Cortical Plasticity in Multilingual Individuals

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SVEUČILIŠTE U RIJECI

ODJEL ZA BIOTEHNOLOGIJU

Preddiplomski sveučilišni studij

„Biotehnologija i istraživanje lijekova“

Dominik Ivandić

KORTIKALNA PLASTIČNOST U VIŠEJEZIČNIM OSOBAMA

Završni rad

Rijeka, rujan 2021.

Mentor rada: doc. dr. sc. Jelena Ban

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LIST OF ABBREVIATIONS

L1 – native (first) language

L2 – second language

MRI – magnetic resonance imaging

fMRI – functional magnetic resonance imaging

CT – computed tomography

AVS – auditory ventral system

ADS – auditory dorsal system

LTP – long term potentiation

LTD – long term depression

IPL – inferior parietal lobule

IFG – inferior frontal gyrus

NMDA – N-methyl-D-aspartate

ACC – anterior cingulate cortex

SUMMARY

The neural basis of language, from acquisition to its functions such as grammar and speech to its pathological issues, has been under scientific exploration for well over a century. Findings so far have mainly linked language to the frontal and temporal lobes of the cortex, extending from the original 19th century association with Broca and Wernicke's areas. Multilingualism, once discouraged as a "distracting influence on children" has slowly been described as a major driver of neuroplastic change in the brain. Since the advent of functional magnetic resonance imaging (fMRI), an increasing number of studies have linked multilingualism to both structural and functional changes, not only in the primary frontotemporal region. Since language employs an extremely wide variety of cognitive functions (from hearing to processing to speech), a wide cortical network is stimulated when learning and using non-native language. The neuroplasticity induced by multilingualism, interestingly, seems to be dependent on several factors: age of acquisition, combination of languages, level of fluency etc., all leading to significantly different adaptations in the brain. Of particular medical interest is the link between multilingualism and dementia, as many studies suggest a neuroprotective effect of language acquisition and second language use. This review summarises some of the most relevant findings in the field over the past two decades, as well as a selection of opinions by the prominent experts in bilingualism and neurolinguistics.

keywords:

neurolinguistics, neuroplasticity, language acquisition, multilingualism

SAŽETAK

Neurološka osnova jezika, od učenja do njegovih funkcija kao što su gramatika i govor do njegovih patoloških problema, tema je znanstvenog istraživanja više od stoljeća. Dosadašnja otkrića uglavnom su povezivala jezik s frontalnim i temporalnim režnjevima korteksa, polazeći od izvorne veze iz 19. stoljeća s Brocinim i Wernickeovim područjem. Višejezičnost, nekoć kritizirana kao "zbunjujući utjecaj na djecu", polako je opisana kao značajni pokretač neuroplastičnih promjena u mozgu. Od pojave funkcionalne magnetske rezonancije (fMRI), sve veći broj studija povezuje višejezičnost sa strukturnim i funkcionalnim promjenama, i to ne samo u primarnoj frontotemporalnoj regiji. Budući da jezik koristi iznimno širok raspon kognitivnih funkcija (od sluha preko obrade do govora), tijekom učenja i korištenja stranog jezika stimulira se široka kortikalna mreža. Zanimljivo je da neuroplastičnost koju izaziva višejezičnost ovisi o nekoliko čimbenika: dobi učenja, kombinaciji jezika, razini tečnosti itd., koji sve vode do značajno različitih prilagodbi u mozgu. Od posebnog medicinskog interesa je veza između višejezičnosti i demencije, jer mnoge studije ukazuju na neuroprotektivni učinak usvajanja jezika i upotrebe drugog jezika. Ovaj pregled sažima neke od najrelevantnijih nalaza na tom području u posljednja dva desetljeća, kao i odabir mišljenja istaknutih stručnjaka na području dvojezičnosti i neurolingvistike.

ključne riječi:

neurolingvistika, neuroplastičnost, učenje jezika, višejezičnost

CONTENTS

THE NEURAL BASIS OF LANGUAGE

The discovery of brain regions responsible for various aspects of language (hearing, speech, grammar, etc.) began with studies on aphasia – the pathological loss of language skills. Already in the mid-19th century, a left frontal region of the brain was identified as a speech-associated part of the human brain, now known as Broca's area. Soon after, also through observations of localised brain damage, another area was linked with the comprehension of language – Wernicke's area. Today, many other regions have been implied in the study of neural bases of language and it is now considered to be a highly non-localised function. [1]

Different aspects of language have been cortically mapped to various extents. Sound, for example, is very well understood and held to be processed by the auditory ventral ("what") and auditory dorsal ("where") system. Motor control of language production is highly distributed but relatively well understood. Other functions, however, remain relatively undescribed. The comprehension of grammar and syntax are more often subjects of philosophical than scientific debate, while the neurological basis of reading has produced an extremely small body of research. [1]

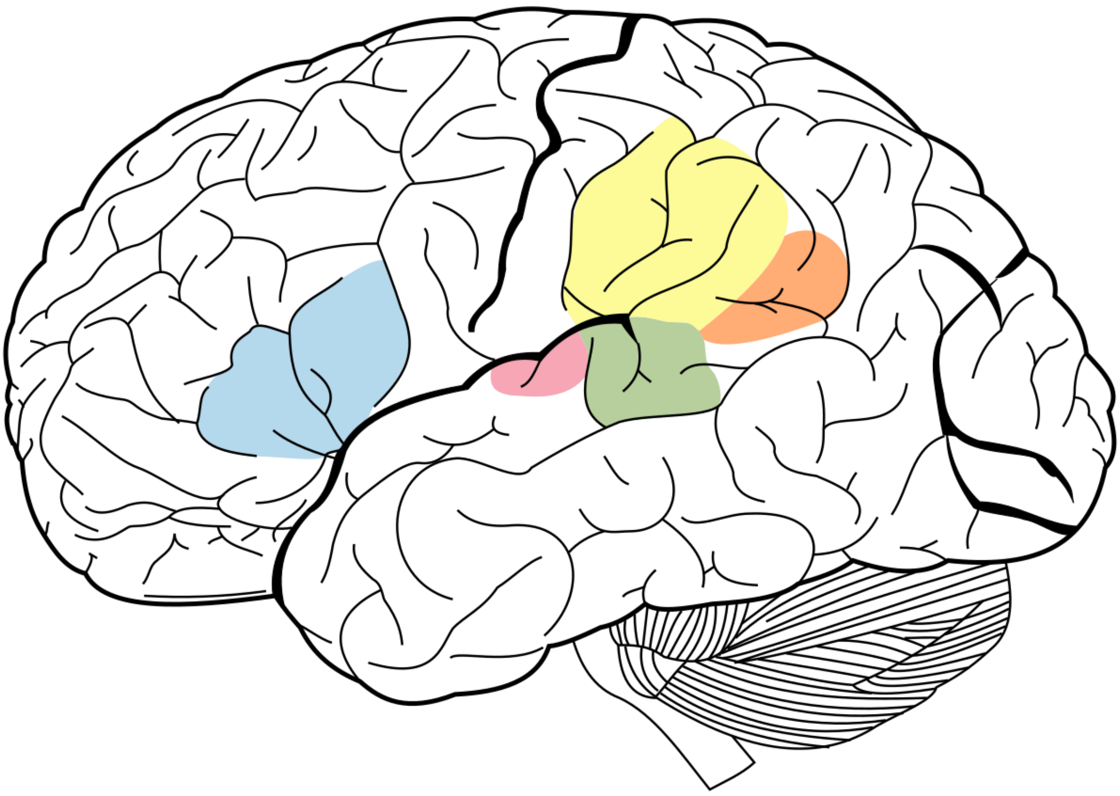

Figure 1. The main cortical areas associated with language. Broca's area in blue, Wernicke's area in green, primary auditory cortex in pink, supramarginal gyrus in yellow and angular gyrus in orange. (Image taken from commons.wikimedia.org/wiki/File: Brain_Surface_Gyri.SVG)

Hearing and sound interpretation occur mainly in Wernicke's area, located in the temporal lobe (Figure 1). First associated with hearing because of its proximity to the auditory cortex, it is now known that Wernicke's area also has a function in comprehending written language. The auditory ventral system (AVS) is sometimes referred to as the "what" system, since it is responsible for sound recognition – connecting the auditory complex to the temporal gyri (Figure 12), it processes sound into recognisable phonemes and words. How much it integrates sounds into linguistic units is yet unclear, but there are signs that some part of sentence parsing is also done in the AVS. The auditory dorsal system (ADS or "where"), on the other side, connects the auditory cortex to the parietal lobe (Figure 2) and is responsible for localising sounds. In addition, it is associated with speech production and phonological working memory, showing a strong correlation between hearing and reproducing sounds, which is the basis of language acquisition. Both pathways also connect to the inferior frontal gyrus, an area linked to a variety of neurolinguistic functions. [2][4]

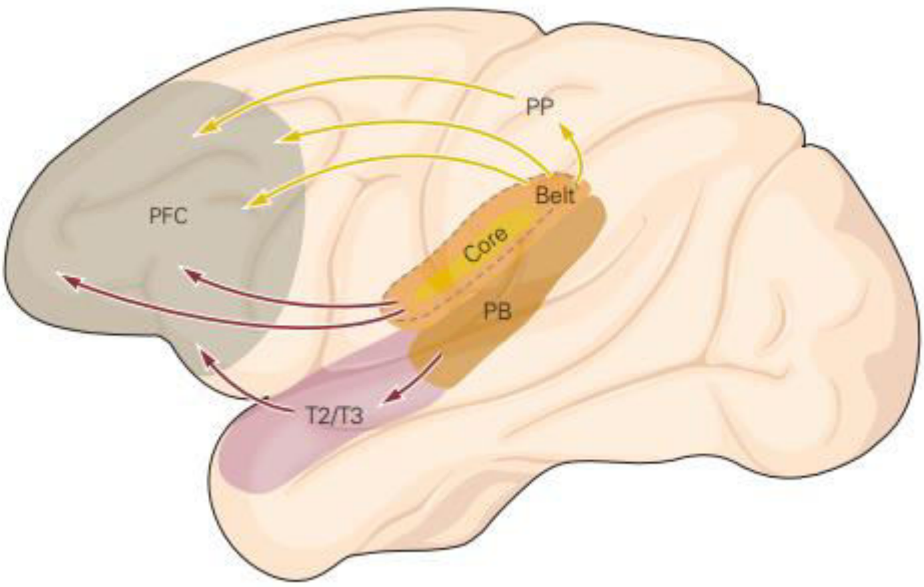

Figure 2. Approximate pathways of the AVS (red arrows) and ADS (yellow arrows) from the auditory to the prefrontal cortex. (Image taken from [1])

Speech and articulation are primarily handled by Broca's area, located posteriorly in the inferior frontal gyrus (Figure 1). While it was first associated with speech production, evidence from aphasia cases also points to a role in comprehension and involvement in grammar and syntax-related tasks. As with other language areas, it is most commonly highly lateralised in the left hemisphere. Other motor areas of the brain, including the cerebellum, also have a role in speech production. Unlike Broca's area, which handles the "linguistic" aspects of speech, these are mostly concerned with motor coordination during pronunciation and also integrating gestures and body language in conversation. [2]

Vocabulary is primarily a memory-related function, but much of its cognitive background remains unclear. One theory separates phonological and semantic memory, where one word regardless of language constitutes one semantic memory, but its translations into other languages are expressed as separate phonological memories. Evidence from aphasia patients and multilingual individuals seems to support this view and presents linguistic memory as an extremely non-localised and complex system that connects to all other language-related systems. [3]

Grammar and syntax have not been strongly associated to any cortical area or pathway. They are believed to be a defining human characteristic and the only linguistic functions in the brain that have no parallel in other animals. Whether they are a skill developed during the period of first language acquisition or an inborn trait (Chomsky's universal grammar – a theory that structural rules of language are innate to the human brain) is an open debate, but from a neuroscientific perspective this field remains highly speculative and unexplored. [3]

Lastly, reading and writing remain poorly explored, but studies have shown correlated activation of visual, motor and memory centres of the brain, pointing to a highly coordinated effort underlying these skills. [3]

One factor of note, and the one primarily explored in this work, is the differences exhibited in the brain when using one's native language (L1) and one's second language (L2). Indeed, bi- and multilingual individuals show not only differences in the functional aspects of language processing (activation patterns), but also neuroplastic structural differences compared to monolinguals. [5]

NEUROPLASTICITY AND LANGUAGE

While the concept of neuroplasticity was first postulated as early as the 18th century, it only received widespread attention and acceptance in the last decades of the 20th century. In its essence, neuroplasticity refers to the brain's ability to change, grow and reorganise on a neuronal level, especially after childhood. One specific form of neuroplasticity is commonly called activity-dependent plasticity, mainly driven by personal experience. As a form of "cognitive fine-tuning", it plays a significant role in all learning processes and is therefore the basis of language-associated neuroplastic changes in the brain. As almost all humans communicate in at least one language, the acquisition of one's mother-tongue cannot easily be studied as a neuroplastic process. Second language learning, however, poses a different perspective and provides an opportunity to observe brain development beyond the monolingual baseline and in relation to several factors which will be further explored in this work. [2] [4]

Neuroplasticity can, in broad terms, be divided into two main forms: structural and functional. Structural neuroplasticity refers to spatial reorganisations within the nervous system, observed mostly via magnetic resonance (MRI) or computed tomography (CT) as changes in white or grey-matter volume in different regions of the brain. Under the presumption that more intense use of a certain region results in an increase in its respective volume, this form of neuroplasticity can offer insight into which areas of the brain demand more use during certain activities. Functional neuroplasticity, on the other hand, is understood as a process of adapting individual synapses based on their usage, so they strengthen or weaken over time. As the function of a neuron changes, new pathways arise and their associated processes become more efficient, faster and less energy demanding. [2]

Both neurogenesis and synaptogenesis are essential components of neuroplastic development. So far, the mechanisms behind these have been explored but not fully explained. Long term potentiation (LTP) occurs when synapses are exposed to frequent stimulation and leads to a lasting increase in efficiency of those synapses (Figure 3). LTP is believed to be the first step toward neuroplastic change, induced by the calcium-activated N-methyl-D-aspartate (NMDA) receptor, which develops in response to higher frequency and intensity activation. Whether it induces or is accompanied by neuro- and synaptogenesis is not yet clear, but a combination of these processes leads to the development of new neuronal structures and connections, ultimately leading to observable neuroplastic development. [2]

A prominent theory on the matter (Bienenstock-Cooper-Munro or BCM theory) combines LTP and long-term depression (LTD – the opposite of LTP), stating that a complex interaction between the two slowly gives rise to new and strengthened synaptic pathways, while at the same time deprecating the ones that receive little or low intensity use. It is based on Hebb's rule – that repeated stimulation from a pre- to a postsynaptic neuron results in more efficient synapses; which is now understood to be a basic postulate of neuroplasticity. According to this, synaptic modification occurs as a result of preferential activation and negligence (synapses which are not stimulated or insufficiently stimulated to produce action potentials), which causes neurons to adapt to use "routes" which are more often in demand. Primarily referring to the visual cortex, it nonetheless presents a reasonable explanation for the mechanisms underlying neuroplasticity. [2]

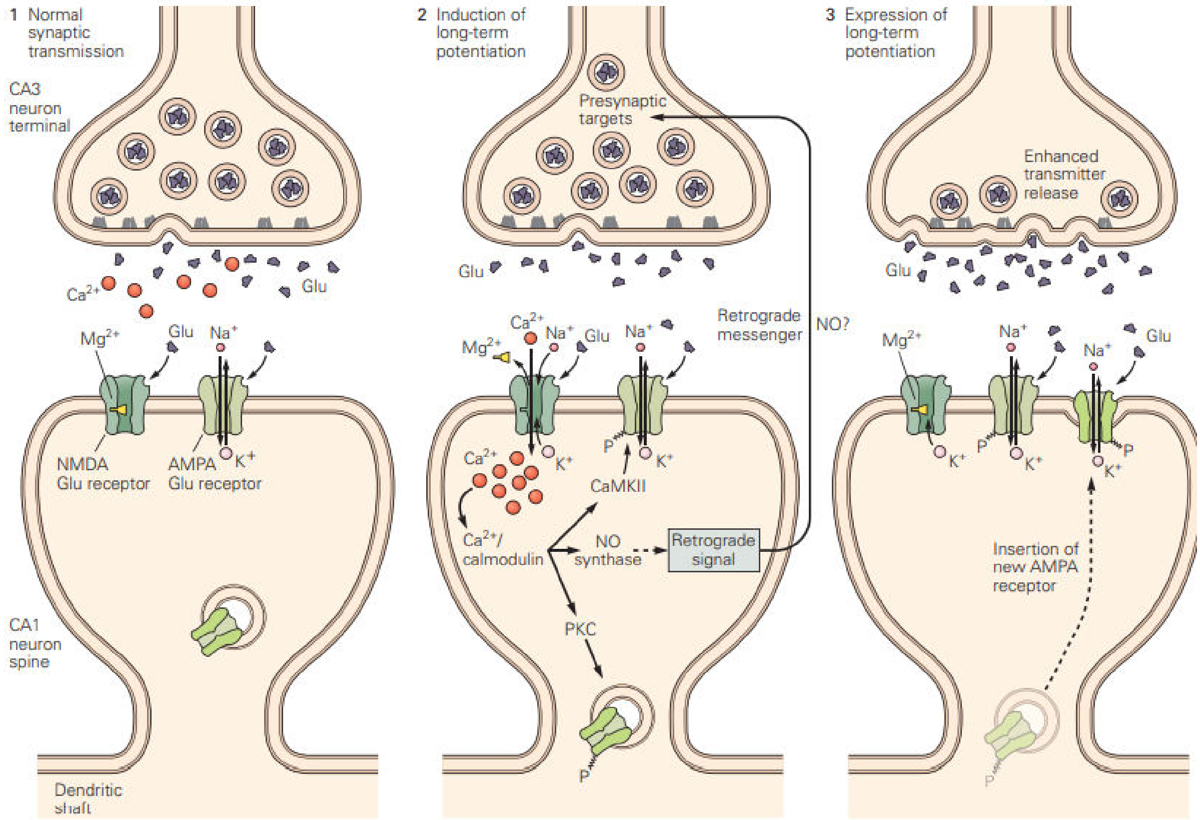

Figure 3. The underlying mechanism of long-term potentiation. (Image taken from [1])

The selective development of synapses and associated post-natal neurogenesis are therefore essential factors of neuroplasticity. Since it is an established fact that the rate of neuroplasticity decreases drastically after the critical period, which is usually estimated to be around three years of age for language functions, the study of language learning after this period provides unique insight into how these mechanisms persist at later stages of development. Given its ubiquitous daily use and versatility, it is only natural to expect language to have major neuroplastic effect on any brain. Research over the past decades has shown significant effects of multilingualism on both structural and functional neuroplastic changes, perhaps owing to the non-localised nature of linguistic functions, which hints at a vast and dynamic cerebral network supporting this distinguishing human capability. [5] [6] [7]

CHANGES IN THE MULTILINGUAL BRAIN

The first hint of cortical adaptation in the bilingual brain comes from analyses of cognitive tasks and activation patterns associated with them. Even non-verbal tasks show different activation patterns compared to monolinguals, as evidenced by functional MRI studies. Cognitive functions such as inhibitory control (the ability to supress an impulsive reaction and chose a more situation-appropriate one) and suppression of interference (the ability to ignore salient background stimuli while focusing on a task) were found to call upon different areas on the brain in bilinguals than in monolinguals. Tasks relating to control of interference (Figure 4) were also found to activate much larger brain areas in bilinguals than in monolinguals. All this suggests neuroplastic changes occurring in the bilingual brain, facilitating the parallel use of multiple linguistic systems and affecting other cognitive functions as well. [8]

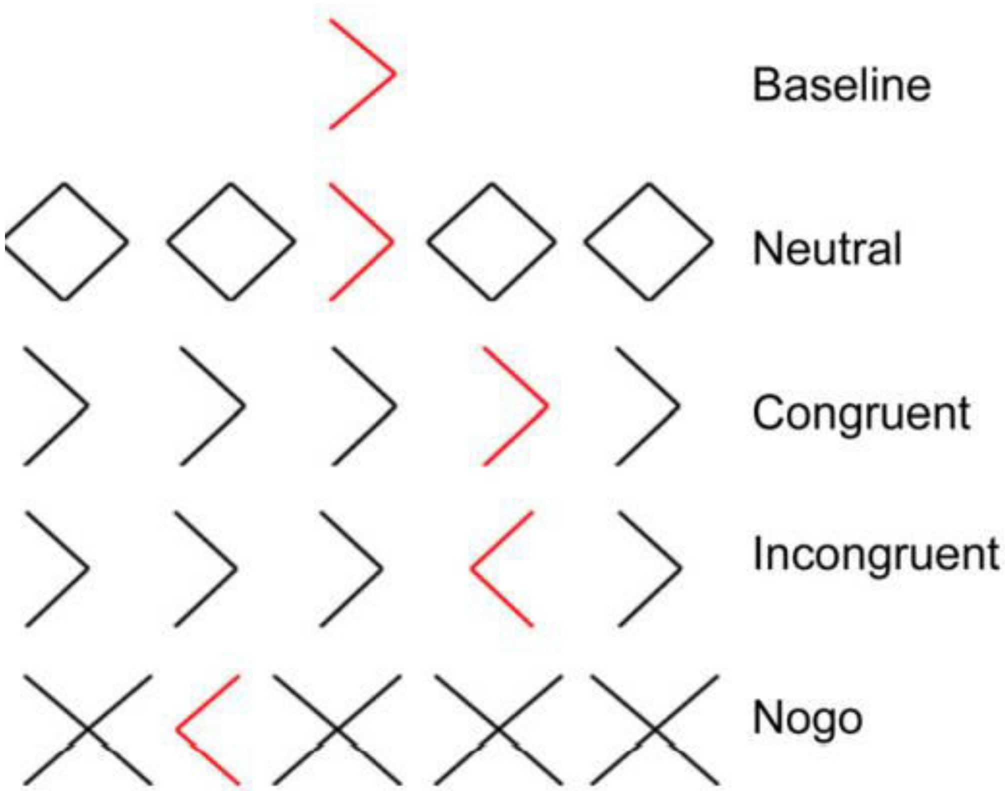

Figure 4. A sample control of interference task (Flanker task), where responding to the red chevron in relation to surrounding stimuli shows how well an individual can separate salient and conflicting information. (Image taken from [8])

Much of the cortical and subcortical network involved in the execution of language is shared between native and secondary languages. Comparisons of activation patterns by fMRI show near-identical results in bilinguals when using L1 as well as L2. Differences, however, are present, representing varied cognitive pathways involved in processing the two. One approach of interest is to separate the areas showing activation based on the functions they are connected with (semantics, grammar, phonology etc.). Data on the cortical areas involved in lexical and semantic functions is conflicting, especially as greater activation has, unexpectedly, been reported in L1 than in L2 use. Distinctions in the grammar-associated areas are clearer: the left insula is strongly involved in L1, whereas the bilateral putamen shows pronounced activation with L2. As for the phonologically-associated areas, the middle temporal gyrus is an example of a structure showing more intense activation when L1 is in use, as compared to L2. The inferior and superior frontal gyri, the left precentral gyrus and the right middle frontal gyrus, the left superior parietal gyrus, and the cerebellum all show greater activation when processing L2. All these areas are expected to show morphological differences in bilinguals, compared to monolinguals, as a result of different patterns of usage. [9]

CORTICAL DIFFERENCES IN THE BILINGUAL BRAIN

Structural differences in bilinguals

MRI studies display major differences between simultaneous and successive bilinguals in brain development: those who learned both languages at the same time show almost no deviation in brain structure from monolinguals, while those who studied their second language (L2) at a later stage display variations in cortical thickness. Specifically, the greater the chronological separation of language acquisition, the more contrast there is between a thicker left inferior frontal gyrus (IFG) and a thinner right IFG. The IFG contains Broca's area, the primary language-production centre of the brain and such results point to a need for structural changes in the brain when studying a language after the critical period. This neuroplastic increase in grey matter volume is thus directly associated with non-native bilingualism. Curiously, studies focusing on specific areas of the brain do find morphological differences in native bilinguals, but consistently with less significant deviation than in non-native subjects. [10]

An opposite correlation appears in the inferior parietal cortex, where individuals who acquired their L2 at an earlier stage exhibit higher grey-matter density than later-stage bilinguals. The same study, however, also pointed to a connection between proficiency (or fluency) and grey-matter density. Accordingly, greater L2 proficiency relates to higher grey-matter density (Figure 5). [11]

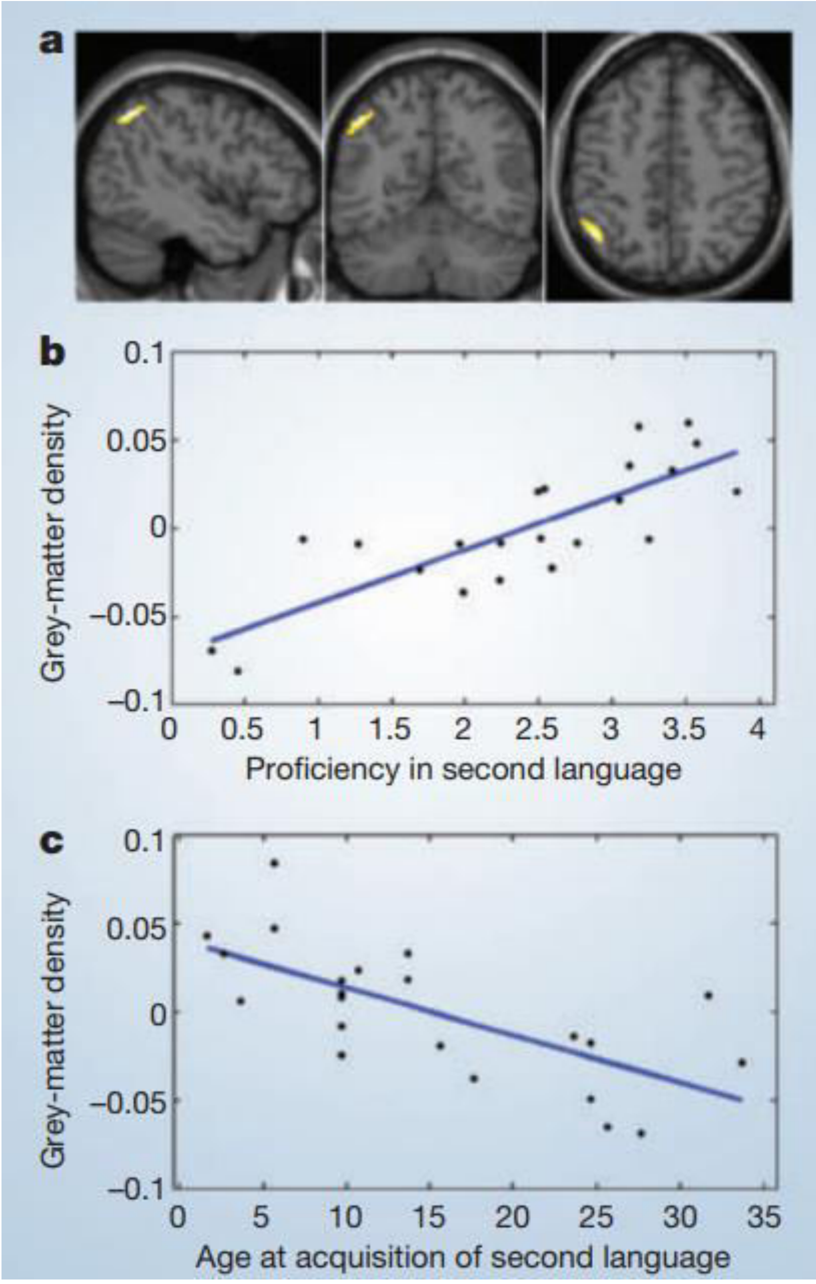

Figure 5. The location of the IPL (a) and its associated grey-matter density in relation to proficiency (b) and age of acquisition (c) of L2. (Image taken from [11])

Other areas, however, do show signs of morphological differentiation correlating with L2 proficiency. All three of the frontal gyri as well the fusiform gyrus were found to have greater grey-matter volume in more proficient bilinguals. The angular gyrus, reportedly responsible for matching letters with sounds, also adapts to bilingual needs in accordance with proficiency, displaying a relative increase in grey-matter in proficient bilinguals. These changes are of particular interest since they were corroborated in a study on Chinese-English bilinguals – two languages with completely different phonetic and orthographic systems. As such, it is possible that morphological differences in these areas are especially prominent given a need for more adaptation between these two languages. [12] The effects of bilingualism on grey-matter volume in the inferior parietal lobule (IPL) appear to be related to L2 proficiency and exposure more than the age of acquisition. Of particular interest is the contrast between the left and the right IPL. Whereas the left IPL shows correlation between increased grey-matter volume and L2 proficiency, the right IPL shows correlation between volume and the length of exposure to the second language. In addition, monolingual individuals show loss of grey-matter in the right IPL with age, while equivalent-age bilinguals do not (the left IPL retains grey-matter volume in both groups regardless of age) (Figure 6). As grey-matter volume loss is a common feature of many forms of dementia, bilingualism may provide a neuroprotective role in this aspect. [13]

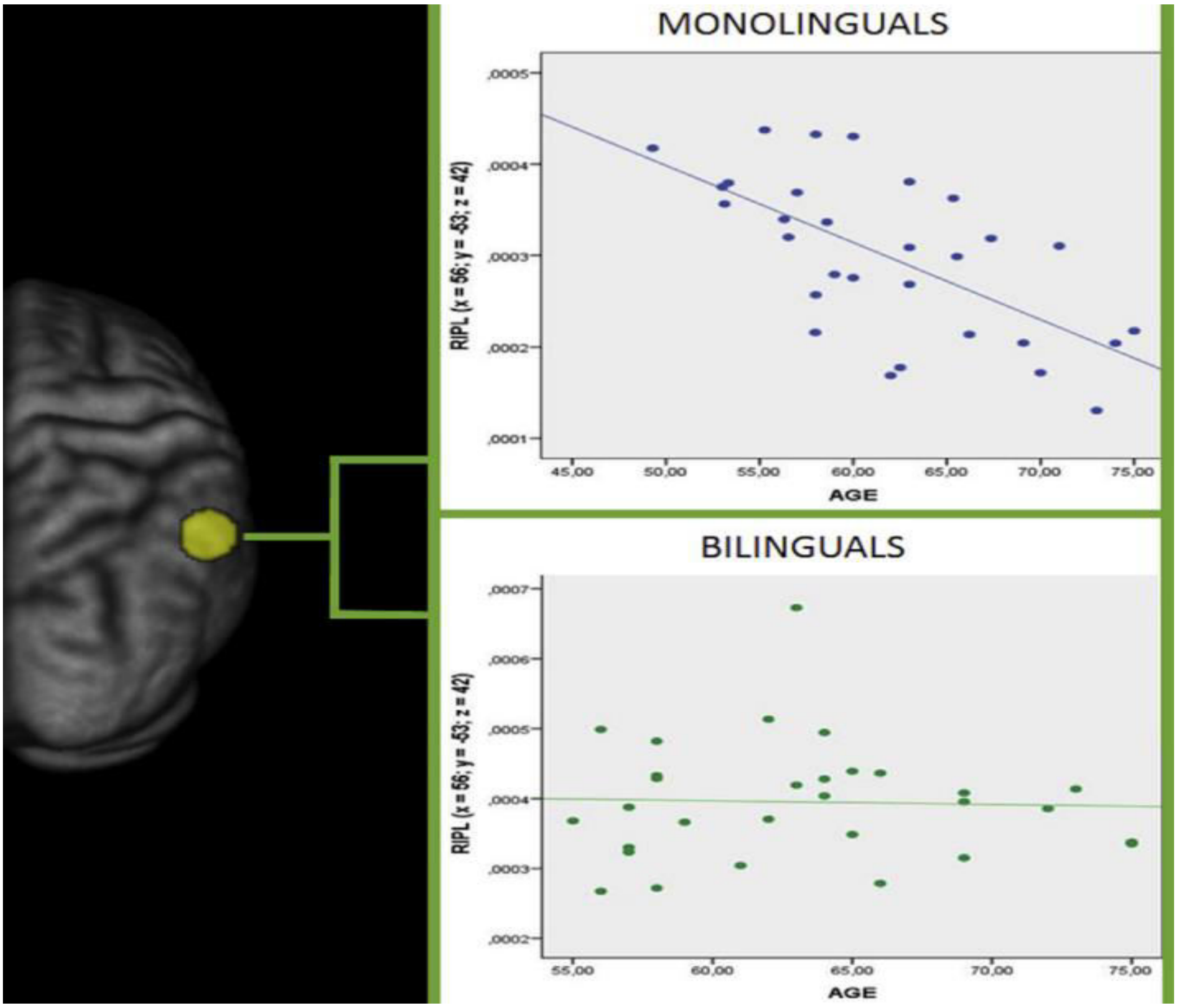

Figure 6. The effect of aging on the volume of the right IPL in monolinguals and bilinguals (Image taken from [13])

Altogether, simultaneous bilingualism does not appear to have noteworthy effect on the morphological development in the cortical areas. Sequential bilingualism, however, confers structural changes in the cortex, generally proportional to age of acquisition and proficiency. This is regarded by most to be a sign that the brain's linguistic capacity is "unlimited" up to a certain stage of development, and that language acquisition after this stage exacts certain adaptations in order to deal with new auditory, cognitive and motor demands. [9] [10] [13]

Functional differences in bilinguals

Since age of acquisition has been linked to the specifics of linguistic function even in monolinguals, there is strong evidence that the critical period of language acquisition is indeed conditioned in the brain. The typical patterns of activation of late-learning monolinguals resemble those of sequential bilinguals, suggesting that language learned after a certain period of brain development cannot be processed in the same way as the one learned before. Late-learners are associated with increased left lateralisation, less activation in anterior cortical areas and more activation in posterior cortical areas. Since functions related to grammar and syntax are mostly localised in anterior regions of the cortex and ones related with phonetic and visual processing are more posterior, it is suspected that language learned beyond infancy is processed using less sophisticated cortical networks. [14]

The size difference relative to age of acquisition recorded in the anterior gyri is supported by evidence of different localisation of L1 and L2. Native bilinguals show activation of almost identical (overlapping) parts of Broca’s area regardless which language they employ, while later-stage bilinguals show spatial separation when using different languages. This anatomical separation once again relates to the critical period of language acquisition, as non-native bilinguals require different functional organisation of Broca’s area in order to accommodate linguistic forms acquired after the critical period. [15]

Some evidence, however, suggests that this spatial separation might also be a function of fluency in L2, as newer studies show decreased separation with advancing proficiency whilst studying a new language. A progressive study comparing activation patterns across the brain during various stages of second language acquisition pointed to the idea that some functions become less and less distinct as the brain becomes more accustomed to the new language (Figure 7). Before learning, exposure to

L2 showed similar activation only in the supplementary motor area and the left IFG. With growing proficiency, the degree of spatial overlap increased, with notable differences depending on the type of task performed. During lexical tasks, the spatial overlap grew in the insular cortex, the inferior frontal gyri, the left inferior parietal cortex and, on the subcortical level, in the left pallidum. Semantic tasks provoked growing activation similarity in the insular cortex, the left inferior frontal gyrus, the left inferior temporal gyrus, and in subcortical structures including the left pallidum and the thalamus. Different tasks naturally require engagement in different areas of the brain, but evidently some of them require more and some less adaptation, regarding both time and volume of change seen. [16] Proficiency in L2 seems to affect other areas as well. The left insular cortex shows greater activation in more proficient bilinguals than in less experienced bilinguals when exposed to foreign sounds. Interestingly, the insular cortex is otherwise associated with grammatical processing, but recent studies indicate its involvement in auditory perception and audio-visual integration. Articular coordination was also linked to the left insula, perhaps expectedly given its connection to Broca’s area. Greater activation of the left insular cortex and the left inferior frontal gyrus may be indicative of more efficient processes relating to phonetic memory. [17] [18]

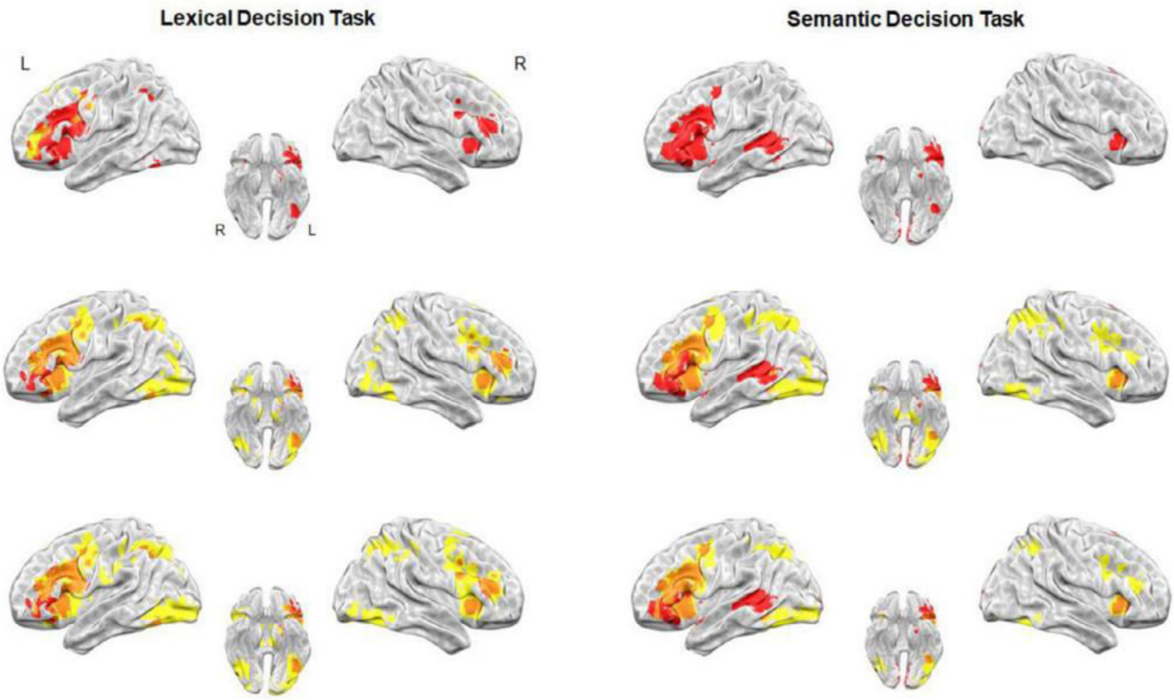

Figure 7. Convergence of activated areas when performing tasks in L1 and L2. As the study period grows (top to bottom) there is less separation between L1 (red) and L2 (yellow) and more convergence (orange). (Image taken from [16])

These findings support studies on non-native speech processing, which show a difference in phonological interpretation between simultaneous and successive bilinguals. In addition, younger bilinguals (those less proficient in L2) process the sounds of their second language over an L1 framework, whereas older bilinguals process these sounds more directly. In younger bilinguals, the superior temporal gyrus (an auditory processing area) is activated when exposed to non-native sounds, the same as in monolinguals. On the other hand, older bilinguals activate the bilateral middle frontal gyrus and the bilateral inferior parietal lobule in the same conditions, showing higher-level processing and distinction. In other words, those less experienced with foreign sounds recruit sensory areas when exposed to them, while those more experienced recruit executive areas to process them. This points to the conclusion that phonological processing is affected by both the amount of phonemes one is familiar with and length of exposure to them. [19]

Even more interestingly, there is evidence that this transition from sensory to cognitive processing may be associated with exposure to language, regardless of acquisition. A study comparing French monolinguals, French-Chinese bilinguals and Chinese children adopted in France when exposed to faux-French words produced similar results in the latter two groups, contrasting with the monolingual one. While effectively monolingual, the adopted children began their lives in Chinese-speaking environments, subsequently switching to exclusively French-speaking environments before the age of three. Despite no overlap in the use of or exposure to the two languages, fMRI data showed them to exhibit the same activation of the left cingulate gyrus, right precuneus and bilateral temporal gyri as the bilingual group. The French monolinguals, conversely, exhibited activation in the left inferior frontal gyrus and the right middle temporal gyrus. Given the vastly different phonetic inventories of the two languages, this suggests that mere exposure to multiple languages induces a transition in auditory processing mechanisms. [20]

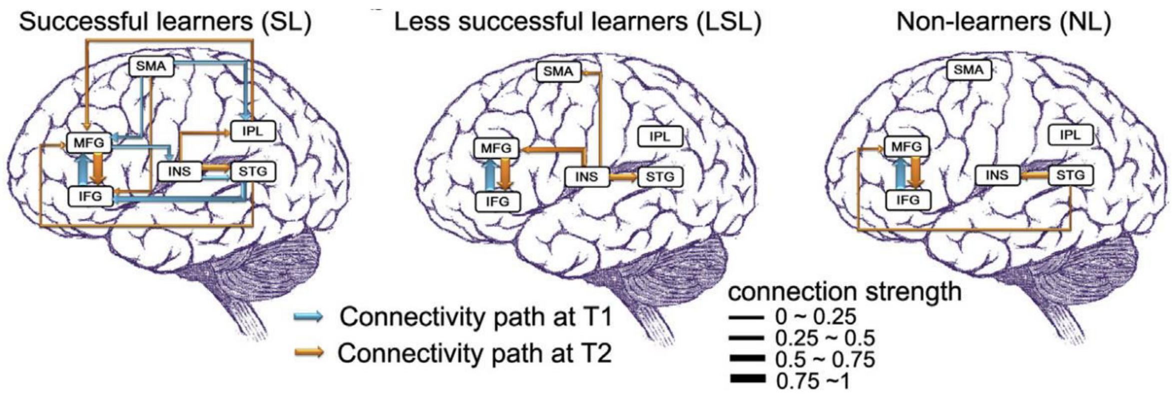

Figure 8. Different pathways and their relative strength used in phonetic processing by successful and non-successful first-time language learners. (Image taken from [21])

Different cognitive pathways related to sound and meaning correlation may arise very early in the process of learning a second language, perhaps accommodating the need to not only connect phonemes with meaning but also separate them based on language input. Comparing early second-language learners based on success of acquisition, several contrasting patterns of activation are seen. More accomplished learners display a strong connective pathway between the superior temporal gyrus and the middle frontal gyrus, as well as one between the supplementary motor area and the inferior parietal lobule. Conversely, less accomplished learners display strong connectivity between the middle frontal gyrus and the inferior parietal lobule, in addition to a pathway between the inferior frontal gyrus and the insular cortex that is completely absent in the first group (Figure 8). Not only does study of language affect these pathways, but a degree of neuroplastic adaptation seems to be a prerequisite for successful language acquisition. [21]

These pathways imply a network of cortical areas that develop stronger connections in bilinguals as a result of more frequent specific use. One particular axis, comprising in order the insular cortex, superior temporal gyrus, pars triangularis, supramarginal gyrus, pars opercularis and the medial superior frontal gyrus (all of the left hemisphere) has been identified as not only a specific route used by the bilingual brain but also for its correlation with proficiency. This pathway shows much stronger collective activation in bilingual brains than in monolinguals and much stronger activation in proficient bilinguals than in beginner learners. Such data points to a prominent neuroplastic adaptation as a direct consequence of language acquisition, consisting of a network of areas involved in a wide variety of linguistic functions. Another axis, composed of the left superior occipital gyrus, the right superior frontal gyrus, the left superior parietal gyrus, the left superior temporal pole and the left angular gyrus, is noted for several peculiarities (Figure 9). Firstly, the widely separated and bilateral distribution implies a role in multimodal processing, possibly as an adaptation to an increase in both phonological and orthographic demands. Secondly, its efficiency was immensely greater than in monolinguals, pointing to an unquestionable origin in bilingualism. This functional reorganisation across multiple brain lobes serves as further evidence of the multifaceted nature of bilingual neuroplasticity. [22]

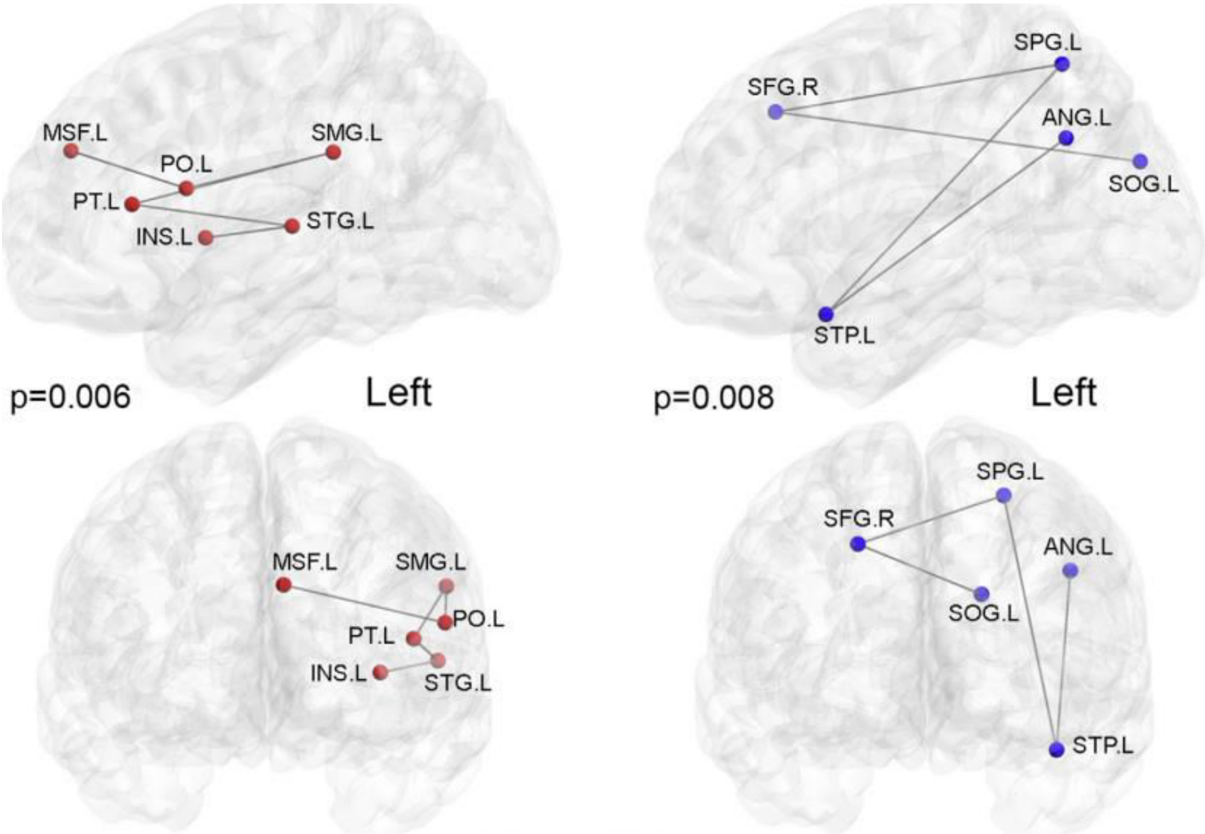

Figure 9. The left hemisphere pathways showing improved connectivity in bilinguals. In red the insular cortex to medial superior frontal gyrus axis, in blue the superior occipital gyrus to angular gyrus axis. (Image taken from [22])

The anterior cingulate cortex (ACC), responsible for conflict control in cognitive tasks, shows interesting differences in performance when comparing monolinguals to bilinguals. Since the use of two or more languages is a conflicting task, the bilingual brain is more exposed to this type of situation and is forced to make adaptations. Indeed, fMRI data suggests that, when performing similar linguistic tasks, the ACC requires significantly less activation in bilinguals than in monolinguals (Figure 10). Also showing a positive correlation between grey-matter volume and the conflict-effect in bilinguals, the ACC seems to be more effectively tuned for distinguishing conflicting information in bilingual brains (Figure 11). [23]

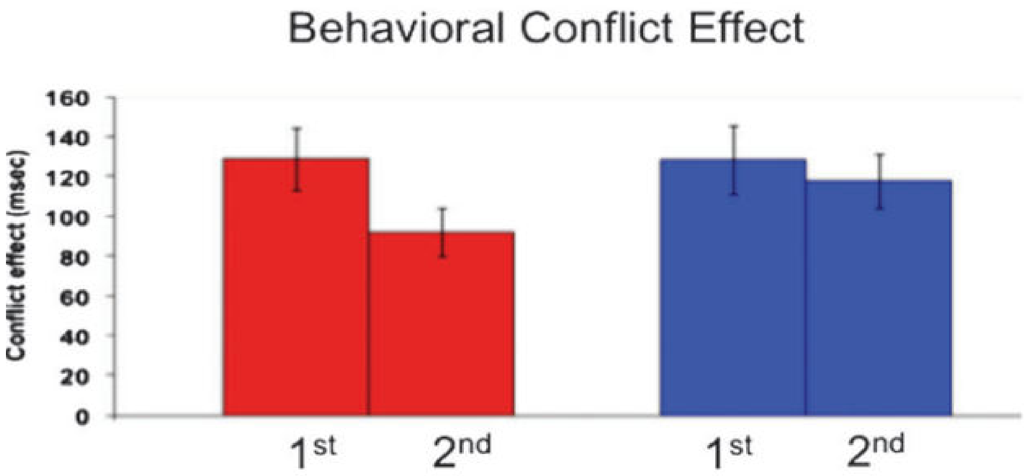

Figure 10. Comparison of response time to conflicting information in a Flanker task, showing more significant improvement in repeated tasks in bilinguals (red) than in monolinguals (blue). (Image taken from [23])

Unlike structural neuroplasticity, functional refits of the brain appear in all bilinguals. Both simultaneous and sequential bilinguals of various levels of fluency exhibit changes in activation patterns and inter-structural connections. Generally, these changes imply that bilingualism forces the brain to adopt new strategies of dealing with information, including both outside auditory and visual stimuli and internal cognitive processes involved in sorting and accessing knowledge. Due to the increased efficiency shown in some of these, a growing consensus is that bilingualism may stimulate the brain to develop more efficient pathways related to conflicting information, auditory perception and other functions. [15] – [23]

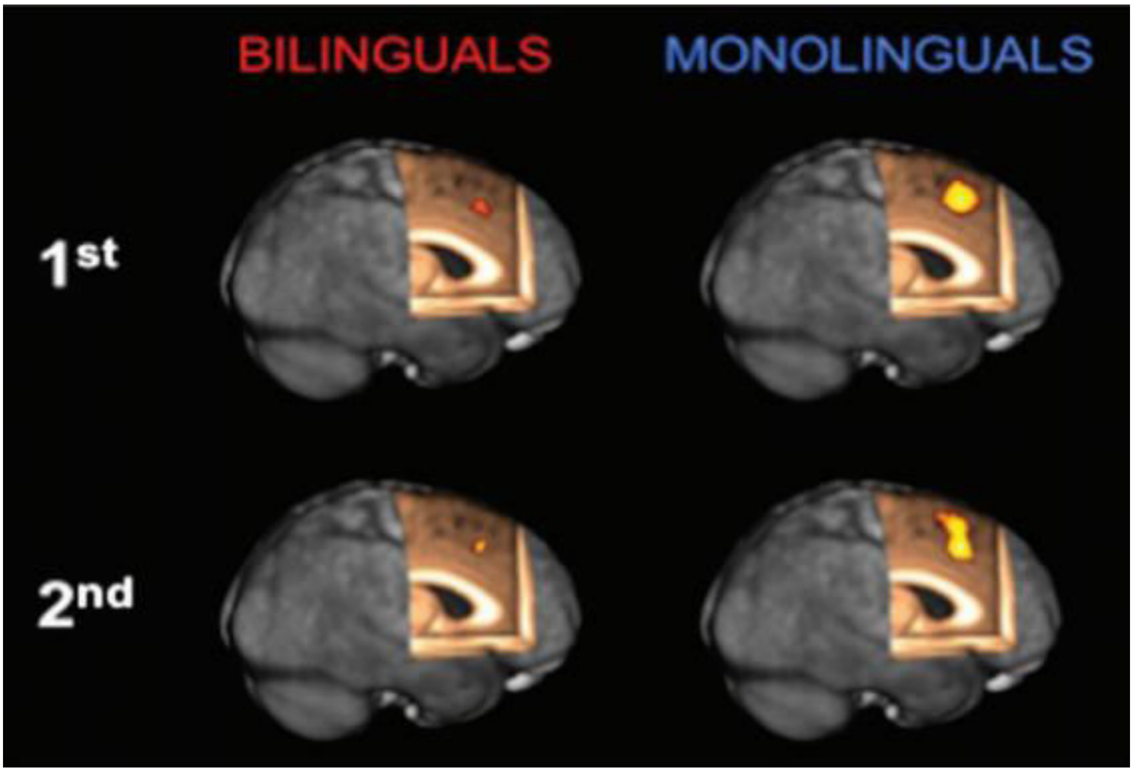

Figure 11. Activation patterns in the ACC during a repeated Flanker task, showing less cognitive demand and more improvement with repetition in bilinguals. (Image taken from [23])

Protective effects of bilingualism on grey-matter

Increase in grey-matter volume in bilinguals contrasts with the loss of grey-matter caused by dementia and provides a possible barrier to cognitive loss. In fact, multilingualism has been found to offer a neural reserve via several mechanisms. Aging is generally associated with grey-matter loss across the cortex, while bilingual and multilingual individuals show increase in grey-matter volume and slower loss of grey-matter with age. While acknowledging that there are multiple factors affecting the onset of dementia, several studies have found that, on average, this occurs four to five years later in bilinguals than in monolinguals. Whether or not socioeconomic and educational factors are dominant in this effect remains to be seen, but evidence so far suggests a definite correlation, induced by changes in neuroplasticity and both grey and white-matter integrity of the bilingual brain. [24]

SUBCORTICAL DIFFERENCES IN THE BILINGUAL BRAIN

Even at the subcortical level, various structures display noteworthy morphological differences in the bilingual brain. The putamen and the thalamus, in addition to the right caudate and left globus pallidus were all found to be larger in bilinguals, with differences as to the axis of expansion (Figure 12). The left putamen shows expansion along the structure, both in the internal and the external surface, whereas the right putamen shows localised expansion in the anterior part of the structure. The thalamus, however, shows a bilateral expansion, relating to its less specialised role in language. A study on Spanish-Catalan simultaneous bilinguals (two closely related languages differing mainly on a phonological basis) found pronounced putaminal expansion compared to Spanish monolinguals, in accordance with the presumed articulatory processing role of the putamen and the larger phonological inventory of Catalan compared to Spanish. Altogether, subcortical structures have more recently been found to contribute to linguistic functions and act in liaison with cortical ones. [25]

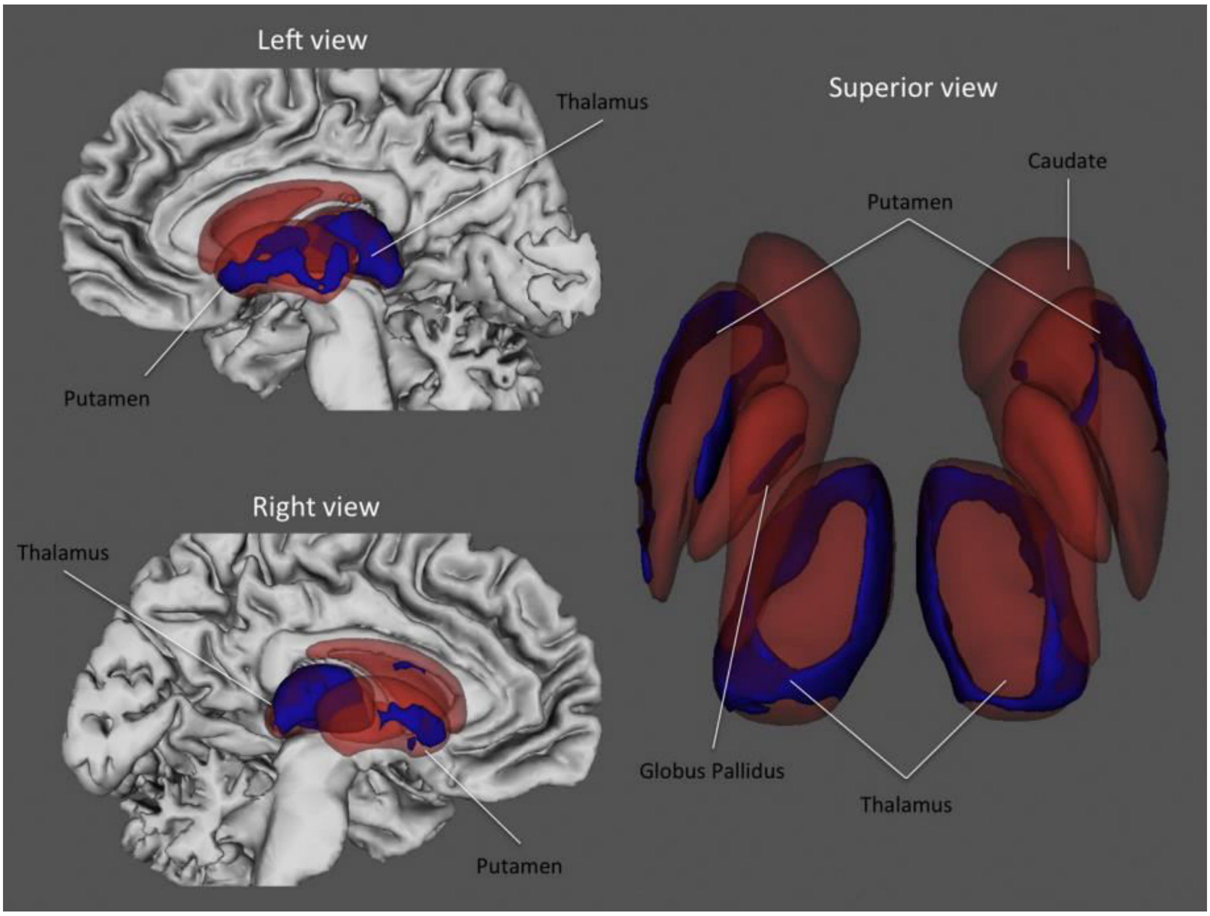

Figure 12. Areas of the thalamus and the putamen showing expansion in bilinguals compared to monolinguals (Image taken from [25])

At the same time, a comparison of these structures between simultaneous and sequential bilinguals showed a correlation between the amount of exposure to the second language and the relative change in morphology. Sequential bilinguals with less immersion were found to have caudate nuclei reshaped in a different manner than other groups of bilinguals, suggesting a role of the caudate nuclei in the early stages of language acquisition. The caudate nuclei are associated with the function of language switching, governing the choice of pathways dependent on the language used. Presumably, this function shifts to another area as experience with L2 grows, since experienced bilinguals showed less deviation from the monolingual norm. This is a unique example of a possible redundancy in the brain's linguistic apparatus. The same study showed the thalamus and the putamen to undergo morphological changes proportional to the amount of exposure to L2, suggesting a permanent role in the bilingual brain. The relationship between volume of change and exposure, while still relatively unexplored, indicates that their functions require additional space to develop individually. A possibility, given the connection with articulation, is that specific sounds receive their own dedicated pathways in these structures. [26]

Expectedly, the corpus callosum also shows structural differences in bilinguals. Even though language shows a strong left lateralisation in the brain, linguistic functions are processed in both hemispheres and the connection between them, i.e., the corpus callosum, requires adaptation to increased phonological demands of bilingualism (Figure 13). These phonological demands include not only phonetic discrimination but also motor correlation in the vocalisation of a larger number of sounds (phonemes). The change in area ratio (area of a substructure vs total corpus callosum area) is most pronounced in the anterior section of the trunk, which occupies a larger proportion of the whole corpus callosum in bilinguals, compared to monolingual individuals. The increased relative volume of the anterior trunk of the corpus callosum indicates its role in relaying language-related information between the hemispheres, with a necessity for additional pathways to support the use of more than one language. [27]

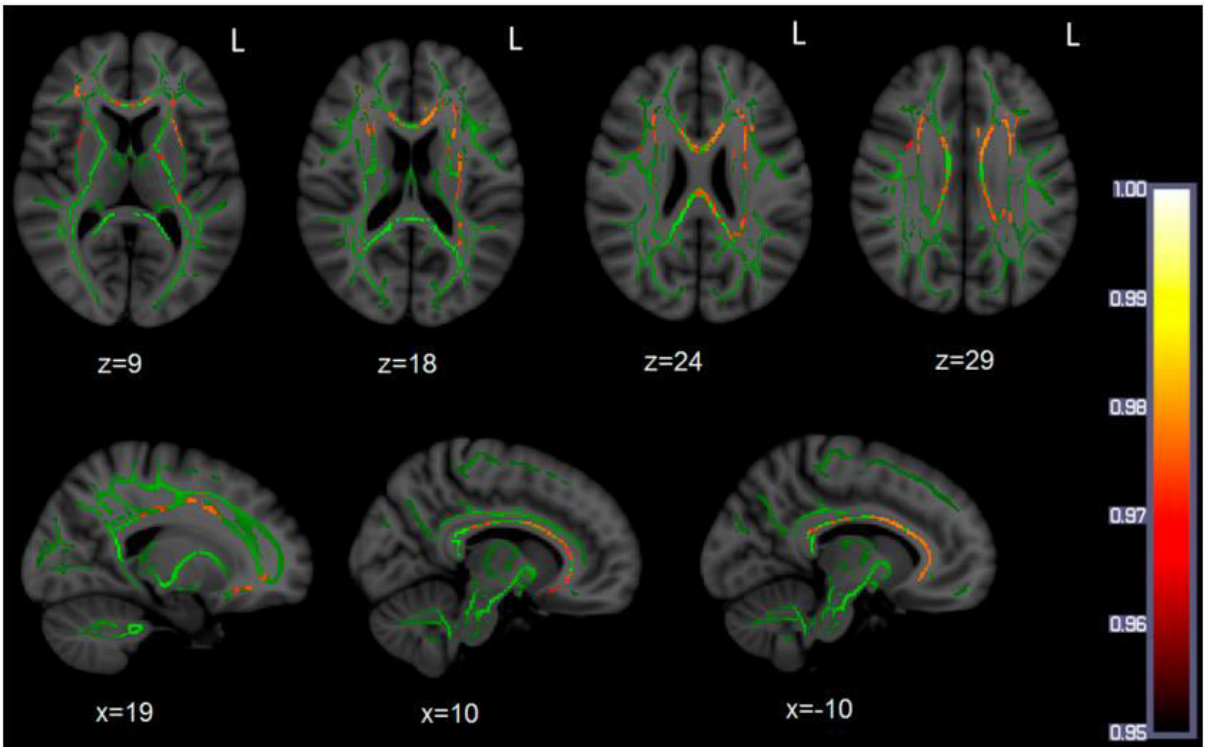

Figure 13. White matter pathways showing stronger activation patterns in bilinguals (red) concentrating around the corpus callosum. (Image taken from [27])

Although evidenced by less studies, there is ample data on neuroplastic white-matter development in bilingual individuals. Indicated as having supporting roles in linguistic functions, the thalamus and the putamen are especially linked with bilingual development, interestingly showing notable morphological changes even in simultaneous bilinguals, unlike most cortical areas. [25] [26]

Protective effects of bilingualism on white-matter

White-matter loss is a common observation with age, leading to loss of cognitive function and forms of dementia, just as with grey-matter loss. However, data demonstrating improved retention of cognitive control in aged bilinguals prompted the question of the neuroprotective role of bilingualism at the subcortical level. Regular recruitment of mechanisms of cognitive control necessary for everyday use of more languages enhances white-matter connective pathways and increases white-matter density. Higher white-matter integrity was recorded in the posterior part of the superior longitudinal fasciculus and anterior parts of the uncinate and inferior occipitofrontal fasciculus, pointing to improved connectivity on the frontal– occipital and frontal–parietal range. This redistribution of white-matter integrity is also maintained with age, offering a possible neuroprotective effect on the bilingual brain. [28]

THE CEREBELLUM IN THE BILINGUAL BRAIN

Alongside its attested role in motor control, the cerebellum has been implicated in language functions as well. Activation of the cerebellum is especially noted during the use of L2, implying its role in coordination of non-native speech. Again, proficiency in L2 is positively correlated with increased grey-matter volume in the cerebellum. As the cerebellum is involved in procedural memory, it is believed to be associated with processing grammatical structures and rules. Studies show it to be most active when performing grammar tasks and its grey-matter density to increase with proficiency and amount of exposure to L2. [29]

THE MULTILINGUAL ADVANTAGE

Despite the fact that the body of work describing neuroplastic changes caused by multilingualism remains limited, summaries and reviews of previous findings attempt to paint a complete picture of this process. Altogether, mounting evidence supports the hypothesis that multilingualism is a path towards improved cortical connectivity, increased cognitive plasticity and a possible neuroprotective benefit. [30] The wide fronto-temporal network strongly associated with language shows definitive improvement in connectivity and performance when compared to monolingual brains and a large body of work relates this to delayed onset of dementia. [31] No concrete and detailed mechanism of first-language acquisition has so far been described, but it is obvious that non-simultaneous L2 acquisition does not follow the same mechanism as this. Repetition and imitation may still form the basis of language study in this case, but other forms of learning are involved, clearly utilising a different cognitive strategy and, at the same time, potentiating the development of these connective pathways. [32] At the same time, the reviews agree that the lack of correlation between the studies so far offers highly diverging evidence, obscuring the possibility of a clear perspective on the subject. A general advantage in brain performance and aging is now almost a matter of consensus, but its actual specifics have not been sufficiently elaborated. [33]

CONCLUSION

Decades worth of study offer conclusive evidence that multilingualism provokes neuroplastic changes in the brain, primarily concentrated in the frontal and temporal regions, but also spanning subcortical areas and even the cerebellum. A contrast is seen between native or simultaneous bilinguals, who show little to no structural neuroplasticity, and sequential bilinguals, showing major structural changes across the brain. Functional changes in connectivity occur in all groups and are linked to improved performance in a variety of cognitive tasks. An obstacle to a conclusive picture, and a cause for further, correlated research, is that several factors (including age of acquisition, fluency, pairing of languages etc.) all apparently lead to different neuroplastic adaptations. Unfortunately, lack of synchronicity between different works in the field makes it difficult to control for specific factors in a wider perspective. Nonetheless, certain trends in plastic development caused by the increased cognitive load of multilingualism can already be identified. While such fundamental concerns provide a purely scientific curiosity, strong links between multilingualism and delayed onset of loss of cognitive function and dementia are a valid reason for continued medical interest in the field.

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	Listening	Reading	Spoken production	Spoken interaction	
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SPANISH	C1	C2	C1	C1	C1
PORTUGUESE	C1	C1	C1	C1	C1
GERMAN	B2	C1	B2	B2	B2
RUSSIAN	B2	B2	B1	B1	B1
ENGLISH	C2	C2	C2	C2	C2

Levels: A1 and A2: Basic user; B1 and B2: Independent user; C1 and C2: Proficient user

DIGITAL SKILLS

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PROJECTS

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Students' educational field trip

Organiser and assistant of students' educational field trips paired with scientific workshops and cultural lectures in fields such as bioplastics, sustainable nutrition, natural cosmetics, local history etc. Managing food, resources and activities for over 100 attendees.

2020 – CURRENT
Student instructions for high school seniors

Organiser and project leader of preparatory classes for high school seniors in mathematics, physics, chemistry and biology led by students from respective disciplines.

11/2020
Conference - Future and Perspective

Assistant organiser and scientific panel moderator in students' employment conference

2017 – 2018
Travelling scientists

Participant in workshops on popularisation of science among children and the general public

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Leader of the Science Office of the Student Council

Coordinating scientific projects across the University of Rijeka, running activites on popularisation of science

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2014 – 2017 – Zadar, Croatia
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