunately, the authors failed to provide a straightforward functional explanation to account for the differentiated neuroanatomical activation as a function of the learning context.

In a recent behavioral study, Legault et al. (2019a) investigated individual differences in L2 performance during the learning of 60 Mandarin Chinese words across two learning sessions, with each participant learning 30 words in immersive Virtual Reality (iVR) and 30 words via a traditional classroom-based method consisting of word–word (WW) paired associations between L2 and L1. Behavioral performance was collected immediately after L2 learning via an alternative forced-choice recognition task. The authors showed that learning via iVR compared to WW association learning provided a benefit as indicated by the significantly higher accuracy in the recognition task. Critically, the main effect of the learning context was only observed in less successful learners (recognition performance < 80%), who showed a significant benefit of iVR. In contrast, successful learners (recognition performance > 80%) did not show a significant benefit of either learning condition. To account for this inter-group difference, the authors suggested that less successful learners need an enriched environment that enhances embodied experiences much more in order to learn new words. On the other hand, one cannot exclude that the absence of benefit found in the highest L2 performers may perhaps reflect a natural predisposition and aptitude towards L2 learning in these individuals. This new technology should be used in further combined fMRI and sMRI longitudinal studies in order to better understand the mechanisms of L2 learning.

The recent sMRI studies which have investigated structural changes as a function of the learning context offer a promising avenue. However, more longitudinal MRI studies should be conducted in order to compare different learning contexts with a systematic retest of vocabulary performance several months after the end of training.

Finally, before concluding we question whether the data in functional brain activity for L2 learning are consistent with the observed anatomical data. As research into structural brain changes induced by L2 learning is

a relatively emerging axis in SLA cognitive neuroscience, only a few studies have directly compared functional neural patterns with structural brain data within the same experiments (for an overview, see Li et al. 2014, 2020). We briefly summarize the main results of the studies that have compared functional and structural brain data for L2 learning.

Based on reviews and meta-analyses of structural neuroimaging data (see Legault et al. 2019b; Li et al. 2014), GM volume increases were reported in response to different modes of L2 learning (natural setting, formal instruction, or lab training) in various cortical and subcortical areas including the inferior frontal gyrus, the middle frontal gyrus, superior temporal gyrus, anterior temporal lobe, inferior parietal lobule, all in the left hemisphere, the cerebellum and the hippocampus in the right hemisphere, and the caudate nucleus mostly in the left hemisphere but in some cases bilaterally. Interestingly, in the functional neuroimaging literature, almost all of these key brain areas for L2 learning have been shown to be crucial in the neurobiology of language, especially for language learning or processing (for a review, see Price, 2010, among others). Therefore, it is not surprising to report increased GM as a function of L2 experience in all these areas. Importantly, the combination of behavioral performance data and functional and structural imaging data in second language vocabulary acquisition allows us to run three-way comparisons and correlations in order to identify more likely, direct relationships between L2 experiences and structural-functional brain adaptations, as well as behavioral consequences in terms of language performances. A related question is whether changes in GM volume, CT, and WM integrity co-occur or co-localize.

Only a few structural MRI studies provide partial answers to this complex question of correspondences within the structural data (GM volume, WM integrity, and CT), as most studies so far focus on only one of the three types of measures. Some studies support an independence between GM and WM changes as suggested by Gold, Johnson, and Powell (2013), who failed to show GM volume changes between bilinguals and monolinguals even when changes in WM integrity were significant between the two groups. In contrast, the data in Golestani, Molko, Dehaene, LeBihan, and Pallier (2007) argue in favor of a correspondence between the measures of structural changes. The authors showed that increased GM volume in a region anterior to the left parieto-occipital sulcus was accompanied by decreased WM density in that region. Consistently with the data of Golestani et al. (2007), GM-WM correspondence was also found in Hosoda et al. (2013) in Japanese learners of English. Specifically, these authors showed increased GM volumes in a number of regions including the inferior frontal gyrus, caudate nucleus, and superior temporal gyrus/supramarginal gyrus after training; importantly, the GM changes corresponded with the patterns of WM connectivity between the right inferior temporal gyrus with the caudate nucleus and with the superior temporal gyrus/supramarginal

gyrus.

5. Conclusions and perspectives

This article provides a review of emerging evidence regarding how functional and structural neuroplasticity occurs in the brain as a result of bilingual experience during L2 vocabulary learning. Functional and structural magnetic resonance imaging data collected in the past 30 years show language experience-dependent alteration in both the macrostructure and the microstructure of the brain. More specifically, the consistent picture emerging from sMRI is that significant anatomical changes in terms of increased GM volume, increased CT, or enhanced WM tract connectivity can be found even after short-term learning, and not only as a result of lifelong experience with two languages. This observation reinforces the idea that the brain is malleable enough to adapt continuously and rapidly in response to cognitive demands such as learning a new language. However, the question of the conditions of training/learning, which could lead to a stabilized state following such brain reorganization will need to be studied longitudinally.

Most studies of second language vocabulary acquisition have focused on morphologically simple words. Little is known about the effect of formal relations such as the morphological relation between lexical units in the lexicon on L2 vocabulary learning. In the context of lexical morphology, it would be particularly relevant to better understand how typological relations between L1 and L2 can speed up or slow down the learning of L2 words. Beyond the linguistic relevance of discussing the role of lexical morphology in SLA, it would be very interesting for scholars investigating the organization of the mental lexicon to better understand which brain network underlies the cognitive network linking lexical units that share morphological properties.

Future studies should adopt a longitudinal approach and compare different learning contexts (classical word-word or word-picture associations, Virtual Reality (VR) and immersive VR) in order to capture the neuroanatomical changes induced by L2 learning. Further experimental studies in laboratory settings could test precisely what amount and type of L2 linguistic experience can affect neural patterns of response causally. Furthermore, we need to better understand how different indicators of structural changes interact and to what extent structural changes correlate with functional changes.

Moreover, although lexical access is one of the fundamental processing stages in the semantic-pragmatic interpretation of a sentence, more studies will be necessary to better understand to what extent learning the grammar of an L2 may impact neuroplasticity. All these studies using MRI could be completed by electroencephalography (EEG), and in particular, neural oscillations, to investigate changes in

language networks during SLA.

Finally, the issue of neuroplastic changes induced by the foreign language could also be addressed in future studies from the perspective of learning an L3. The cohabitation of three probably coactivated languages in the same brain but with different levels of linguistic dominance (see Birdsong, 2018) would lead to new questions about both linguistic and language control systems, and their interplay during foreign language acquisition.

References

- Abutalebi, J., Della Rosa, P.A., Green, D.W., Hernandez, M., Scifo, P., Keim, R., ... Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex*, *22*(9), 2076–2086. <https://doi.org/10.1093/cercor/bhr287>
- Abutalebi, J., & Green, D.W. (2008). Control mechanisms in bilingual language production: Neural evidence from language switching studies. *Language and Cognitive Processes*, *23*, 557–582. <https://doi.org/10.1080/01690960801920602>
- Assaf, Y., & Pasternak, O. (2008). Diffusion tensor imaging (DTI)-based white matter mapping in brain research: A review. *Journal of Molecular Neuroscience*, *34*(1), 51–61. <https://doi.org/10.1007/s12031-007-0029-0>
- Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829–839. <https://doi.org/10.1038/nrn1201>
- Barsalou, L.W. (2008). Grounded cognition. *Annual Review of Psychology*, *59*, 617–45. <https://doi.org/10.1146/annurev.psych.59.103006.093639>
- Bedoin, N., Abadie, R., Krzonowski, J., Ferragne, E., & Marcastel, A. (2019). A combined forced-attention dichotic listening – go/nogo task to assess response inhibition and interference suppression: An auditory event-related potential investigation. *Neuropsychology*, *33*(8), 1136–1150. <https://doi.org/10.1037/neu0000586>
- Binder, J.R., & Desai, R.H. (2011). The neurobiology of semantic memory. *Trends in Cognitive Science*, *15*(11), 527–536. <https://doi.org/10.1016/j.tics.2011.10.001>
- Birdsong, D. (2018). Plasticity, variability and age in second language acquisition and bilingualism. *Frontiers in Psychology*, *9*:81. <https://doi.org/10.3389/fpsyg.2018.00081>
- Blanco-Elorrieta, E., Emmorey, K., & Pylkkänen, L. (2018). Language switching decomposed through MEG and evidence from bimodal bilinguals. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(39), 9708–9713. <https://doi.org/10.1073/pnas.1809779115>
- Breitenstein, C., Jansen, A., Deppe, M., Foerster, A.-F., Sommer, J., Wolbers, T., et al. (2005). Hippocampus activity differentiates good from poor learners of a novel lexicon. *NeuroImage*, *25*(3), 958–968. <https://doi.org/10.1016/j.neuroimage.2004.12.019>
- Brodman, K. (1909). Beiträge zur histologischen Lokalisation der Grosshirnrinde. VI. Die Cortexgliederung des Menschen. *Journal of Psychology and Neurology*, *10*, 231–246.
- Chung, M.K., Dalton, K.M., Shen, L., Evans, A.C., & Davidson, R.J. (2006). *Unified cortical surface morphometry and its application to quantifying amount of gray matter*. Technical report No. 1122. Department of Statistics, U. of Wisconsin-Madison.
- Costa, A., & Sebastián-Gallés, N. (2014). How does the bilingual experience sculpt

- the brain? *Nature Reviews Neuroscience*, 15(5), 336–345.
<https://doi.org/10.1038/nrn3709> Cummine, J., & Boliek, C.A. (2013). Understanding white matter integrity stability for bilinguals on language status and reading performance. *Brain Structure & Function*, 218(2), 595–601.
<https://doi.org/10.1007/s00429-012-0466-6>
- Della Rosa, P.A., Videsott, G., Borsa, V.M., Canini, M., Weekes, B.S., Franceschini, R., et al. (2013). A neural interactive location for multilingual talent. *Cortex*, 49(2), 605–608. <https://doi.org/10.1016/j.cortex.2012.12.001>
- Dewaele, J.-M. (2009). Individual differences in second language acquisition. In W.C. Ritchie & T.K. Bhatia (Eds.), *The new handbook of second language acquisition* (pp. 623–646). Bingley: Emerald Group Publishing Limited.
- Elmer, S., Hänggi, J., & Jäncke, L. (2014). Processing demands upon cognitive, linguistic, and articulatory functions promote grey matter plasticity in the adult multilingual brain: Insights from simultaneous interpreters. *Cortex*, 54, 179–189.
<https://doi.org/10.1016/j.cortex.2014.02.014>
- Fiebach, C.J., Friederici, A.D., Müller, K., & von Cramon, D.Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience*, 14, 11–23. <https://doi.org/10.1162/089892902317205285>
- Fiebach, C.J., Ricker, B., Friederici, A.D., & Jacobs, A.M. (2007). Inhibition and facilitation in visual word recognition: Prefrontal contribution to the orthographic neighborhood size effect. *NeuroImage*, 36, 901–911.
<https://doi.org/10.1016/j.neuroimage.2007.04.004>
- Filler, A. (2009). MR neurography and diffusion tensor imaging: Origins, history & clinical impact of the first 50,000 cases with an assessment of efficacy and utility in a prospective 5,000 patient study group. *Neurosurgery*, A29–A43.
<https://doi.org/10.1227/01.NEU.0000351279.78110.00>
- Fischl, B., & Dale, A.M. (2000). Measuring the thickness of the human cerebral cortex from magnetic resonance images. *Proceedings of the National Academy of Sciences*, 97(20), 11050–11055.
<https://doi.org/10.1073/pnas.200033797>
- Friederici, A.D. (2011). The brain basis of language processing: From structure to function. *Physiological Reviews*, 91, 1357–1392.
<https://doi.org/10.1152/physrev.00006.2011>
- Friston, K.J., Frith, C.D., Liddle, P.F., & Frackowiak, R.S.J. (1993). Functional connectivity: The principal component analysis of large (PET) data sets. *Journal of Cerebral Blood Flow and Metabolism*, 13, 5–14.
<https://doi.org/10.1038/jcbfm.1993.4>
- Garcia-Penton, L., Perez, F.A., Iturria-Medina, Y., Gillon-Dowens, M., & Carreiras, M. (2014). Anatomical connectivity changes in the bilingual brain. *NeuroImage*, 84, 495–504. <https://doi.org/10.1016/j.neuroimage.2013.08.064>
- Gates, K.M., Molenaar, P., Hillary, F.G., Ram, N., & Rovine, M.J. (2010). Automatic search for fMRI connectivity mapping: An alternative to Granger causality testing using formal equivalences among SEM path modeling, VAR, and unified SEM. *NeuroImage*, 50, 1118–1125.
<https://doi.org/10.1016/j.neuroimage.2009.12.117>
- Godel, R. (1957). *Les sources manuscrites du Cours de linguistique générale de F. de Saussure*, Genève: Droz.
- Gold, B.T., Johnson, N.F., & Powell, D.K. (2013). Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. *Neuropsychologia*, 51(13), 2841–2846.

- <https://doi.org/10.1016/j.neuropsychologia.2013.09.037>
- Golestani, N., Molko, N., Dehaene, S., LeBihan, D., & Pallier, C. (2007). Brain structure predicts the learning of foreign speech sounds. *Cerebral Cortex*, *17*(3), 575–582. <https://doi.org/10.1093/cercor/bhk001>
- Grant, A., Fang, S.Y., & Li, P. (2015). Second language lexical development and cognitive control: A longitudinal fMRI study. *Brain and Language*, *144*, 35–47.
<https://doi.org/10.1016/j.bandl.2015.03.010>
- Green, D.W. (2003). Neural basis of lexicon and grammar in L2 acquisition: The convergence hypothesis. In R. van Hout, A. Hulk, F. Kuiken, & R. Towell (Eds.). *The interface between syntax and the lexicon in second language acquisition* (pp. 197–208). Amsterdam: John Benjamins. <https://doi.org/10.1075/lald.30.10gre>
- Green, D.W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*, 515–530.
<https://doi.org/10.1080/20445911.2013.796377>
- Green, D.W., Crinion, J., & Price, C.J. (2006). Convergence, degeneracy and control. *Language Learning*, *56*(S1), 99–125.
<https://doi.org/10.1111/j.1467-9922.2006.00357.x>
- Grogan, A., Jones, O.P., Ali, N., Crinion, J., Orabona, S., Mechias, M.L., et al. (2012). Structural correlates for lexical efficiency and number of languages in non-native speakers of English. *Neuropsychologia*, *50*(7), 1347–1352.
<https://doi.org/10.1016/j.neuropsychologia.2012.02.019>
- Heidlmayr, K., Hemforth, B., Moutier, S., & Isel, F. (2015). Neurodynamics of executive control processes in bilinguals: Evidence from ERP and source reconstruction analyses. *Frontiers in Psychology*, *6*:821.
<https://doi.org/10.3389/fpsyg.2015.00821>
- Hernandez, A.E. (2013). *The bilingual brain*. Oxford, UK: Oxford University Press.
<https://doi.org/10.1093/acprof:oso/9780199828111.001.0001>
- Hernandez, A.E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish-English bilinguals: An fMRI study. *Neuroimage*, *14*, 510–520. <https://doi.org/10.1006/nimg.2001.0810>
- Hernandez, A.E., & Li, P. (2007). Age of acquisition: Its neural and computational mechanisms. *Psychological Bulletin*, *133*(4), 638–650.
<https://doi.org/10.1037/0033-2909.133.4.638>
- Hernandez, A.E., Woods, E.A., & Bradley, K.A.L. (2015). Neural correlates of single word reading in bilingual children and adults. *Brain and Language*, *143*, 11–19.
<https://doi.org/10.1016/j.bandl.2015.01.010>
- Hickok, G. (2009). The functional neuroanatomy of language. *Physics of Life Reviews*, *6*(3), 121–143. <https://doi.org/10.1016/j.plrev.2009.06.001>
- Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, *8*(5), 393–402.
<https://doi.org/10.1038/nrn2113>
- Hosoda, C., Tanaka, K., Nariai, T., Honda, M., & Hanakawa, T. (2013). Dynamic neural network reorganization associated with second language vocabulary acquisition: A multimodal imaging study. *Journal of Neuroscience*, *33*(34), 13663–13672.
<https://doi.org/10.1523/JNEUROSCI.0410-13.2013>
- Isel, F., Baumgaertner, A., Thrän, J., Meisel, J.M., & Büchel, C. (2010). Neural

- circuitry of the bilingual mental lexicon: Effect of age of second language acquisition. *Brain and Cognition*, 72, 169–180.
<https://doi.org/10.1016/j.bandc.2009.07.008>
- Isel, F., Gunter, T.C., & Friederici, A.D. (2003). Prosody-assisted head-driven access to spoken German compounds. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29(2), 277–288.
- Isel, F., & Shen, W. (2020). Perception of lexical neutral tones in Mandarin compounds: Electroencephalographic evidence from an oddball paradigm. *Neuropsychologia*, 147, 107557.
<https://doi.org/10.1016/j.neuropsychologia.2020.107557>
- Kim, J., Zhu, W., Chang, L., Bentler, P.M., & Ernst, T. (2007). Unified structural equation modeling approach for the analysis of multisubject, multivariate functional MRI data. *Human Brain Mapping*, 28, 85–93.
<https://doi.org/10.1002/hbm.20259>
- Klein, D., Mok, K., Chen, J.-K., & Watkins, K.E. (2013). Age of language learning shapes brain structure: a cortical thickness study of bilingual and monolingual individuals. *Brain and Language*, 131, 20–24.
<https://doi.org/10.1016/j.bandl.2013.05.014>
- Kroll, J.F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language*, 33, 149–174.
<https://doi.org/10.1006/jmla.1994.1008>
- Kwok, V., Niu, Z., Kay, P., Zhou, K., Mo, L., Jin, Z., et al. (2011). Learning new color names produces rapid increase in gray matter in the intact adult human cortex. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, 108(16), 6686–6688.
<https://doi.org/10.1073/pnas.1103217108>
- Lee, H., Devlin, J.T., Shakeshaft, C., Stewart, L.H., Brennan, A., & Glensman, J. (2007). Anatomical traces of vocabulary acquisition in the adolescent brain. *Journal of Neuroscience*, 27(5), 1184–1189.
<https://doi.org/10.1523/JNEUROSCI.4442-06.2007>
- Legault, J., Fang, S-Y, Lan, Y.-J., & Li, P. (2019a). Structural brain changes as a function of second language vocabulary training: Effects of learning context. *Brain and Cognition*, 134, 90–102. <https://doi.org/10.1016/j.bandc.2018.09.004>
- Legault, J., Zhao, J., Chi, Y.-A., Chen, W., Klippel, A., & Li, P. (2019b). Immersive virtual reality as an effective tool for second language vocabulary learning. *Languages*, 4(13), 1–132. <https://doi.org/10.3390/languages4010013>
- Lenneberg, E.H. (1967). *Biological foundations of language*. Wiley.
- Li, P., Legault, J., Klippel, A., & Zhao, J. (2020). Virtual reality for student learning: Understanding individual differences. *Human Behaviour and Brain*, 1(1), 28–36. <https://doi.org/10.37716/HBAB.2020010105>
- Li, P., Legault, J., & Litcofsky, K.A. (2014). Neuroplasticity as a function of second language learning: anatomical changes in the human brain. *Cortex*, 58, 301–324.
<https://doi.org/10.1016/j.cortex.2014.05.001>
- Luo, D., Kwok, V.P.Y., Liu, Q., Li, W., Yang, Y., Zhou, K., Xu, M., Gao, J.-H., & Tan, L.H. (2019). Microstructural plasticity in the bilingual brain. *Brain and Language*, 196, 1–9. <https://doi.org/10.1016/j.bandl.2019.104654>
- Mårtensson, J., Eriksson, J., Bodammer, N.C., Lindgren, M., Johansson, M., Nyberg, L., et al. (2012). Growth of language-related brain areas after foreign language learning. *NeuroImage*, 63(1), 240–244.

<https://doi.org/10.1016/j.neuroimage.2012.06.043>

Mechelli, A., Crinion, J.T., Noppeney, U., O'Doherty, J.P., Ashburner, J., Frackowiak, R.S., et al. (2004). Structural plasticity in the bilingual brain: proficiency in a second language and age at acquisition affect grey-matter density. *Nature*, *431*(7010), 757.

<https://doi.org/10.1038/431757a>

Mei, L., Chen, C., Xue, G., He, Q., Li, T., Xue, F., et al. (2008). Neural predictors of auditory word learning. *Neuroreport*, *19*(2), 215–219.

<https://doi.org/10.1097/WNR.0b013e3282f46ea9> Milad, M.R., Quinn, B.T., Pitman, R.K., Orr, S.P., Fischl, B., & Rauch, S.L. (2005). Thickness of ventromedial prefrontal cortex in humans is correlated with extinction memory. *Proceedings of the National Academy of Sciences of the United States of America*, *102*, 10706–10711.

<https://doi.org/10.1073/pnas.0502441102>

Penfeld, W., & Roberts, L. (1959). *Speech and brain mechanisms*. Princeton: Princeton University Press. <https://doi.org/10.1515/9781400854677>

Poline, J.-B., Vandenberghe, R., Holmes, A.P., Friston, K.J., & Frackowiak, R.S.J. (1996). Reproducibility of PET activation studies: Lessons from a multi-center European experiment: EU concerted action on functional imaging? *NeuroImage*, *4*(1), 34–54. <https://doi.org/10.1006/nimg.1996.0027>

Price, C.J. (2010). The anatomy of language: a review of 100 fMRI studies published in 2009. *Annals of the New York Academy of Sciences*, *1191*(1), 62–88.

<https://doi.org/10.1111/j.1749-6632.2010.05444.x>

Price, C.J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage*, *62*, 816–847.

<https://doi.org/10.1016/j.neuroimage.2012.04.062>

Purves, D., Augustine, G.J., Fitzpatrick, D., Hall, W.C., LaMantia, A.S., McNamara, J.O., & White, L.E. (2008). *Neuroscience* (4th ed.). Sunderland, MA: Sinauer Associates. pp. 15–16.

Reiterer, S., Pereda, E., & Bhattacharya, J. (2011). On a possible relationship between linguistic expertise and EEG gamma band phase synchrony. *Frontiers in Psychology*, *2*, 1–11. <https://doi.org/10.3389/fpsyg.2011.00334>

Richardson, F.M., & Price, C.J. (2009). Structural MRI studies of language function in the undamaged brain. *Brain Structure & Function*, *213*(6), 511–523.

<https://doi.org/10.1007/s00429-009-0211-y>

Rodríguez-Fornells, A., Cunillera, T., Mestres-Missé, A., & de Diego-Balaguer, R. (2009). Neurophysiological mechanisms involved in language learning in adults. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *364*(1536), 3711–3735.

<https://doi.org/10.1098/rstb.2009.0130>

Schlegel, A.A., Rudelson, J.J., & Tse, P.U. (2012). White matter structure changes as adults learn a second language. *Journal of Cognitive Neuroscience*, *24*(8), 1664–1670. https://doi.org/10.1162/jocn_a_00240

Schumann, J. (2004). The neurobiology of aptitude. In J. Schumann, S.E. Crowell, N.E. Jones, N. Lee, S.A. Schuchert, & L.A. Wood (Eds.), *The neurobiology of learning. Perspectives from second language acquisition* (pp. 7–21). Mahwah, NJ: Erlbaum.

Segui, J. (1992). Le lexique mental et l'identification des mots écrits: code d'accès et rôle du contexte. *Langue Française*, *95*, 69–79.

<https://doi.org/10.3406/lfr.1992.5772>

- Segui, J. (2015). Évolution du concept de lexique mental. *Revue de Neuropsychologie*, 7(1), 21–6. <https://doi.org/10.3917/rne.071.0021>
- Squire, L.R. (1992). Memory and the hippocampus: a synthesis from findings with rats, monkeys, and humans. *Psychological Review*, 99, 195–231. <https://doi.org/10.1037/0033-295X.99.2.195>
- Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., Wiest, R., ... Dierks, T. (2012). Structural plasticity in the language system related to increased second language proficiency. *Cortex*, 48(4), 458–465. <https://doi.org/10.1016/j.cortex.2010.10.007>
- Thompson-Schill, S.L., D'Esposito, M., Aguirre, G.K., & Farah, M.J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences*, 94(26), 14792–14797. <https://doi.org/10.1073/pnas.94.26.14792>
- Veroude, K., Norris, D.G., Shumskaya, E., Gullberg, M., & Indefrey, P. (2010). Functional connectivity between brain regions involved in learning words of a new language. *Brain and Language*, 113(1), 21–27. <https://doi.org/10.1016/j.bandl.2009.12.005>
- Warburton, E., Wise, R.J.S., Price, C.J., Weiller, C., Hadar, U., Ramsay, S., & Frackowiak, R.S.J. (1996). Noun and verb retrieval by normal subjects. Studies with PET. *Brain*, 119, 159–179. <https://doi.org/10.1093/brain/119.1.159>
- Wartenburger, I., Heekeren, H.R., Abutalebi, J., Cappa, S.F., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron*, 37, 159–170. [https://doi.org/10.1016/S0896-6273\(02\)01150-9](https://doi.org/10.1016/S0896-6273(02)01150-9)
- Weber-Fox, C.M., & Neville, H.J. (1996). maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience* 8(3), 231–256. <https://doi.org/10.1162/jocn.1996.8.3.231>
- Weber-Fox, C., & Neville, H.J. (1999). Functional neural subsystems are differentially affected by delays in second-language immersion: ERP and behavioral evidence in bilingual speakers. In D. Birdsong (Ed.), *New perspectives on the critical period for second language acquisition* (pp. 23–38). Hillsdale NJ: Lawrence Erlbaum.
- Wong, P.C.M., Perrachione, T.K., & Parrish, T.B. (2007). Neural characteristics of successful and less successful speech and word learning in adults. *Human Brain Mapping*, 1006, 995–1006. <https://doi.org/10.1002/hbm.20330>
- Wong, P.C.M., Warrier, C.M., Penhune, V.B., Roy, A.K., Sadegh, A., Parrish, T.B., et al. (2008). Volume of left Heschl's gyrus and linguistic pitch learning. *Cerebral Cortex*, 18(4), 828–836. <https://doi.org/10.1093/cercor/bhm115>
- Xiang, H., Dediu, D., Roberts, L., van Oort, E., Norris, D.G., & Hagoort, P. (2012). The structural connectivity underpinning language aptitude, working memory, and IQ in the perisylvian language network. *Language Learning*, 62(Suppl. 2), 110–130. <https://doi.org/10.1111/j.1467-9922.2012.00708.x>
- Yang, J., Gates, K.M., Molenaar, P., & Li, P. (2015). Neural changes underlying successful second language word learning: An fMRI study. *Journal of Neurolinguistics*, 33, 29–49. <https://doi.org/10.1016/j.jneuroling.2014.09.004>
- Yang, J., & Li, P. (2012). Brain networks of explicit and implicit learning. *PLoS One*, 7(8), e42993. <https://doi.org/10.1371/journal.pone.0042993>

Zhang, L., Xi, J., Xu, G., Shu, H., Wang, X., & Li, P. (2011). Cortical dynamics of acoustic and phonological processing in speech perception. *PLoS ONE*, 6(6), e20963.

<https://doi.org/10.1371/journal.pone.0020963>

Zou, L., Ding, G., Abutalebi, J., Shu, H., & Peng, D. (2012). Structural plasticity of the left caudate in bimodal bilinguals. *Cortex*, 48(9), 1197–1206.

<https://doi.org/10.1016/j.cortex.2011.05.022>

Online appendix

The figure and tables in this article can be found in the online appendix at:
<https://doi.org/10.1075/lia.20023.ise.appendix>

Résumé

Cet article passe en revue une série d'études d'imagerie par résonance magnétique (IRM) fonctionnelles et structurales, centrées sur la neuroplasticité de l'acquisition du vocabulaire dans une langue seconde. Cette synthèse montre que les changements cérébraux induits par l'apprentissage d'un nouveau vocabulaire sont observés à la fois au niveau fonctionnel et structurel. Il est important de noter que certaines études ont clairement montré que l'expérience en langue seconde est capable de façonner les structures cérébrales après un entraînement de courte durée de quelques semaines seulement. La démonstration empirique que l'expérience linguistique peut sculpter le cerveau d'apprenants tardifs d'une langue seconde, et ce même après un entraînement de courte durée en laboratoire, constitue un argument solide qui remet en question les approches théoriques postulant que les facteurs environnementaux joueraient un rôle secondaire lors de l'apprentissage d'une langue. Les données en neuroimagerie montrent que l'expérience linguistique a un effet déterminant au niveau lexical sur l'émergence des connaissances linguistiques lors de l'acquisition d'une langue seconde.

Author's address

Frédéric Isel
University Paris Nanterre
Department of Language Science
200 avenue de la République
92000 Nanterre
France
fsel@parisnanterre.fr