Understanding Second Language Acquisition:
Can Structural MRI bring the Breakthrough?

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Abstract

Many speculations exist about how second and/or third languages are represented in the brain. The pattern that emerges from functional neuroimaging studies is far from consistent. While some investigators found at least partly different representations for different languages, others reported findings that do not support the hypothesis that different languages are represented in distinct brain regions. In a few studies, shared neural substrates were found. However, most of these different results can be explained by differences of the proficiency level of the bilingual- and multilingual participants. Recently, the focus has moved from the functional to the structural level. Are there any structural plastic changes in the human brain during the process of second language acquisition? Is there a specific (second) language acquisition area? In this paper, functional and structural neuroimaging data will be discussed to answer these questions.

Language Representation

Many speculations exist about how second and/or third languages are represented in the brain. A major hypothesis is that, in bilinguals and polyglots, the different languages are represented and processed in distinct brain regions. Some indirect evidence for this hypothesis has been found by Paradis [37]. Paradis conducted studies with bilinguals and/or polyglots suffering from aphasia. In these participants, it was occasionally observed that only one of the mastered languages was affected [3], [38]. Moreover, it is not unusual to find that different languages recover to different degrees or that there even is an antagonistic pattern of recovery between two languages [36]. More evidence in favour of the hypothesis was found in electrical stimulation studies. There it was shown, that in multilingual speakers, different languages may be disrupted selectively [10], [34], [35]. Neurosurgery as well, may lead to a selective impairment of one language in bilinguals [19]. Furthermore, the idea of different representations for multiple languages is in line with the observation that under normal circumstances bilinguals can easily keep their two languages apart [54].

Recently, neuroimaging techniques such as PET and fMRI have allowed a more direct study of the neural representation of language in bilinguals and polyglots. However, the pattern that emerges from PET and fMRI studies is far from consistent. While some investigators [15], [25], [41], [58], found at least partly different representations for different languages, others [23], [26], [27] reported findings that do not lend support to the hypothesis that different languages are represented in distinct brain regions. In a few studies [13], [28], [44], [50], [54], shared neural substrates were found, even for such contrasting languages as Mandarin and English.
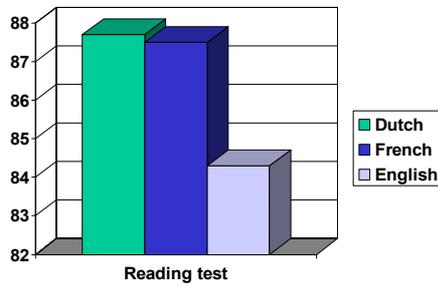
FMRI-Studies

Comprehension Reading

The purpose of the first study was to investigate the cerebral activation associated with comprehension reading in the mother tongue and the non-native languages of multilinguals [51].

Twelve healthy right-handed male volunteers participated in this study. Participants were native speakers of Dutch (Flemish). French and English were learned as a foreign language in classroom settings at a mean age of respectively 10.3 (SD = 0.5) and 13.5 (SD = 2.0) years old. To determine language background and proficiency, the participants completed a language background questionnaire based on the Bilingual Aphasia Test [39]. During the scanning period, participants silently read visually presented texts in Dutch, English, and French. The texts were selected from newspapers of equal reputation (Dutch: De Standaard; English: The Times; French: Le Monde). Texts were matched as far as possible for length (approximately 100 words), difficulty, and content. The control condition of the comprehension reading task required the reading of nonsense texts. These nonsense texts were also matched for length and consisted of pseudowords that were orthographically regular, pronounceable strings of letters that were neither real words nor homophones of real words of the different languages. The comprehension reading task was divided into six blocks, each consisting of three epochs of 30 s of experimental task (reading in Dutch, English, and French) and one 60 s epoch of a control task (reading nonsense text). The order of the languages was randomized over the blocks [43]. The data were acquired using a 1.5 Tesla Siemens Symphony MRI scanner using an EPI sequence (TR=3.0 s, TE=60 ms, flip angle 90º, voxel size 3 x 3 x 5 mm). All data processing and group analyses were performed using statistical parametric mapping (SPM 99).

The paper and pencil version for the comprehension reading task consisted of answering difficult factual multiple-choice questions referring to the stories read during fMRI scanning. As can be seen in Fig 1, the participants averaged 87.7% (SD = 15.1%) correct responses in Dutch, 87.5% (SD = 17.5%) correct in French, and 84.3% (SD = 15.6%) in English. Differences in mean scores between languages on this task were not found significant by paired samples t tests.

Brain areas involved in meaningful reading in Dutch were BA 21 and BA 39 bilaterally. Regions that appeared active during comprehensive reading in the foreign language conditions were BA 21 bilaterally and BA 45, BA 47, and BA 6 (see Fig 2).

Our results suggest that the performance of comprehensive reading in different languages engages largely the same cerebral areas. However, the brain seems to engage more neural substrates for later acquired languages in order to perform at a comparable proficiency level.
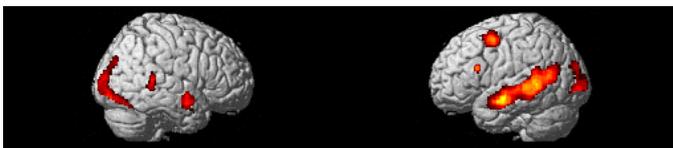

Fig 1. Percentages of correct answers per language on a multiple-choice test consisting of questions referring to the stories read during fMRI scanning.
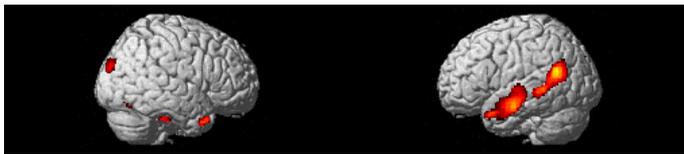
(A)
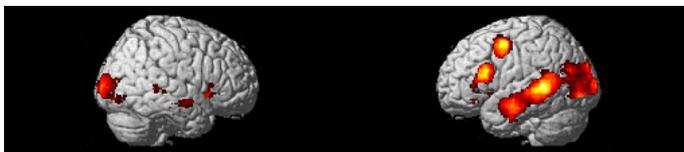
 (B)

(C)

Fig 2. Results from the FMRI study. In general, overlapping regions of activation for the languages (A = Dutch, B = French, C = English) were found. However, the foreign languages also elicited left frontal activation in speech and premotor areas ($p < .01$).
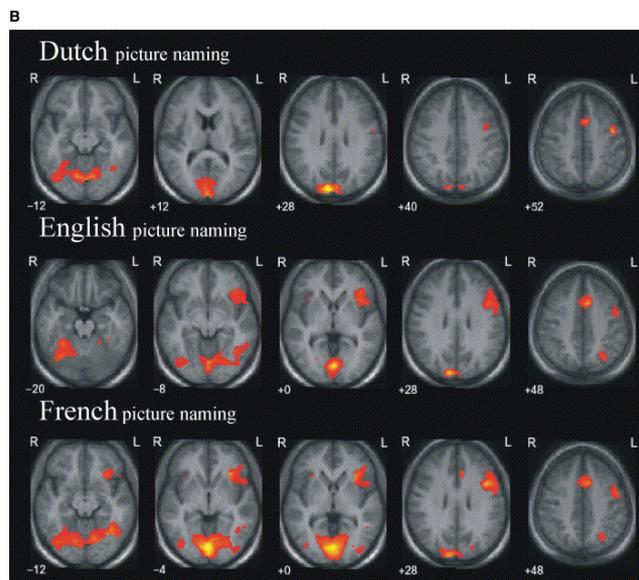
Picture Naming

The purpose of the second study was to investigate the cerebral activation associated with object naming in the mother tongue and the non-native languages of multilinguals [55].

Twelve healthy right-handed male volunteers were native speakers of Dutch and learned English and French as a foreign language in classroom settings after the age of seven. Pre-scan behavioral data revealed good to excellent proficiency of the three languages in all participants. The naming task required covert naming of visually presented line drawings in each given language. Six sets of twelve line drawings, matched for difficulty on the basis of their frequency of occurrence, were constructed. The naming task was run in 6 blocks each consisting of three epochs of 30 s naming in Dutch, English, and French. After twelve pictures, the language in which the participants had to name the line drawings changed as indicated by the presentation of a new language above the picture. Presentation was stimulus-paced with stimuli presented at the rate of one every 2.5 s. The data were acquired using a 1.5 Tesla Siemens Symphony MRI scanner using an EPI sequence (TR=3.0 s, TE=60 ms, flip angle 90°, voxel size 3 x 3 x 5 mm). All data processing and group analyses were performed using statistical parametric mapping (SPM 99).

In the out-of-scan picture naming task, participants were required to name 12 visually presented pictures in each language. In Dutch, all volunteers achieved a maximal score of 100% correctly named pictures. In English and in French the average naming score was 95.8% (SD = 5.6) and 93.8% (SD = 9.5), respectively. Paired-samples t tests on the mean scores of the picture naming tasks appeared significant when Dutch and English ($t[11] = 2.57$, $P < .05$) and Dutch and French ($t[11] = 2.28$, $P < .05$) were compared. An identical analysis of mean scores for picture naming in English and French revealed no significant difference.

Significant occipital and left frontal activation was elicited in all language conditions. As can be seen in Fig 3, direct comparison of the naming task between the different languages revealed clear interlanguage differences. During the native language there was significantly more activation in the posterior right hemisphere (BA's 7, 39, and 40) compared to the foreign languages. In contrast, the foreign languages recruited additional left hemispheric and predominantly anterior regions (BA's 44, 45, and 47).

This is not in agreement with the claim that in late learners and less proficient bilinguals there would be more right hemisphere involvement in the second language than in the mother tongue [49]. In fact, our results rather point in the direction of more right hemisphere activation in the native language and more left hemisphere activation in languages learned later in life. More right hemisphere activation of the mother tongue could reflect differences in language-associated emotional load, or could be interpreted as a remnant of the more equipotential contribution of both hemispheres in the acquisition of conceptual knowledge in association with (the first, i.e. native) language during infancy and early childhood.

Fig 3. Areas of significant cerebral activation during picture naming in Dutch, English, and French.

Discussion of the fMRI Studies

Evidently, more research is necessary before any definite conclusions can be drawn, regarding the representation of languages in bilinguals and multilinguals. Several factors are implied in the cortical representation of language such as gender, handedness, and age of acquisition. Although these factors were not the subject of the present investigation, they were controlled for. All subjects were male, were consistently right-handed, and learned English and French at approximately the same age. Exposure and subjective proficiency of both foreign languages, however, differed significantly and this offered the possibility to investigate this effect separately. The most important finding of the study is that similar language tasks performed by multilinguals in different languages activate largely the same areas of the brain. In the non-native languages the activated areas are somewhat larger and this is most notable in the left inferior frontal region reflecting increased sub-vocal effort with less familiar speech patterns and/or more elaborate retrieval effort with less familiar lexical labels. Finally, a consequent effect of exposure was found for reading, where increased familiarity engages more occipital activation, whereas decreased familiarity appears to be associated with increased left hemispheric inferior frontal activation.

Structural Plasticity

Lately, the emphasize has always been on functional MRI. The pattern that emerges from these studies is far from consistent. While some investigators [15], [25], [41], [58], found at least partly different representations for different languages, others [23], [26], [27] reported findings that do not lend support to the hypothesis that different languages are represented in distinct brain regions. In a few studies [13], [28], [44], [50], [54], shared neural substrates were found, even for such contrasting languages as Mandarin and English. However, most of these different results can be explained by differences of the proficiency level of the bilingual- and multilingual participants. Recently, the focus has moved from the functional to the structural level. Are there any structural plastic changes in the human brain during the process of second language acquisition? [52]

In a recent study by Mechelli et al [33], voxel-based morphometry [4], [20], was used to investigate structural plasticity in healthy right-handed English and Italian bilinguals. To test for differences in the density of grey and white matter between bilinguals and monolinguals, they recruited 25 monolinguals who had had little or no exposure to a second language; 25 "early" bilinguals, who had learned a second European language before the age of 5 years and who had practised it regularly since; and 33 "late" bilinguals, who had learned a second European language between the ages of 10 and 15 years and practised it regularly for at least 5 years. All volunteers for this test were native English speakers of comparable age and level of education.
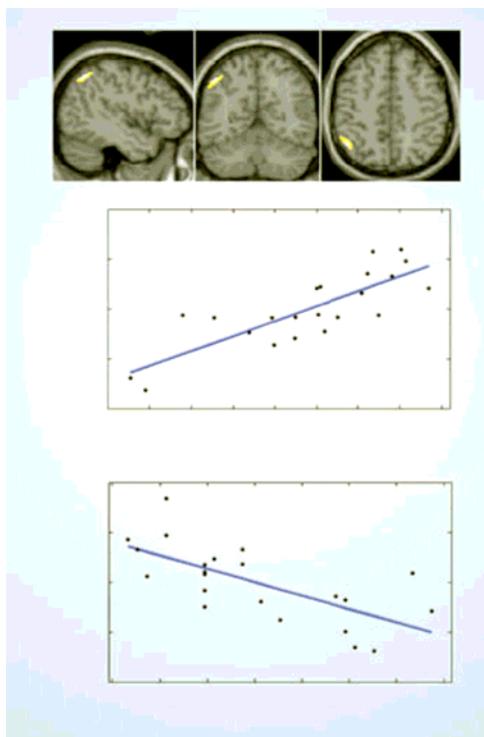
Voxel-based morphometry revealed that grey-matter density in the inferior parietal cortex was greater in bilinguals than monolinguals (Fig 4a). This effect was significant in the left hemisphere (x = -45, y = -59, z = 48; Z-score = 7.1; P < .05, corrected for multiple comparisons across the whole brain) and a trend was also evident in the right hemisphere (x = 56, y = -53, z = 42; Z-score = 3.4; P < .001, uncorrected). Although increased grey-matter density in the inferior parietal cortex was common to both early and late bilinguals, the effect was greater in the early bilinguals in the left (x = -48, y = -62, z = 44; Z-score = 3.5; P < .001, uncorrected) and right (x = 45, y = -65, z = 47; Z-score = 3.5; P < .001, uncorrected) hemispheres. No other significant effects were detected in either grey or white matter.

In addition, they investigated whether there was a relation between brain structure and proficiency in the second language and age at acquisition. Twenty-two native Italian speakers who had learned English as a second language at an age between 2 and 34 years were tested. Second-language reading, writing, speech comprehension, and production were assessed using a battery of standardized neuropsychological tests (see supplementary information). It was found that overall proficiency, as indexed by principal component analysis, correlated negatively with age at acquisition (P < .01; r = -0.855). Remarkably, voxel-based morphometry revealed that second-language proficiency correlated with grey-matter density in exactly the same left inferior parietal region that they had already identified (x = -48, y = -59, z = 46; Z-score = 4.1; P < .05, corrected after 10-mm small-volume correction; Fig 4b). In addition, grey-matter density in this region correlated negatively with the age of acquisition of the second language (x = -50, y = -58, z = 42; Z-score = 3.2; P < .05, corrected after 10-mm small-volume correction; Fig 4c). There were no other significant effects in grey or white matter.

The authors have therefore identified an increase in the density of grey matter in the left inferior parietal cortex of bilinguals relative to monolinguals, which is more pronounced in early rather than late bilinguals, and have

also shown that the density in this region increases with second-language proficiency but decreases as the age of acquisition increases. These effects could result from a genetic predisposition to increased density, or from a structural reorganization induced by experience [18]. Early bilinguals probably acquire a second language through social experience, rather than as a result of a genetic predisposition. According to the authors [33], the findings therefore suggest that the structure of the human brain is altered by the experience of acquiring a second language. The inferior parietal region that is associated with second-language acquisition is exactly the same area that has been shown by functional imaging to become activated during verbal-fluency tasks [42], [57]. Whether grey-matter reorganization in this region is related to changes in neuropil, neuronal size, dendritic or axonal arborisation, will be revealed by methods other than whole-brain magnetic resonance imaging. These results are consistent with growing evidence that the human brain changes structurally in response to environmental demands, for example, structure is already known to alter as a function of learning in domains other than language [16], [31].

The authors conclude that the degree of this structural reorganization in bilinguals is correlated with their second language performance. The relationship between grey-matter density and performance discovered here could be an example of a more general structure-function principle that extends beyond the domain of language. However, does this mean that there is no specific brain area in which structural changes can be found during the process of (second) language acquisition?

Fig 4. Structural reorganization in the bilingual brain. **a,** Sagittal ($x = -45$), coronal ($y = -59$) and axial ($z = 48$) view of the left inferior parietal region, which has increased grey-matter density in bilinguals relative to monolinguals. **b,** Grey-matter density, measured as cubic millimetres of grey matter per voxel in the left inferior parietal region, as a function of second-language proficiency. Second-language proficiency was estimated for each subject from a battery of standardized neuropsychological tests, using principal component analysis (for details, see supplementary information). **c,** Grey-matter density, measured as for **b,** as a function of age at acquisition [33].

Structural Changes in the Corpus Callosum

The rapid growth in brain imaging technologies has been matched by an extraordinary increase in the number of investigations focusing on the structural and functional organization of the brain. An intense amount of research

has been directed towards analyzing the structure and function of the *corpus callosum*, the main fiber tract connecting the two brain hemispheres, which consists of approximately 200-350 million fibers in humans [1], [2]. Surgical transection of this structure in humans provides evidence that the *corpus callosum* functions to communicate perceptual, cognitive, mnemonic, learned, and volitional information between the two brain hemispheres [11]. Given the importance of sensory, motor, and cognitive callosal relay between hemispheres it is not surprising that this anatomic region has been a focus of studies examining structural and functional neuropathology [48]. However, surprisingly the role of the corpus callosum in the process of second language acquisition has never been the focus of research. Could the corpus callosum play a key-role in the process of second language acquisition?

Embryonic Period

Growth of the normal human brain occurs in a highly regular and well-defined manner. Anatomic neuronal development progresses in a posterior to anterior as well as ventral to dorsal fashion. Growth of the corpus callosum also occurs in an orderly manner. The development of the corpus callosum is initiated between 8-17 weeks of gestation. A thickening of the telencephalon, along the rostral wall, forms the *lamina reuniens,* which is the precursor to the white matter bundles of the anterior commissure and corpus callosum. As cells from the *lamina reuniens* migrate superiorly they form the *massa* which will form the bed for the extension of the crossing fibers of the corpus callosum. The corpus callosum does not develop homogenously, and axons of the genu develop first followed by the body and splenium. One exception to this anterior to posterior growth pattern is the rostrum. This is the last component of the callosum to project crossing fibers, at approximately 18-20 weeks gestation [47].

The major components of the corpus callosum are established prenatally, yet development is far from complete at birth. Although neuronal differentiation has concluded at birth, myelination of cortical axons has just begun. Myelination is the process whereby axons become encased by myelin sheaths. This process insulates axons and enhances the speed of neuronal conduction. Myelination of the central nervous system generally occurs in a caudal to rostral fashion. Spinal cord and brain stem pathways myelinate first, during prenatal stages, and frontal and association areas of the cerebrum myelinate postnatally. Continued myelination has been reported until 30, and this may reflect increased efficiency in the synthesis of information [47].

Parallelling the growth processes in the cerebrum, myelination of callosal axons also proceeds in a posterior to anterior fashion and may be the primary component of the growth observed in the callosum. It has been reported that the corpus callosum more than doubles in size between birth and two years of age. Barkovich and Kjos also observed that the newborn corpus callosum appears thin and flat, with substantial thickening occurring around 3 months of age. Substantial area increases are seen in the splenium, followed by more gradual increases in the body and rostrum. The genu of the corpus callosum consists mainly of fibers which traverse inferior frontal and anterior/inferior parietal regions, while the splenium carries fibers from homologous visual and visual association areas. The observed pattern of callosal development is not surprising: sensorimotor and visual areas may be most important as the neonate develops binocular vision and becomes coordinated in various body movements such as grasping objects. Prefrontal and posterior association areas may initially be less important to the infant, as these regions integrate sensory experiences and subserve higher cognitive processes such as planning. Increases in corpus callosum size may reflect increases in the complexity of interactions between an infant and its environment [47].

Childhood and Adolescence

The most dramatic developmental changes of the corpus callosum occur during the first years of life, yet continued maturational changes have been reported until late childhood and adolescence. In those studies the total callosal area in a cohort of 90 participants was measured. Area increases were found until the third decade of life. In addition, cross-sectional studies of total callosal area have corroborated increases in callosal volume until adulthood [47].

In children, longitudinal, four-dimensional studies of growth patterns in the corpus callosum have been explored using probabilistic approaches within individual participants and averaged as a group. These studies demonstrate selective areas of enlargement in the corpus callosum that vary as a function of age and cortical development. In childhood (3-6 years), the anterior portion of the corpus callosum (just posterior to the genu) changes most rapidly while in later development (7-15 years), the isthmus of the corpus callosum demonstrates the most dramatic change concomitant with neocortical alterations in the parietal and temporal regions [47] (Fig 5). Fibers

from the language areas in the superior temporal gyrus (Wernickes' area, planum temporale) pass through the isthmus area [56]. The isthmus of the corpus callosum sends fibers selectively to Wernicke's language area at the cortex. There was also a prominent growth in the language cortex itself, suggesting a key maturational phase in brain regions that support the learning of new languages.
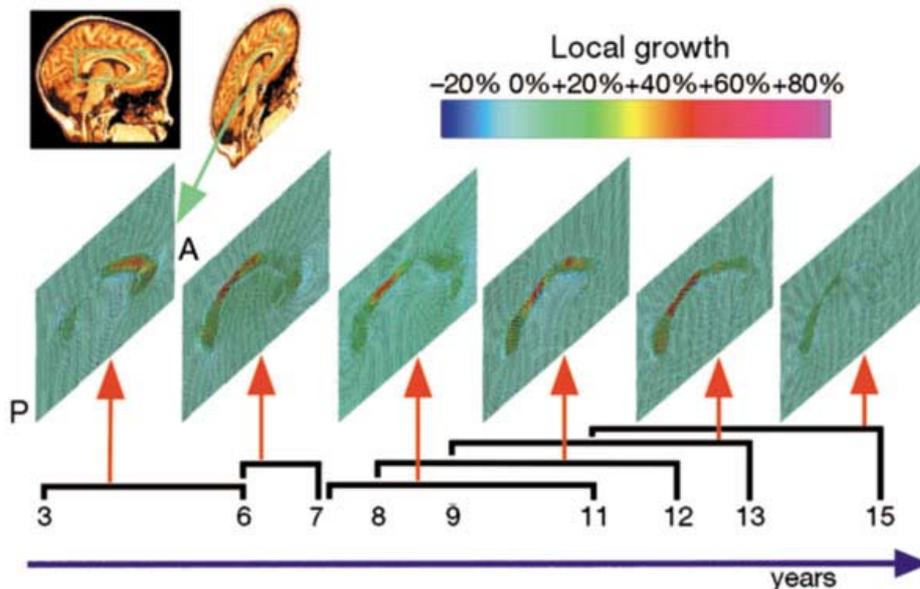
Fig 5. Growth patterns in the developing human brain detected at ages 3–15 years. A rostro-caudal wave of peak growth rates is detected in young normal subjects scanned repeatedly across time spans of up to four years. Between ages 3 and 6 years, peak growth rates (red colours; 60–80% locally) were detected in the frontal circuits of the corpus callosum, which sustain mental vigilance and regulate the planning of new actions. Older children displayed fastest growth at the callosal isthmus, which innervates temporo-parietal systems supporting spatial association and language function. Between ages 11–15 years, growth rates still peak at the isthmus, but are attenuated [47].

Evidence for a Critical Period?

Age of acquisition plays an important role in second language acquisition. An "earlier is better" rule of thumb captures the negative correlation between age of learning onset and eventual asymptotic performance. A considerable body of experimental data is consistent with this generalization. Most of these studies offer a maturational account of age effects and suggest that a critical period limits both L1 acquisition and L2 acquisition [9], [30].

The existence of a critical period for language acquisition has been one of the most widely debated issues in second language acquisition research [22]. That children are more efficient second language learners than adults was given its first scientific formulation by Penfield and Roberts [40] in an account where the biological and neurological basis for children's advantages in language learning was specified. They suggested that the child's brain has a specialized capacity for learning language and that there is something like a biological clock of the brain.

Later, Lenneberg suggested that the loss of biological predisposition for language acquisition could be explained by the completion of hemispheric lateralization, which in his view coincided with puberty, and labelled the time-span between age 2 and puberty a critical period for language acquisition [29].

If a critical period limits second language acquisition, one would expect that linguistic performance should correlate negatively with the age at which L2 learning begins. Importantly, this effect should be observed in cases where L2 learning begins prior to the end of maturation. Moreover, there should be few if any late learners who perform in the range of native controls. Finally, if limits on attainment are maturational in nature, then they should apply to L2 acquisition generally. Johnson and Newport [24], proposed their maturational model of L2 attainment based on these kinds of evidence [9].

Johnson and Newport used a grammaticality judgment task in their experiment. A group of Chinese and Korean learners of English participated in the study. The results of the grammaticality judgment task were in line with the first two types of evidence. Moreover, Johnson and Newport argued that their results should generalize to other L1 and L2 contexts.

Although the findings and interpretations of Johnson and Newport have been widely accepted, there is also evidence against this maturational account.

In some studies, postmaturational age effects were found [5], [6], [7], [17]. In other studies, significant numbers of late learners were found, who perform like natives on various linguistic tasks [12], [14], [53].

To conclude, the controversy about the existence of a critical period remains as intense as ever [8], [21], [32], [45], [46]. Future research should give us the answer if the isthmus of the corpus callosum plays a key-role in this debate. Results from the corpus callosum research so far showed a peak in maturation of the isthmus of the corpus callosum around +/- 15 years followed by a decrease in maturation until +/-40 years. In this period, it is possible for some individuals to reach a native level in their L2 as a result of individual differences in maturation. After the age of 40 it seems impossible to reach a native level.

General Discussion

Many speculations exist about how second and/or third languages are represented in the brain. The pattern that emerges from functional neuroimaging studies is far from consistent. Recently, the focus has been moved from the functional to the structural level. Are there any structural plastic changes in the human brain during the process of second language acquisition? Is there a specific (second) language acquisition area? In this paper, functional and structural neuroimaging data were presented to answer these questions. The results of the structural neuroimaging study are consistent with growing evidence that the human brain changes structurally in response to environmental demands, for example, structure is already known to alter as a function of learning in domains other than language [16], [31]. The authors conclude that the degree of this structural reorganization in bilinguals is correlated with their second language performance. The relationship between grey-matter density and performance discovered here could be an example of a more general structure–function principle that extends beyond the domain of language. However, does this mean that there is no specific brain area in which structural changes can be found during the process of (second) language acquisition? The answer to this question is not clear yet. In the end of this paper, we discussed the possible role of the corpus callosum in (second) language acquisition. Previous structural neuroimaging research on the corpus callosum [47] showed that fibers from the language areas in the superior temporal gyrus (Wernickes' area, planum temporale) pass through the isthmus area [56]. The isthmus of the corpus callosum sends fibers selectively to Wernicke's language area at the cortex. Moreover, a prominent growth in the language cortex itself was found, suggesting a key maturational phase in brain regions that support the learning of new languages. Future bilingualism/multilingualism research should give us the answer whether the isthmus of the corpus callosum plays a key-role in the processing of (second) language acquisition.

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