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Neurology of foreign language aptitude

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Abstract
This state-of-the art paper focuses on the poorly explored issue of foreign language aptitude, attempting to present the latest developments in this field and reconceptualizations of the construct from the perspective of neuroscience. In accordance with this goal, it first discusses general directions in neurolinguistic research on foreign language aptitude, starting with the earliest attempts to define the neurological substrate for talent, sources of difficulties in the neurolinguistic research on foreign language aptitude and modern research methods. This is followed by the discussion of the research on the phonology of foreign language aptitude with emphasis on functional and structural studies as well as their consequences for the knowledge of the concept. The subsequent section presents the studies which focus on lexical and morphosyntactic aspects of foreign language aptitude. The paper ends with a discussion of the limitations of contemporary research, the future directions of such research and selected methodological issues.

Keywords: foreign language aptitude, neurology, neurolinguistics, individual differences

1. Introduction

In the research on individual differences, foreign language aptitude (FL aptitude) has recently become one of the most often debated topics among scholars not only in the field of SLA and language education but also neurolinguistics. The research on the construct has always been considerably inspired by the sciences of cognitive psychology, genetics and neurology; however, only in the recent twenty years have the developments in neurology allowed genuine progress in the field (cf. Long, 2013, p. 33). As early as the 1980s, researchers trying to find the source of exceptional linguistic abilities concentrated on the neurological basis underlying talent for learning languages (Fein & Obler, 1988; Novoa, Fein, & Obler, 1988; Obler, 1989; Schneiderman & Desmarais, 1988a, 1988b). In their classic study of gifted foreign language learners, Schneiderman and Desmarais (1988a, 1988b) suggested that linguistic talent denotes greater neurocognitive flexibility as well as bilateral processing of the brain. Currently, the first part of this intuitive hypothesis referring to brain flexibility has been confirmed by experimental research conducted by Susanne Reiterer and her coworkers (Reiterer, Hu, Sumathi, & Singh, 2013), who, as a result of functional neuroimaging, provided evidence that phonetically talented subjects are more neurocognitively flexible than less gifted individuals.

Recently, the knowledge of human cognitive abilities has greatly expanded owing to new discoveries in related science fields such as psychology of individual differences, cognitive science, neuroscience and genetics, with the effect that the construct has been updated and reconceptualized. FL aptitude is now defined as a conglomerate of various cognitive abilities (Carroll, 1993; Dörnyei, 2010), subject to the same biological, that is, genetic and neurological, principles as all other abilities, such as mathematical or musical ones. The functioning of the neural system is a basis for individual differences in cognitive abilities. In this respect, there are three sources of ability differentiation: neural conduction velocity, neural efficiency, and gray and white matter volumes. As Jensen (1997, 2002), a major proponent of the hereditarian position, argues, all the variation in mental performance has a biological basis. He explains that there is a negative correlation between the intelligence quotient (IQ), which is a measure of general cognitive ability, and the reaction time of a person. According to this correlation, the higher the IQ level of a person is, the less time he or she needs to solve a problem or to learn something. His arguments rest on interdependencies between the results obtained using functional magnetic resonance imaging (fMRI), electroencephalogram (EEG), event related potential (ERP), emission tomography (PET), and studies of nerve conduction velocity and IQ scores. Thanks to these neuroscientific methods of analysis, it has been well evidenced that intelligence is related to both brain functioning and structure. For example, an fMRI study demonstrated that the general cognitive factor appears to be based on the volume and location of gray matter tissue in the brain (Haier, Jung, Yeo, Head, & Alkire, 2004). Many studies have converged on the view that the frontal lobes are essential for fluid intelligence, a distinctive role being attributed to the lateral prefrontal cortex (Schoenemann, Sheehan, & Glotzer, 2005). Consequently, at the moment there is no academic discussion about individual differences, especially cognitive factors, without neuroscientific research. Applied linguists and language educators cannot fail to include these breakthroughs from neuroscience into FL aptitude research.

2. Neurolinguistic research on foreign language aptitude

Neurolinguistics has become the most informative and ground-breaking source of knowledge about SLA, complementing earlier dependence on behavioral records (cf. Long, 2013, p. 33). The number of studies on neurological substrates of FL aptitude is growing and the data obtained from them are becoming more consistent and replicable (cf. Chee, Soon, Lee, & Pallier, 2004; Díaz, Mitterer, Broersma, & Sebastián-Gallés, 2012; Golestani, Price, & Scott, 2011; Hu et al., 2013; Pereda, Reiterer, & Bhattacharya, 2011; Reiterer et al., 2011a; Reiterer, Pereda, & Bhattacharya, 2011b; Sebastián-Gallés et al., 2012). Nevertheless, there are many neglected or poorly investigated areas and, generally, the redefinition of the construct is far from complete. This situation originates from a variety of sources. The most important are the following: the heterogeneity and extension of the FL aptitude construct, the high level of individualization of the brain, and, last but not least, a small number of researchers interested in FL aptitude and specialized in neurolinguistics.

One of the most important obstacles in examining FL aptitude is the heterogeneity of the construct. To start with Carroll's (1959) classic model of FL aptitude, which conceptualized the construct as comprising four distinct and relatively independent abilities: *phonetic coding ability*, *grammatical sensitivity*, *inductive language learning ability* and *rote memorization ability*, all the successive models (Grigorenko, Sternberg, & Ehrman, 2000; Robinson, 2002; Skehan, 2002; Sparks, Javorsky, Patton, & Ganschow, 1998) have attached extra aptitudes reflecting current views and advances in the domain of SLA. Skehan's (2002) aptitude model underscores the importance of incorporating developments in SLA research to update FL aptitude theory, while Robinson's (2002) aptitude complexes framework highlights the dynamic interactions between FL aptitude profiles, task features and their implications for L2 instruction. Moreover, both models lay emphasis on the role of the memory factor in language acquisition. Grigorenko et al.'s (2000, see also Sternberg & Grigorenko, 2000) CANAL-F theory stresses the ability to cope with novelty and ambiguity when learning a foreign language, whereas Sparks et al.'s (1998) *linguistic coding differences hypothesis* (LCDH) emphasizes the dynamic nature of FL aptitude and postulates that native language (L1) skills are essential for predicting foreign language (L2) learning. Besides, such constructs as working memory (WM), phonological short-term memory and noticing ability have been incorporated in all the contemporary models of FL aptitude (Robinson, 2002; Skehan, 2002), which extends the FL aptitude research to the fields usually associated with psychology. Particularly, the proposal to include WM in the array of FL aptitudes seems to have gained increasing attention among SLA researchers in recent years (DeKeyser & Koeth, 2011; Doughty, 2013; Juffs & Harrington, 2011; Wen & Skehan, 2011; Williams, 2012). Overall, the whole construct of FL aptitude is highly complex and multifaceted, which is reflected by Dörnyei's (2005, p. 33) statement that it has become an umbrella-term for a number of cognitive factors creating a composite gauge regarded as the general capacity to master a foreign language. This has effects on the research on the neurology of FL aptitude, where some mechanisms which serve language learning behavior are better investigated than others. For example, neural mechanisms for procedural and declarative memory, memory consolidation and attention (Schumann, 2004a, p. 1), phonological abilities (Reiterer et al., 2013), and the congenital nature of L1 and L2 aptitude (Díaz et al., 2012) are often investigated. Others, for example analytic aptitude required for grammar processing, the ability to learn vocabulary, noticing ability, WM as FL aptitude, pragmatic ability and semantic fluency, remain neglected. It seems that these disproportions largely reflect weak areas in the theory of FL aptitude.

Another major problem that complicates the foundation of a unified neurological picture of FL aptitude is a high level of the individualization of the brain. According to Schumann (2004b, p. 7), "all brains are different—as different as faces . . . and these differences have consequences for learning." Some differences result from genetic inheritance; for example, greater brain plasticity (cf. Díaz et al., 2012; Golestani, 2012; Sebastián-Gallés & Díaz, 2012; Sebastián-Gallés et al., 2012). Some others are considered adaptive changes in the brain occurring in response to experience (Golestani, Molko, Dehaene, LeBihan, & Pallier, 2007; Green, Crinion, & Price, 2006). Accordingly, high FL aptitude might be a consequence of both inborn functional and structural/ anatomical characteristics as well as an individual brain response to an idiosyncratic experience of learning a language. De Bot (2006) expresses his opinion on this interrelationship in the following way:

> There are individuals who will have both exceptional language skills and deviant brain structures. . . . it is likely that learning might have an impact on brain structures, although it is unclear how plastic the brain is and to what extent specific teaching and learning methods might enhance plasticity or make optimal use of it. (p. 130)

According to Schumann (2004b), there are five sources of variation among brains, which result in differences in FL aptitude, namely *genetic*, *developmental*, *experiential*, *degeneracy* and *individual appraisal system*. His claim is in most part based on classic theories of heritability (cf. Jensen, 1997; Plomin, 1997), ascribing significant genetic contributions to cognitive abilities. Genetic variance in a child attributable to parental genes accounts for about 50% of correlation between siblings and is higher for monozygotic twins (about .86) and lower for fraternal twins (.60) and for regular siblings (.48), which means that genes are the most influential factor in the development of cognitive ability. The second source is the specific chemical environment during the embryonic stage of development. As a result, human brains are similarly constructed but differ significantly at the microstructural level. The third source of variation are the interactions with the environment, with the effect that they channel the brain's anatomy, that is, the increase of neurons and connections among them. Because each individual has idiosyncratic environmental experience, these influences contribute to additional microstructural variation in the neural structure. The fourth process which contributes to variation between brains is called degeneracy. This term describes a situation when two or more different neural systems subserve the same goal, that is to say, when the same behavior can be achieved by different underlying processes. These alternate systems discriminate individual brains (Indefrey & Gullberg, 2006; Schumann, 2004b). The fifth source of variance are idiosyncratic preferences and aversions, that is, an individual appraisal system (Scherer, 1984). Individual experiences and affective reactions are stored in memory and used to evaluate future experiences, and consequently affect individual choices. Moreover, people seek environments fitting their genotype, which in turn influences their abilities (Jensen, 1997). Jensen (1997) also points to the fact that randomness or luck should be considered another source of variation.

The development of FL aptitude might be a consequence of evolutionary selection processes (Schumann, 2004b), which means that individuals can be differently prepared to respond to environmental changes, and, consequently, to survive and to transmit their genes. Adaptation to the environment can generate a *hypertrophy*, which is a structural (anatomical) abnormality in the brain (Van den Noort, Nordby, Bosch, & Hugdahl, 2005), which, in turn, can result in a specific ability. The brain of a talented individual with a particular hypertrophy responds to the learning process strengthening certain neural connections or creating new neural pathways. This, in sequence, facilitates learning, and, consequently, the talented individual might achieve high expertise in the field of study (cf. Golestani et al., 2011; Perani, 2005; Reiterer et al., 2013).

Generally, neurological differences between foreign language learners, which might be assigned to different domains of FL aptitude, are divided into *functional* (i.e., those connected with brain activation) and *structural* (i.e., those connected with brain anatomy). These differences are associated with distinct aspects and levels of language processing starting with simple perceptual/cognitive functions such as nonnative sound learning and articulation, and phonetic expertise, through more complex ones such as WM for verbal and lexical information, to the most compound processes including reading, syntax, bilingual functioning and executive control over linguistic fluency. Most of the research in the domain of language has focused on brain functioning using such methods as fMRI, EEG, and magnetoencephalography (MEG). However, over the last 17 years the number of studies examining brain structure or a change over time, that is, plasticity, has grown significantly thanks to the development of very advanced technologies such as anatomical magnetic resonance imaging (aMRI) and diffusion tensor imaging (DTI; Golestani, 2012, p. 2). Neuroimaging techniques are described in Table 1.

Table 1 Neuroimaging techniques

Technique	Definition
PET (positron emission tomography)	Used for localization of different neural functions by means of injection of radioactive tracers. More active brain areas have higher levels of blood flow and, consequently, of the tracer. By creating pictures of the tracer distribution, a neuroscientist can obtain a pattern of brain functioning. PET has high spatial resolution (Goswami, 2004: 5-6).
fMRI (functional magnetic resonance imaging)	Gives similar results to PET, but relies on measuring the magnetic resonance signal generated by the protons of water molecules in neurons. fMRI has high spatial resolution (Goswami, 2004: 5-6).
ERP (event related potential)	ERP is, unlike PET and fMRI, based not on localization of neural activity, but on the timing of neural events. ERP has high temporal resolution. Electrodes placed on the skin of the scalp record activity of the brain. This experimental technique is based on EEG (encephalography) (Goswami, 2004: 5-6).
MEG (magnetoencephalography)	A diagnostic technique which measures the level of magnetic signals as a result of electrical activity in the brain. MEG has high temporal resolution. (http://psychologydictionary.org/magnetoencephalography-imegl/)
aMRI (anatomical magnetic resonance imaging)	A high resolution technique which can be used to describe the shape, size and integrity of grey and white matter structures in the brain. (http://fmri.ucsd.edu/Research/whatisfmri.html)
DTI (diffusion tensor imaging)	It can be used to map white matter fibre tracks (http://fmri.ucsd.edu/Research/whatisfmri.html)

Traditionally, it is believed that changes in brain functioning are rapid whereas those in brain structure take longer. However, these new methods of brain investigation have revealed that also structural changes can occur rapidly, basically within hours (Golestani, 2012). Another important discovery is that, generally, the same regions which functionally subserve cognitive processes involved in language processing also structurally correlate with these processes. As a result, a number of anatomical differences have been found in more versus less proficient foreign language learners. For example, Mechelli et al. (2004) discovered that the acquisition of multiple languages results in an expansion of grey matter in the left parietal cortex. Green et al. (2006) studied anatomical changes implicated in processing a language among simultaneous interpreters as compared to monolingual, bilingual and multilingual speakers. What they found was higher grey matter density in interpreters in three regions: bilateral putamen, the inferior and superior colliculi, and the bilateral dorso-medial thalami, a phenomenon ascribed to long-term effects of the acquisition of a very advanced linguistic skill, which, in turn, makes the acquisition of succeeding languages easier. Stein and colleagues' (Stein et al., 2012) study provided evidence for brain structural plasticity as a result of second language learning. They conducted a longitudinal study by means of aMRI on native speakers of English learning German prior to and after five months of learning. As a result, they discovered structural changes over time in the left inferior frontal gyrus and in the left anterior temporal lobe, which positively correlated with individual differences in the increase in second language proficiency during training. Generally, the differences in the left inferior parietal cortex and in the left inferior frontal cortex associated with bilingualism are related to the age of acquisition and predict second language proficiency (Golestani, 2012, p. 20). Interesting as they are, these studies explain differences in proficiency between learners, but proficiency does not equal aptitude. Accordingly, Reiterer, Pereda and Bhattacharya (2009, p. 98) point to the fact that "language proficiency" is an ambiguous term involving various factors including aptitude for languages. Therefore, most of the studies presented in this review must be interpreted as indirect evidence of differences in FL aptitude.

All the above mentioned research provides evidence for brain plasticity as a result of experience. However, many studies offer an alternative interpretation of this phenomenon, tracing the roots of anatomical specificity to genetic factors (cf. Golestani, 2012). The example of a polyglot Emil Krebs (1867-1930), who fluently spoke more than 60 languages, is presented as classic evidence for a peculiar inborn brain architecture that facilitates FL aptitude. Apparently, the cell structure in his Broca's area was significantly different from a normal brain cell structure (Amunts, Schleicher, & Zilles, 2004). In contrast, no plausible explanation for talent has been discovered in the brain of a linguistic savant, Christopher (Smith, Tsimpli, Morgan, & Woll, 2011). The discussion of the origination of hypertrophies will be addressed at greater length in the following section. For the sake of clarity, the following review will present both functional and anatomical studies in the fields of phonology, grammar and lexis with respect to FL aptitude.

3. Neurology of phonological aptitude

The phonological aspect is the best investigated of all the components of FL aptitude (Christiner & Reiterer, 2013; Díaz et al., 2012; Golestani et al., 2011). As far as anatomy is concerned, differences in the phonological cognitive functioning include the auditory cortex, the parietal cortices and the inferior frontal gyrus, all of which are related to such levels of phonetics as auditory processing, the perception of nonnative sounds, the use of tonal information, and the ability to imitate nonnative sounds. Differences in auditory processing have been found in left Heschl's gyrus (HG) anatomy, which means that higher gray matter density is associated with better performance (Sutherland et al., 2012; Warrier et al., 2009).

A significant factor related to language aptitude is phonetic perception, which is required for phonetic production, accent imitation, verbal WM, as well as semantic perception and production. Many studies have confirmed substantial individual differences among people in the perception, recognition and learning of foreign sounds (Golestani et al., 2007; Golestani, Paus, & Zatorre, 2002; Golestani et al., 2011; Sebastián-Gallés et al., 2012). As a result of the examination of brain structure in expert phoneticians, Golestani and her team discovered that phonologically talented learners have more grey matter and white matter in parietal regions, in particular in the left hemisphere. Their results suggest that this morphological difference is inborn and might have existed before the onset of phonetic training thus affecting career choices of the subjects. As they explain, complementary influences of inborn predispositions and experience-dependent brain pliability interact in determining not only how experience shapes the human brain, but also why some individuals become engaged in certain fields of expertise (Golestani et al., 2011, p. 4213). Left parietal cortex is pertinent to phonetic tasks and is the location of phonological verbal WM; therefore, the anatomy fundamental for WM in the left auditory cortex also predicts phonological aptitude. The researchers explain the asymmetry in the amount of white matter in more talented learners in terms of greater myelineation, that is, an increase in myelin volume (white matter), which indicates a better isolation of the transport of electric signals, which, in turn, leads to faster and more efficient neural processing vital in learning the phonetics of a language. The researchers conclude that morphological differences in parietal white matter can predict the pace and efficiency of learning new sounds.

There is a number of other hypertrophies that differentiate more from less able L2 learners, mostly related to the anatomy of the HG. For example, higher white matter density has been found in the left HG, as well as in a split or a duplicate of the HG, in more able learners. In fact, there can be two or three HG per hemisphere. Additionally, the right insula and HG are more superiorly located in slower learners (Golestani et al., 2011). What is more, a larger volume of grey matter in the HG has been found in musicians, which positively correlates with musical aptitude (Schneider et al., 2002; cf. Christiner & Reiterer, 2013).

Generally, a global displacement of components of the language area in the left hemisphere can predict the learning of speech sounds. There is also evidence that variation in perisylvian anatomy is related to oral language ability. Abnormalities have been found in children with dyslexia and other language disorders. Abnormal asymmetry of the planum temporale has been detected in people with poor verbal ability (Golestani et al., 2007). Moreover, an increase in grey matter has been observed in the mid-body of the corpus collosum which connects the two hemispheres in highly proficient L2 speakers (Coggins, Kennedy, & Armstrong, 2004; Van den Noort, Bosch, & Hugdahl, 2006). Interestingly, the differences lie not only in the auditory cortex, but also in the more general language network and even in the right hemisphere. For example, greater white matter density has been observed in certain visual brain regions, which means that those are also engaged in phonological processing (Golestani et al., 2007).

Sebastián-Gallés et al. (2012) examined neuroanatomical markers of individual differences in vowel perception. They compared brain morphology in two groups of highly proficient early bilinguals, equally proficient in an L2, but differing in their ability to perceive both native and nonnative vowels. Voxel-based morphometry analysis revealed that there is a larger white matter volume in the right insulo/fronto-opercular region in poorer perceptual discriminators of native and nonnative vowels. The higher white matter volumes in poor perceivers indicate a stronger activation of these areas which are used as a compensatory mechanism that enhances auditory discrimination abilities. This conclusion accords with similar results obtained by Reiterer et al. (2011a), Reiterer et al. (2011b) and Wong, Perrachione, and Parrish (2007), where a more extended or bilateral activation in poorer language learners was observed.

Another group of studies refers to the use of tonal information linguistically. Wong and colleagues (Wong, Chandrasekaran, Garibaldi, & Wong, 2011; Wong et al., 2007; Wong et al., 2008) confirmed larger volume of the left HG in more successful learners using fMRI, aMRI and DTI. Moreover, Wong et al. (2011) found that white matter connectivity in the left temporoparietal region correlated positively with the use of tonal information. Summing up, there is a partial dissociation between the structural correlates of phonetic perception and production (Golestani, 2012, p. 15).

Functional studies on phonological processing generally corroborate three hypotheses related to FL aptitude, that is (a) a stronger and bilateral activation of brain areas of less gifted individuals in comparison to those of more gifted ones, (b) the dual genetic/environmental source of aptitude differences, and (c) the common neural basis for L1 and L2 aptitudes (Díaz, Baus, Escera, Costa, & Sebastián-Gallés, 2008; Golestani & Zatorre, 2004; Reiterer et al., 2011a; Reiterer et al., 2011b; Wong et al., 2007).

One of the earliest questions asked by neurolinguists was whether neural correlates for an L1 and L2 are the same or different. Most studies have converged on the view that unlike an L1, which always activates the same areas in the left hemisphere, an L2 activates a very changeable network of both hemispheres (Dehaene et al., 1997). This observation is typically not ascribed to differences in aptitude but to the age of onset and level of proficiency. In many studies late-onset, low proficiency L2 learners have demonstrated greater right hemisphere activation, whereas areas of L1 and L2 activation tend to overlap in early-onset, more proficient learners (Kim, Relkin, Lee, & Hirsch, 1997). More recently, these results have been replicated by Golestani and Zatorre (2004), Indefrey and Gullberg (2006), Reiterer et al. (2011a); Reiterer et al. (2011b), Sebastián-Gallés et al. (2012) and Wong et al. (2007), all of whom reported a more extended or bilateral activation in the brains of less successful language learners. Specifically, more active cortical regions in less proficient learners during L2 processing concentrate in the left posterior inferior frontal gyrus (IFG) (Indefrey, 2006; Stowe, 2006; Van den Noort et al., 2005). In Indefrey's (2006, p. 300) interpretation, the IFG is optimized for an L1 and less efficient for an L2. Effort increases activation, which means that learners might compensate for lower efficiency in an L2 by driving this region more strongly or activating a bigger number of neurons to perform a task, whereas automatized activities require less effort, and, consequently, less activation. All of this indicates that the efficiency of the neural organization, next to brain anatomy, might establish a neurological basis for FL aptitude. Indefrey and Gullberg (2006) postulate that with the increase in L2 proficiency, the processing profile in an L2 becomes similar to an L1. What causes higher activation in lower-proficiency L2 speakers is the increased "control effort" (Reiterer, 2009; Reiterer et al., 2011a). Generally, most contemporary researchers choose a moderate view termed *partial overlap* (Reiterer, 2009, p. 160). According to this opinion, there is a basic core overlap for L1 and L2 processing; however, in all probability, the level of proficiency or fluency triggers brain activation in additional areas for an L2.

Golestani and Zatorre (2004) investigated changes in brain activity during phonetic processing by means of fMRI. Their subjects were ten monolingual English-speaking individuals, who were scanned during performing an identification task of a sound unknown to them: a Hindi dental retroflex. The fMRI was conducted before and after five sessions of training. As a result, they confirmed that the successful learning of a nonnative phonetic contrast causes the employment of the same areas that are active in the processing of native contrasts. Moreover, frontal speech regions are less active in successful learners as compared to poor learners, which indicates that the phonetic processing is more automatized and more efficient in the first group.

Díaz et al. (2008) compared mismatch negativity (MMN), an electrophysiological brain response, in two groups of bilinguals, extremely good and poor, at various tasks testing their perception ability. They found individual differences between these two groups with respect to phonetic discrimination ability detected in both languages of the subjects, the native and the foreign one. The conclusion was that foreign language phonetic abilities can be predicted from native phonetic abilities; moreover, these abilities belong to language-specific rather than general acoustic abilities. Díaz et al. (2012) argue that the large variety among late bilinguals in their mastery of L2 phonology, particularly L2 phonological contrasts, is grounded in their varied discrimination of native phonological contrasts. If the age of onset is controlled for, individual differences in L2 proficiency are caused by a general language mechanism (cf. Golestani & Zattore, 2004). Moreover, both early- and late-onset bilinguals are able to display a native-like performance on L2 phonological tasks that involve pre-lexical processes, that is, phoneme categorization, but their abilities deteriorate as the task becomes more lexicalized, as, for example, in selecting a word (Sebastián-Gallés & Díaz, 2012).

Wong et al. (2007) report a study assessing the neural correlates of learning to use pitch patterns in words by English-speaking adults. The use of pitch patterns resulted in changes in a network of brain activation, that is, successful learning was associated with activation in left superior temporal region after training, whereas bilateral auditory cortex activation was discovered in less successful foreign language learners both before and after training. It is worth mentioning that in the less successful learners the regions responsible for nonlinguistic pitch perception as well as those for increased WM and attentional effort were more activated. This means that left auditory cortex is involved in learning pitch patterns in words and that some phonological processes are prewired and independent of practice.

A number of studies of phonetically talented L2 learners conducted by Reiterer (2009) and her colleagues (cf. Christiner & Reiterer, 2013; Hu et al., 2013; Hu & Reiterer, 2009; Nardo & Reiterer, 2009; Reiterer, Berger, Hemmelmann, & Rappelsberger, 2005; Reiterer et al., 2011a; Reiterer et al., 2013; Reiterer et al., 2009; Reiterer et al., 2011b; Rota & Reiterer, 2009) have provided remarkable insights into the interdependencies between phonetic abilities, cognitive and personality factors, and brain activation patterns in talented L2 learners. Their preliminary results basically confirmed the findings of previous studies, that is, a greater activation of language-related areas in less talented L2 learners. For example, in a neurological study, Reiterer et al. (2005) investigated the impact of proficiency level among German students of English on the cortical organization of foreign language processing. Two groups of learners, high and low proficiency, were subjected to EEG coherence analysis during native and foreign language processing. The researchers observed reduced EEG coherence in highly proficient foreign language speakers in both foreign and native language processing. The study corroborated previous research results, namely that less proficient learners activate more brain areas than more proficient ones (cf. Chee et al., 2004; Haier et al., 1992; Perani et al., 2003). The authors suggest that the lower activation of cortical regions during both L1 and L2 processing may result from such factors as extensive training and exposure, a more efficient approach to language learning during the acquisition of L1 or genetically predisposed language aptitude. Because brain activation patterns correlated with pronunciation aptitude scores, Reiterer (2009, p. 176) suggests that the primary factor of FL aptitude correlates with reduced effort in speech production as well as increased cortical efficiency. The reduced effort is a consequence of higher proficiency; therefore, FL aptitude can be a result of an interaction between inborn aptitudes, early experience and training.

The question why some late-onset adult bilinguals display different abilities for imitating foreign accents remains unanswered. A study that addressed this problem was conducted by Reiterer et al. (2011a). The subjects were 141 German-speaking individuals studied for their mimicry capacity, which is a factor indicating their abilities for the imitation of foreign sounds. They displayed significant individual differences in imitating words, sentences and texts in both their L2, English, and in Tamil and Hindi, natural languages unknown to them. Moreover, the late-onset bilinguals revealed large individual differences in the employment of left-hemisphere speech areas, namely the left inferior parietal cortex (supramarginal gyrus) and the left inferior frontal/premotor area (Reiterer et al., 2011a), with higher activation in the case of low ability and enhanced gray matter volume in high ability subjects. As in the previous studies of this kind, the conclusion is that increased "control effort" causes higher activation in lower-proficiency L2 speakers. The same rule applied to all the languages tested, that is, the L1 (German), the L2 (English) and the L0 (Hindi/Tamil), which indicates that there are high similarities between L1 and L2 phonetic processing dependent on either the level of expertise or the inborn abilities of the speaker, with the latter explanation being more plausible as the individuals were not exposed to the L0 before (cf. Golestani & Zatorre, 2004). This conclusion is valuable because it presents evidence for an inborn character of abilities.

Hu et al. (2013) investigated behavioral predictors and neural substrates of aptitude for pronunciation in advanced L2 learners. Previous research provided evidence for a correlation between phonological WM, as measured by digit span and pseudo-word repetition, and language learning ability in early-stage learners, which declines in more advanced learners. This study confirmed this by demonstrating that there was no association between phonological WM and L2 pronunciation aptitude in advanced learners. One hundred and nine German university students and graduates, who began learning English at the age of ten, participated in the behavioral part of the study. Students outside one standard deviation from the mean were classified as high and low aptitude speakers. Among those, two subgroups were selected to participate in fMRI experiments. Behavioral tests included English pronunciation aptitude, phonetic coding ability, phonological WM, musical aptitude, intelligence and personality. It turned out that phonetic coding ability and empathy together, but not the classic measures of phonological WM, predict language pronunciation aptitude in advanced learners. The authors attribute the contribution of empathy to the role of mirror neurons, which can play an important role in SLA being responsible for speech comprehension and prosody. When it comes to the neuroimaging study, in the advanced L2 learners enhanced hemodynamic responses were found in the speech-motor neural network and speech-auditory perception areas. The authors conclude that these areas contribute to the talent for L2 pronunciation in advanced learners. Unlike in early-stage learners, the areas responsible for phonological WM were not related to the individual differences in L2 pronunciation aptitude, which, together with the lack of phonological WM among the predictors of pronunciation aptitude, leads the authors to conclude that this cognitive factor is not equally crucial at all stages of learning. Apparently, aptitude for pronunciation is a dynamic process which requires different neural networks at different phases of learning.

Another breakthrough study was conducted by Reiterer et al. (2013), who maintain that it is possible to predict phonetic talent from purely biometric data. They investigated individual differences in speech-imitation ability in late-onset bilinguals using the neuro-acoustic approach. The researchers tested the imitation ability of an unknown language, Hindi, in 138 German-English bilinguals. Twenty-six participants with the highest and the lowest scores were further tested using a functional neuroimaging experiment in which they were supposed to imitate sentences in three different conditions. Clearly more widespread activations with higher peak activities in the left supramarginal gyrus and postcentral areas were observed for the low ability group. As the left supramarginal gyrus is also a site of the phonological loop of verbal WM, its stronger activation in the poor imitators implicates their weak verbal WM (cf. Hu et al., 2013; Reiterer et al., 2011a). As Reiterer et al. (2013) conclude, this result fits in with behavioral data confirming a strong correlation between WM and both native language processing and foreign language learning success (cf. Linck, Osthus, Koeth, & Bunting, 2013). In their experiment, Reiterer and her collaborators (2013) used a newly developed analysis termed “articulation space” and found that the high ability subjects had a larger articulation space allowing access to a wider range of sounds, which, in turn, makes them better sound imitators. The researchers claim that very talented speech imitators have more flexible phonetic categories and are not limited to the mother tongue sound pronunciation schemas. As the authors conclude: “There is higher neuro-cognitive flexibility, reflected by higher articulatory flexibility in the group of the more talented speech imitators” (Reiterer et al., 2013, p. 11). For these exceptional learners, there is no interference in phonological learning from the L1. As a result of their study, the researchers refute the critical period for sound learning for some very talented learners; however, they admit that interference from an L1 is rather a norm for the less talented ones.

A study examining the link between singing talent and speech imitation ability was done by Christiner and Reiterer (2013). The research question was whether good singing ability predicts good sound imitation ability. The researchers examined four factors, namely the ability to sing, musical talent, the ability to imitate speech and WM in 41 singers ranging from beginners to advanced. As the authors argue, singing is a better indicator of the ability to imitate speech than playing a musical instrument. As much as 66% of the speech imitation ability can be explained by WM together with singing performance, that is, the singer’s sense of rhythm and quality of voice. According to Nardo and Reiterer (2009), Reiterer et al. (2011a) and Hu et al. (2013), 15% of adult or late second language learners can imitate sounds to a high degree. There is a clear connection between musicality in general and articulation ability. The higher the musicality, the better the pronunciation and imitation in a second language, and the ability to sing is the clearest indicator of this. Musicians, thanks to their improved auditory WM, remember speech streams longer (Nardo & Reiterer, 2009). Moreover, the processing of verbal material and of music in the brain largely overlap in the areas responsible for short-term memory. The enhanced WM in singers and musicians can be connected with their tendency to rehearse. Singers retain perceptual plasticity and are open to new sound combinations. Interestingly enough, Jordan (2014) suggests that there is a difference between musicians and nonmusicians in WM capacity and that the phonological loop might be enhanced as a result of musical training. Summing up, it seems that both the aptitude for singing and for the imitation of unknown sounds rely on common neural networks, vocal and motor flexibility and auditory memory.

4. Neurology of lexis and morphosyntax

The ability to learn new words is marginally investigated neurologically. This is because most neuroscientific research focuses on the phonological aspect of learning foreign words (cf. Hu et al., 2013), overlooking the semantic aspect. The learning of new words and syntax are complex processes based on the functioning of WM, which underlies language learning in general (Robinson, 2003). Verbal WM, which is crucial for learning languages, is associated with grey matter density in the left posterior superior temporal sulcus (STS; Richardson et al., 2011).

Words in a foreign language are processed in WM and stored in long-term memory. Vocabulary knowledge reveals large differences between subjects and is related to many factors such as general intelligence, the number of languages a person knows, education and socio-economic status. There are a few neuroscientific studies of lexical knowledge and semantic memory, which show correlates in the left and right posterior supramarginal gyri and in the posterior STS and temporo-parietal cortex (Lee et al., 2007; Richardson, Thomas, Filippi, Harth, & Price, 2010). Grey matter density of the bilateral posterior supramarginal gyri depends on the number of words the subject knows; what is more, this area is connected to the brain areas that process sounds and meanings of words. Therefore, the bilateral posterior supramarginal gyri may be places where phonological and semantic information is integrated. De Zubicaray, Rose and McMahon (2011), making use of the aMRI and DTI methods, examined the relationship between semantic memory and brain structure in healthy older adults. They found that semantic memory, as assessed by six standardized neuropsychological tests, was correlated with gray matter volumes in a predominantly left lateralized network. With the use of fMRI, Breitenstein et al. (2005) examined 14 learners acquiring new vocabulary in order to test changes in the activation of the brain and track which of these learning-related activity changes correlate with semantic knowledge. They discovered that the proficiency in the learning of new words depends on correlated amplitude changes between the left hippocampus and neocortical regions and that the learning-related hippocampus activity is an indicator of the ability to acquire both native and foreign vocabulary.

Analytical aptitude implicated in learning the structure of a language is also poorly investigated. A few studies have addressed the problem of morphosyntactic attainment in late-onset learners (Lopez-Barroso et al., 2011; Wong, Morgan-Short, Ettlinger, & Zheng, 2012; Wood Bowden, Steinhauer, Sanz, & Ullman, 2013). Lopez-Barroso et al. (2011) provided evidence that the phonological component of WM, that is, articulatory rehearsal, influences the learning of syntax. By blocking rehearsal, segmentation and rule learning in an L2 are significantly impaired as compared with a learning condition without interference or interference with the phonological store. Moreover, white matter density in the left ventral language pathway was related to learning variability under rehearsal blockage.

Wong et al. (2012) tapped into the neurogenetic source of variability in learning syntax, in particular the role of the dopaminergic system. It is known that the genes encoding dopamine receptors and transcriptors have an impact on different types of procedural learning. Dopamine is also associated with WM and attention. All of this indicates that dopamine-related genes can contribute to variation in grammar learning, with the effect that individuals with different genetic profiles may have different learning abilities. The research revealed that subjects with an increased impact of dopamine are better at procedural learning, WM capacity and executive function. As a conclusion, the authors suggest that different genotypic profiles can benefit from different types of training.

Wood Bowden et al. (2013) suggest that late-onset university learners are capable of attaining native-like brain processing of syntax as well as native-like syntactic proficiency. The subjects of their study were 32 late learners of Spanish, who were divided into two groups: low-intermediate, with little experience; and advanced, with more experience in learning, including immersion. With the use of the ERP method, both groups were compared with native speakers of Spanish while performing two types of violation tasks: semantic and syntactic. In the semantic violation tasks there were no differences between all the three groups, but in the syntactic violation tasks there was no difference only between the advanced and native groups, which indicates that the syntactic processing in these groups was subserved by the same neurocognitive processing. The authors argue that unlike L2 semantic processing, which always depends on L1 neurocognitive mechanisms, L2 syntactic processing initially differs from L1 processing but can develop into native-like provided there is sufficient proficiency and exposure.

Syntax processing and artificial grammar learning have been examined in two studies of white matter structural connectivity (Flöel, de Vries, Scholz, Breitenstein, & Johansen-Berg, 2009; Nauchi & Sakai, 2009). The studies showed correlates in the left pars opercularis and pars triangularis subregions of Broca's area, thus confirming that verbal processing is left-lateralised.

Finally, language control which engages speech networks as well as a high level, left-lateralized fronto-parieto-subcortical brain network (Golestani, 2012, p. 19) affects semantic and phonemic fluency. Studies on executive aspects of speech processing show correlations with brain morphology in regions including the caudate nucleus and the superior frontal gyrus. Grogan, Green, Ali, Crinion, and Price (2009) examined brain structural correlates of semantic and phonemic fluency and found that performance on semantic fluency was linked to gray matter in the left inferior temporal lobe, and on phonemic fluency to the pre-supplementary motor area and head of the caudate nucleus bilaterally. Summing up, the limited knowledge available does not allow any general conclusions, especially in view of the fact that all the above-described studies do not refer to FL aptitude directly. A review of the most important studies is presented in Table 2.

Table 2 Review of the most important neurolinguistic studies on FL aptitude presented chronologically

Study	Findings
	Phonology
Golestani and Zatorre (2004)	Successful processing of native and nonnative phonetic contrasts activates the same brain areas.
Reiterer et al. (2005)	Less proficient learners activate more brain areas than more proficient ones.
Van den Noort et al. (2006)	Increase in grey matter in the mid-body of the corpus collosum in highly proficient L2 speakers.
Golestani et al. (2007)	Abnormal asymmetry of the planum temporale related to poor verbal ability.
Wong et al. (2007)	Bilateral auditory cortex activation in less successful learners both before and after training.
Díaz et al. (2008; 2012)	L2 phonetic abilities can be predicted from L1 phonetic abilities.
Golestani et al. (2011)	Phonologically talented learners have more grey matter and white matter in parietal regions, in particular in the left hemisphere. Hypertrophies are mostly related to the anatomy of the left HG.
Reiterer et al. (2011a, 2011b)	High similarities between L1 and L2 phonetic processing depend on inborn abilities. More extended activation in poorer learners.
Wong et al. (2011)	Larger volume of the left HG in more successful learners.
Sebastián-Gallés et al. (2012)	Larger white matter volume in the right insulo/fronto-opercular region in poorer perceptual discriminators of native and nonnative vowels.
Hu et al. (2013)	Phonetic coding ability and empathy together predict language pronunciation aptitude in advanced learners.
Reiterer et al. (2013)	High ability subjects have larger articulation space allowing access to a wider range of sounds, which, in turn, makes them better sound imitators.
Christiner & Reiterer (2013)	66% of the speech imitation ability can be explained by WM together with singing performance.
	Vocabulary
Breitenstein et al. (2005)	Proficiency in learning of new words depends on correlated amplitude changes between the left hippocampus and neocortical regions. The learning-related hippocampus activity is an indicator of the ability to acquire both native and foreign vocabulary.
	Semantic memory
De Zubicaray et al. (2011)	Semantic memory is correlated with gray matter volumes in a predominantly left hemisphere.
	Syntax
Flöel et al. (2009)	Integrity of white matter fiber tracts arising from Broca's area is linked with the ability to extract grammatical rules.
Nauchi and Sakai (2009)	Inferior frontal gyrus proposed as the grammar center.
Lopez-Barroso et al. (2011)	Articulatory rehearsal in WM influences the learning of syntax.
Wong et al. (2012)	Subjects with an increased impact of dopamine are better at grammar learning.
Wood Bowden et al. (2013)	L2 syntactic processing initially differs from L1 processing, but can develop into native-like provided there is sufficient proficiency and exposure.

Semantic and phonemic fluency	
Grogan et al. (2009)	Performance on semantic fluency is linked to gray matter in the left inferior temporal lobe, and on phonemic fluency to the pre-supplementary motor area and head of the caudate nucleus bilaterally.

5. Conclusions and suggestions for further research

Neuroscience is a relatively new field, which includes disciplines such as neurology, psychology and biology. Neurological techniques of brain examination have ushered in a new era in research on SLA in general and on individual differences in particular. Methods such as PET, fMRI, aMRI, ERP, and DTI, which measure either changes in brain activity or in brain anatomy, help to discover how a foreign language is organized in the brain, how the age of onset, aptitude, proficiency level and training affect this organization, and what functional and structural features differentiate monolinguals from bilinguals at different levels of linguistic proficiency and with different lengths of exposure to a foreign language. Nevertheless, neurolinguistic research on FL aptitude is, for the most part, in the commencing stage, with one notable exception, which is phonological abilities. This area of FL aptitude is relatively thoroughly analyzed and research results are reliable, replicable and practically applicable (e.g., Golestani et al., 2011; Reiterer et al., 2013). Other groups of abilities, that is, those involved in learning lexis, syntax, pragmatics and communication skills, remain on the sidelines of neurolinguistics. As has been suggested, the main reason for this disproportion is the lack of a unified definition of the construct of FL aptitude, but also its complexity and extension. For example, the paradigm of WM, although very popular among applied linguists (cf. Robinson, 2003), cognitive psychologists (Cowan, 2014) and neuroscientists (Postle, 2014), and proposed as another FL aptitude (cf. Doughty, 2013; Wen & Skehan, 2011), has attracted relatively little attention in the neuroscientific research on individual differences with respect to SLA, which is a major oversight in view of the developments in the field of WM. For instance, Baqués, Castellà, and Bowers (2014) suggest that implicit memory for words does not rely on the phonological loop, whereas explicit memory for words does. Many studies have found that individual differences in WM capacity can be partly attributed to differences in attentional processes, especially these involved in inhibiting irrelevant information. Both functional and anatomical studies have confirmed that prefrontal cortex, basal ganglia and thalamus perform attentional control over WM in parietal cortex (Ekman, Fiebach, Tittgemeyer, & Derrfuss, 2014). Also Majerus et al. (2014) provided evidence for common neural patterns underlying verbal WM storage and attention. Finally, a new interpretation of WM capacity, termed *process* *overlap theory* (Conway, 2014), which refers to the pattern of positive correlations (the positive manifold) between various cognitive tests accounted for in terms of complex intercorrelations between domain-general and domain-specific processes, seems to be relevant for FL aptitude theory. In the words of its author, “the theory accounts for the hierarchical structure of cognitive ability, the strong relationship between WMC and fluid intelligence, the worst performance rule, and ability different” (Conway, 2014, p.3).

Neurological studies cast some light on very controversial aspects of FL aptitude, for instance, the partial overlap of L1 and L2 aptitude (Reiterer et al., 2011a), greater plasticity of the brain of more successful language learners (Reiterer et al., 2013), a more bilateral activation in less successful learners (Reiterer et al., 2005), particular hypertrophies in the brain of more phonologically gifted individuals (Golestani et al., 2011), and, probably the most controversial of all, the contribution of genes and environment to the development of linguistic giftedness (Golestani et al., 2011; Perani, 2005). Golestani (2012), for example, argues that solid grounds exist to believe that certain aptitudes are genetically predisposed: “We found evidence for a potential brain structural ‘intermediate phenotype’ . . . for a domain-specific aptitude which can, with adequate opportunity and training, lead to expertise” (p. 22). In a similar vein, Perani (2005) hypothesizes that the diversity between bilingual brains is genetic and might rely on functional differences in processes connected with mirror neurons. She argues for the prewired patterns of functional and anatomical variability, which condition the development of specific talents. From this perspective, these individuals who are born with anatomical differences predisposing specific talents will reach a high level of proficiency.

A recurring question in the research on phonology-related regions refers to the impact of training on brain structure. Generally, it appears that different parts of the cortex depend on heritable factors to different degrees, that is to say, some are more stable and others more subject to change. Genetic studies show that the morphology of Broca’s area may be more pliable as a result of experience than the morphology of the HG (Peper, Brouwer, Boomsma, Kahn, & Poll, as cited in Golestani, 2012). To quote Golestani (2012): “It is likely that *both* genetics and the environment play a role in shaping brain structure and cognitive aptitudes, with different relative contributions in different brain areas” (p. 22). This implicates the possibility of an increase in FL aptitude attributable to training and practice. What is more, genetics and the environment interact in accordance with individual choices and interests of people, who tend to select the environment compliant with their genetic predispositions (cf. Jensen, 1997). Now, after a few decades of the ardent debate, these scientific problems still remain largely unexplored. As far as research methodology is concerned, Golestani

(2012) suggests a multiple approach including functional, structural and behavioral analyses of subjects in order to discover the underlying mechanisms of learning languages and language learning aptitudes. Thanks to the combined methods, further research could explore the relationship between innate genetically-driven factors and the effects of experience and training, as well as the plasticity of the brain and different language aptitudes (cf. Golestani et al., 2011).

Another aspect worth further investigation is the relationship between musical aptitude and FL aptitude. So far, we have learnt a great deal about the anatomy underlying both abilities. Multiple or split transverse gyri in the left auditory cortex predispose individuals to become phoneticians or to work in other domains requiring detailed auditory processing, such as, for example, sound technicians, acousticians, musicians and other language experts (Golestani 2012; see also Christiner & Reiterer, 2013). Although evidence from both functional and structural experiments indicates a solid link between these two groups of aptitudes as well as their congenital nature, it would be interesting to examine the alleged transfer of musical training, in particular of the vocal skill (cf. Christiner & Reiterer, 2013), to the development of imitation skills.

Summing up, the neurology of phonological aptitude is quite well explored, whereas morphosyntactic, lexical and pragmatic aspects of processing in the brain of poor *versus* successful foreign language learners belong to the less-well-explored regions of SLA. These areas need to be attended to in neuroscientific research on FL aptitude.

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