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der Universität Freiburg (Schweiz)

***Effects of early second language acquisition on the  
cortical language network in multilinguals:  
evidence from fMRI***

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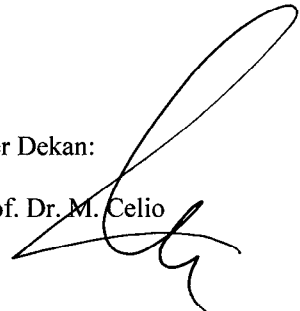
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# Glossary

Activation maximum	Voxel with a regional highest magnitude of the BOLD effect compared to the surrounding voxels.
BOLD effect	Blood Oxygen Level Dependent effect which is observed in susceptibility sensitive MR images and caused by the paramagnetic properties of oxyhemoglobin.
Brodmann area (BA)	Anatomical cortical region defined by its cytoarchitectonic characteristics.
SPM	Statistical Parametric Mapping (SPM) is a statistical technique to assess differences in brain activity recorded during functional neuroimaging experiments. It may also refer to world-wide applied software developed by the Wellcome Department of Imaging Neuroscience (University College London) to perform such analyses.
Talairach coordinates	Cartesian coordinates that are based on the coordinate system of the human brain atlas defined by J. Talairach and P. Tournoux.
voxel	Volume element, smallest three-dimensional unit of an volume.
Early multilingual	Multilingual subject who has acquired two languages already early in life. The early multilinguals investigated in the present study have acquired a second language before age three and one or more further languages after age nine.
Late multilingual	Multilingual subject who has acquired the second language as adolescent or adult. The late multilinguals investigated in the present study have learned the second language after age nine and one or more languages at an even later stage.
Declarative memory	Memory system that underlies the representation of knowledge that is consciously learned and of which we can be aware. It contains both episodic (i.e., experiential) and semantic (i.e., general knowledge) memories, and contrasts with procedural memory.
Procedural memory	Memory system that underlies the representation of skilled competence. The implicit competence which underlies the performance of motor, cognitive and language skills is said to be procedural.



Explicit learning	Learning of which individuals are aware and that they are capable of representing to themselves and verbalizing on demand; it is represented in declarative memory.
Implicit learning	Learning of languages which is related to the establishment of knowledge that allows systematic verbal performance even the individuals themselves are not aware of the nature of this knowledge

## Abstract

Research on language acquisition has shown that language development depends on language experience during early childhood. Early acquisition of one as opposed to two languages should therefore influence the development of language capabilities. Various psycholinguistic studies have provided support for this idea. The impact of early second language acquisition on the establishment of the cortical network, however, remains elusive. In the present study we used functional magnetic resonance imaging (fMRI) to investigate this aspect. Language related brain activity was assessed in two groups of multilinguals with different ages of second language acquisition: “early multilinguals” had acquired a second language (L2) in early childhood (before the age of three years); “late multilinguals” learned a second language (L2) in early adolescence or later (after the age of nine years). Of particular interest was the previously unexplained question of whether the brain representation of languages learned as adolescents or adults is influenced by early second language acquisition. With this perspective in mind, all early and late multilinguals included in the study had also learned a third language (L3) after the age of nine years, so that not only early, but also late learned languages could be compared between both groups. All multilinguals were tested in their three languages (L1, L2 and L3) by fMRI. The brain activity was measured during a language production task in which the subjects had to report the happenings of the previous day. To reduce influences not specifically related to language processes such as variable attention or valuation of the described experiences, the subjects were tested twice, on different days. The average brain activity during processing of L1, of L2 and of L3 has been statistically assessed for the groups of early and late multilinguals separately, including both tested runs.

The comparison of the early acquired languages between both groups revealed striking differences in language related neuronal activity. Indeed, the analysis of the data shows that early multilinguals in both of their early acquired languages (L1 and L2) use cortical language regions more than late multilinguals in their L1. Particularly, increased neuronal activity was observed in regions of the left frontal lobe i.e. Broca’s area and the adjacent prefrontal cortex. It should be noted that the early acquisition of a second language (L2) determines not only its own cortical representation, but also that of the first acquired language (L1).

The cortical region which is most influenced by the effect of early second language acquisition i.e. the prefrontal cortex, plays a crucial role during early procedural language acquisition. Here, higher activation could indicate the engagement of functions related to the resolution of cross-linguistic interference. Indeed, left prefrontal regions support processes necessary for a selection between competitive alternatives of a motor plan. In early multilinguals, specific cross-linguistic interference between the early acquired languages seemed to manifest itself during the preparation for the speech action.

Further evaluation of the data provided more evidence for the involvement of cortical functions to resolve cross-linguistic interference between two early acquired languages. This is apparent from the comparison of the language-related activation pattern in left perisylvian regions between early and late multilinguals, particularly in Broca’s area and in the supramarginal gyrus. The neuronal network connecting these brain regions supports sensory-motor integration of phonological information, i.e. the function of the “phonological loop”. The evaluation led to the discovery of a pronounced motor load of the activated network in early multilinguals. It is known that such a functional adjustment is necessary to resolve interference of sensory-

related language information at the phonological level. Thus, the comparison of early acquired languages between early and late multilinguals could indicate, that early second language acquisition influences the function of the cortical language network to resolve various aspects of cross-linguistic interference. Since the changes in brain activity could be demonstrated in adults, the results of the present study indicate a persistent adaptation of brain language functions to the early presence of two languages.

The comparison of the later-learned L3 between both groups showed principally the same result as the comparison of the early acquired languages: in early multilinguals, functions of language networks supporting resolution of language interference seem to be more established than in late multilinguals. This is the first study which has described an influence of early second language acquisition on the organisation of the cortical language network of subsequent late learned languages. An effect of early second language acquisition on the use of the language network by later-learned languages could however not be described. Indeed, later-learned languages of both groups showed similar differences to the early acquired languages.

By demonstrating that exposure to a second language during early childhood not only manifests in the cortical language network of early but also of late acquired languages, this study extends the current view of the importance of early language acquisition for the establishment of the cortical language network.

## **Zusammenfassung**

Auf dem Gebiet der Spracherwerbsforschung gilt es als erwiesen, dass frühe Spracherfahrung die Sprachentwicklung nachhaltig beeinflusst. Der frühe Erwerb einer oder zweier Sprachen müsste sich deshalb unterschiedlich auf die Ausbildung späterer Sprachkompetenzen auswirken. Einige psycholinguistische Untersuchungen konnten dies betätigen. Bis heute wurde jedoch der Einfluss früher Zweisprachigkeit auf die Ausbildung des kortikalen Sprachennetzwerkes wenig erforscht. Diesen Aspekt der Sprachentwicklung untersucht die vorliegende Arbeit mittels funktioneller Magnetresonanztomographie (fMRI). Dazu wurden zwei Gruppen von Mehrsprachigen gebildet: die erste von „frühen Mehrsprachigen“, die eine Zweitsprache (L2) im Kleinkindalter (bis drei Jahren); die zweite von „späten Mehrsprachigen“, die eine Zweitsprache (L2) als Heranwachsende oder später (ab neun Jahren) gelernt haben. Im Gegensatz zu früheren Arbeiten mit bildgebenden Verfahren beherrschten die in dieser Studie erfassten frühen und späten Mehrsprachigen eine weitere, als Heranwachsende oder später erworbene Drittsprache (L3). Die neuronale Hirnaktivität in den drei Sprachen (L1, L2 und L3) früher und später Mehrsprachiger wurde durch eine Sprachproduktionsaufgabe erfasst, somit auch für L3, wodurch der mögliche Einfluss früher Mehrsprachigkeit auf diese Drittsprache zum ersten Mal beurteilt werden konnte. Die sprachliche Aufgabe bestand darin, dass die Probanden in der jeweils getesteten Sprache über die Ereignisse des vergangenen Tages berichten mussten. Um den Einfluss nicht sprachspezifischer Einflüsse wie variable Aufmerksamkeit oder unterschiedlichen Bezug zum gerade Erlebten auf die gemessene Aktivierung zu verringern, wurde die Messung zweimal, und zwar an unterschiedlichen Tagen, durchgeführt. Die Durchschnittsaktivierungen von L1, L2 und L3 wurden für die Gruppen von frühen und späten Mehrsprachigen statistisch berechnet, wobei beide Messungen in die Auswertung einbezogen wurden.

Der Vergleich der Hirnaktivität früh erworbener Sprachen zwischen beiden Gruppen früher und später Mehrsprachiger zeigte auffallende Unterschiede in der Nutzung des Sprachennetzwerkes. In der Tat gebrauchen die frühen Mehrsprachigen in ihren beiden früh gelernten Sprachen die Sprachregionen im Gehirn mehr als die späten Mehrsprachigen in ihrer Erstsprache. Höhere neuronale Aktivität wurde vor allem in Bereichen des linken Frontallappens, insbesondere im Broca Areal und dem daran angrenzenden präfrontalen Kortex beobachtet. Es ist bemerkenswert, dass sich früher Erwerb einer zweiten Sprache hier nicht nur auf die Funktion dieser Zweitsprache sondern auch auf diejenige der Erstsprache auswirkt.

Die kortikale Region, welche offensichtlich durch die Auswirkung frühen Zweitspracherwerbs besonders in ihrer Funktion beeinflusst wurde –der präfrontale Kortex-, gilt als essentiell während der frühen prozeduralen Phase des Spracherwerbs. Dieser regionale Unterschied zwischen frühen und späten Mehrsprachigen weist darauf hin, dass in frühen Mehrsprachigen der Lösung von Interferenz zwischen den unterschiedlichen Sprachen eine grössere Bedeutung zukommt als in späten Mehrsprachigen. Tatsächlich weisen präfrontale Hirnregionen erhöhte neuronale Aktivität auf wenn zwischen konkurrierenden Bewegungsplänen entschieden werden muss; es ist wahrscheinlich, dass hier bei frühen Mehrsprachigen während des Spracherwerbvorgangs Interferenz zwischen den beiden damals gelernten Sprachen die Ausbildung des neuronalen Systems für den Sprechakt beeinflusst hat.

Die vertiefte Auswertung der Studie gab einen weiteren Hinweis dafür, dass in frühen Mehrsprachigen kortikale Funktionen zur Interferenzlösung zwischen den beiden frühgelernten Sprachen abgestimmt sind. Diese Beobachtung ergibt sich aus dem Vergleich des sprachspezifischen Aktivierungsmusters beider Gruppen in perisylvischen Arealen der linken Hemisphäre, insbesondere im Broca-Areal und im supramarginalen Gyrus. Das neuronale Netzwerk, welches zwischen diesen Regionen ausgebildet ist, unterstützt unter anderem als „phonologischer loop“ sensorimotorische Integration phonologischer Information. In frühen Mehrsprachigen fällt die im Vergleich zu späten Mehrsprachigen überwiegend motorische Ausrichtung in der Aktivierung dieses Netzwerkes auf. Dies ist bekanntlich notwendig, wenn Interferenz zwischen sensorisch abgelegten phonologischen Sprachinformationen auftritt.

Der Vergleich frühgelernter Sprachen zwischen frühen und späten Mehrsprachigen zeigte also, dass frühe Zweisprachigkeit die Funktion(en) des Sprachnetzwerkes dahingehend beeinflusst, dass eine Interferenz zwischen den Sprachen vermindert werden kann. Die Tatsache, dass die veränderte Hirnaktivität früher Mehrsprachiger im Erwachsenenalter nachweisbar ist, lässt darauf schliessen, dass sich der Einfluss früher Mehrsprachigkeit permanent auf die Funktion des sprachlichen Systems ausgewirkt hat.

Der Vergleich der spätgelernten L3 zwischen den beiden Gruppen von Mehrsprachigen zeigte im Wesentlichen den gleichen Befund wie derjenige früh erworbener Sprachen: frühe Mehrsprachige greifen in ihrer Drittsprache vermehrt auf Hirnregionen zurück, welche Interferenzlösung unterstützen. Diese Studie konnte so zum ersten Mal einen Einfluss früher Mehrsprachigkeit auf die Funktion später erworbener Sprachen beschreiben. Ein Einfluss frühen Zweitsprachenerwerbs dahingehend, dass später gelernte Sprachen das bestehende Sprachnetzwerk besser nutzen können konnte, liess sich jedoch nicht feststellen. Tatsächlich wiesen in beiden Gruppen spät gelernte Sprachen ähnliche Unterschiede zu früh erworbenen Sprachen auf.

Diese Studie zeigt, dass sich der Erwerb einer Zweitsprache zu einem frühen Zeitpunkt nicht allein auf die Funktion dieser einen Sprache auswirkt, sondern dass alle Sprachen, sogar erst später gelernte Sprachen beeinflusst werden. So konnte in dieser Arbeit die umfassende Bedeutung frühen Spracherwerbs für die Ausbildung des kortikalen Sprachnetzwerkes aufgezeigt werden.

# 1 Introduction

Research in neuroscience has provided evidence for an interaction between brain and environment both during early development and in adulthood; the brain function is continuously shaped by experience. In particular, it should be noted that experience during early development is crucial for the establishment of brain functions. This is exemplified by the impact of early impairment of visual and auditory experience on cortical systems in humans (Bavelier et al., 2000; Roder et al., 1999). This study aims to show the implications for early language development; the influence of early mono- as compared to bilingual language acquisition on the establishment of the cortical language network has been investigated.

For a long time, human language could only be assessed on a behavioural level. These investigations demonstrated the intimate interplay between language exposure and the creation of mental representations of language (Kuhl, 2000). Furthermore, it has been argued that language experience during early childhood is necessary for normal language development (Lenneberg, 1969). Young children frequently grow up with two or more languages simultaneously. Given the importance of language stimuli during the first years of life, the acquisition of one as opposed to two languages during this period should set different parameters for language development. This idea is supported by the results of psycholinguistic studies in the field of early second language acquisition (Bosch and Sebastian-Galles, 1997; Weber-Fox and Neville, 1996). A question that raises controversial discussions is, whether bilingual children build up one language system or two. In this context, one proposition is to further determine the influence of one language on the processing of the other language - cross-linguistic interference-, which can be observed in the bilingual's language systems (Mueller N, 1998). In fact, according to J. Paradis and S. Navarro (Paradis and Navarro, 2003), if cross-linguistic interference was due to interaction of two languages in an unitary system, one would expect this interaction at any linguistic level. Alternatively, the authors argue that interference of two separate but not entirely autonomous systems would express as a "controlled and systematic phenomenon".

With the recent development of functional neuroimaging techniques (e.g. PET, fMRI) insight into the pattern of brain activation associated with cognitive tasks has become possible. These new methods allow regionalization of different components of language processing in the brain. For the first time, the potential influence of early second language acquisition on the organization of the cortical language network could be assessed. Previous studies in this field investigated subjects with early or late onset of second language experience; early and late bilinguals were compared. Two studies described differences between early and late bilinguals (Kim et al., 1997; Mahendra et al., 2003). Kim and colleagues (1997) tested the production of narratives in bilinguals and found that early bilinguals process the two early acquired languages in overlapping regions of Broca's and Wernicke's area, whereas late bilinguals recruit separate neuronal substrates in Broca's area but overlapping regions in Wernicke's area for both the early and the late acquired language respectively. Investigating word and sentence generation, Mahendra et al. (2003) reported that in both languages of early bilinguals the classic language areas (the inferior frontal gyrus including Broca's

area and the superior temporal gyrus including Wernicke's area) were more extensively activated than in the languages of late bilinguals. These findings suggest that second language learning during an early period shows in the organization of the cortical language network. However, previous studies were not fully satisfying in that they did not clearly delimitate the regions of different activity in early and late bilinguals in the classic language areas or include other brain regions in the analysis. Interestingly, Mahendra et al. (2003) argue that a more extensively activated neuronal network characteristic for early bilinguals could be the neuronal correlate of a different interaction of the two early acquired languages within the language network. Thus, both psycholinguistic and fMRI studies converge in their interest to explain cross-linguistic interference related to early second language acquisition. Here also a thorough investigation of neuronal correlates related to early second language acquisition promises to give further insight into how the early bilinguals' languages interact. Further, considering the importance of early experience for language development, one would expect that the processing of additional languages learned as adults is differently influenced by exposure to one as compared to two languages. However, previous functional imaging studies did not consider this issue; the cortical representation of languages learned as adults has never been compared between early and late multilinguals.

Based on this state of the matter, we designed a functional magnetic resonance imaging (fMRI) study for a comprehensive investigation of the language related brain activity in multilinguals with early second language acquisition. Brain activity was assessed during language production in two groups of multilinguals. The first group (early multilinguals) consisted of multilinguals which had acquired two languages early in life (before age three) and learned one or more further languages later in life (after age nine). The second group (late multilinguals) consisted of multilinguals which had acquired a second language later in life and learned one or more languages at an even later stage. Notably, this is the first study which investigated a third late acquired language in early and late bilinguals. In addition, contrary to previous studies in this field, the subjects were not only tested once, but twice, on different days. This allowed controlling for effects of variable performance during the language test. The comparison of language related neuronal activity between both groups was expected to provide further insights in language related brain activation associated with early bilingualism. In addition, since early and late multilinguals were included in the study on condition that they learned at least one additional language as adults, it was possible for the first time to report the influence of early bilingual language exposure on further language learning later in life. After the elaboration of this thesis the following hypothesis has been formulated and it is expected that it will be corroborated and elaborated by further experimental work:

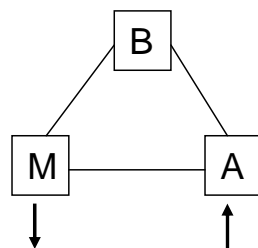
*In multilinguals, learning of two languages during an early period in life (early second language experience) has the permanent effect of higher neuronal activity during language processing (any of the multilinguals' early or subsequently later acquired languages). It is postulated that this is the neuronal correlate of specific cross-linguistic interference.*

## 2 Survey

### 2.1 Wernicke's model of neuronal language organization

Wernicke's model of neuronal language organization (Wernicke, 1874) still serves as reference for recent neuroanatomical models of language processing (Aboitiz and Garcia, 1997; Hickok and Poeppel, 2000).

Pierre Paul Broca (1824-1880), Carl Wernicke (1848-1904) and their contemporaries investigated neuronal language organization mainly by studying brain lesions in patients with language disorders such as aphasia. P. Broca described a region in the left frontal lobe that is important during language production, later referred to as Broca's area. C. Wernicke localized a sensory language center in the left temporal lobe that is now known as Wernicke's area. Later, Carl Wernicke developed the concept that linguistic information, represented in distinct brain regions, is interconnected to create the cortical language system. In his model of language processing, Wernicke proposes, that language processing is supported by two centers, one in the auditory cortex with sound-based representations of words and the other in the motor cortex with the motor-based representation of the articulatory gestures to produce words. These two language centers are directly connected to one another and also to a highly distributed network involved in the representation of conceptual knowledge (Figure 2.1).



**Fig. 2.1 Wernicke's/Lichtheim model of the functional neuroanatomy of language.**

Nodes M and A are centers for representing the sensory and motor traces of linguistic events: A, center for auditory word representation ('akustisches Sprachzentrum'); M, center for motor word representation ('motorisches Sprachzentrum'). B, distributed cortical network for conceptual knowledge representation ('Begriffszentrum').

Wernicke assumed that during language comprehension, acoustic input activated stored auditory representations associated with the sound pattern of words; these auditory word representations then activated their associated conceptual representations. He proposed that language production started with the activation of conceptual representations which in turn activated both their auditory and motor



representation in parallel. The activation of auditory word representation served to constrain the selection of the appropriate word via the direct auditory-motor pathway.

„...jedenfalls gelangt von dem Orte des Reflexvorganges ein Klangbild des Wortes oder der Silbe in einen sensorischen Theil des Gehirnes, das Inervationsgefühl der ausgeführten Bewegung als Sprachbewegungsvorstellung in das motorische Stirnhirn. Geschieht später die spontane Bewegung, das bewusst ausgesprochene Wort, so ist von dem Erinnerungsbilde des Klanges aus die associirte Bewegungsvorstellung innerviert worden“ (Wernicke, 1874).

## 2.2 Broca's and Wernicke's area

According to Broca (Broca MP, 1861), the region implicated in the production of “articulate language”, Broca's area, is localized in the posterior part of the left inferior frontal gyrus. He based this conclusion on both clinical and neuropathologic, macroscopic examinations of his aphasic patients. Considering the location of the lesions in these historical brains it has been hypothesized that Brodmann areas (BA) 44 and 45 are the cytoarchitectonic correlates of Broca's region (Signoret et al., 1984). This anatomical assignment is still largely accepted (Aboitiz and Garcia, 1997; Amunts et al., 1999). Accordingly, in this study, we refer to Broca's area as BA 44 and BA 45.

Wernicke observed language comprehension deficits in patients with lesions in the left superior temporal cortex, posterior to primary auditory cortex. The posterior part of the left superior temporal gyrus (pSTG) was the localization he assumed for the center for processing of sound based representation of words, Wernicke's area (Wernicke, 1874). Recently, Wernicke's area has also been associated to phonetic analysis of speech in the left STG anterior to the primary auditory cortex (Demonet et al., 1992a) or to integration of auditory with visual language information in cortical regions which allow heteromodal processing, for example in the supramarginal gyrus (Mesulam, 1998).

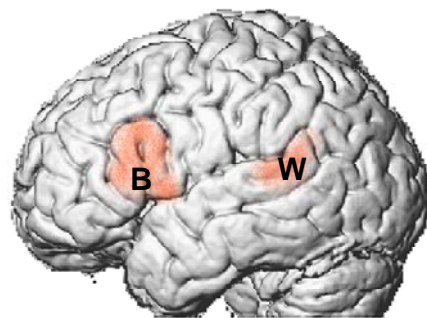
However, here we refer to Wernicke's area exclusively as the left posterior superior temporal gyrus including the posterior superior temporal sulcus and the planum temporale.

More unclear than the anatomical localization remains the question to which extend Broca's and Wernicke's areas assume the functions traditionally assigned to them. Indeed, previous imaging studies showed that Broca's is not only activated during propositional speech and cued word generation but also during word retrieval and that Wernicke's area supports not only auditory word perception and repetition but also propositional speech production (Blank et al., 2002; Price et al., 1996; Wise et al., 2001). This signalizes that both language perception and production rely on a left lateralized language network and suggests that the function of Broca's and Wernicke's area rather consists in a management of the processes they are known for. In so far in the present context the denomination “Broca's area” and “Wernicke's area” has to be understood as anatomical delimitation rather than as functional classification. Furthermore, there is also evidence that the language network

comprises widely distributed extrasylvian regions which are in particular localized in the left temporal lobe and left prefrontal regions not belonging to Broca's and Wernicke's area and also subcortical regions (Price, 2000). These regions seem to support semantic access to words and thus mediate between conceptual knowledge and processes related directly to speech perception or speech production (Damasio et al., 1996). Notably, these processes are particularly relevant for higher level language functions such as those required in conversational situations (Blank et al., 2002).

One can not critically examine the function in Broca's and Wernicke's area without taking into account the non-language functions of these regions. Particularly Broca's area and its right homologue seem to be specialized for a wide range of executive functions. Notably, neuronal activity in Broca's area is necessary during tasks that require motor preparation. Krams and colleagues for example reported activation in this region and in its right homologue in an experiment that required performance of non-verbally cued finger movements after a delay (Krams et al., 1998). Moreover, Rizzolatti and collaborators (Rizzolatti et al., 2001) provided evidence for a so-called mirror system which activates Broca's area both when a subject performs specific hand or mouth actions and when it observes other individuals making similar actions. The authors argue that resonance of the observers own motor system in response to actions performed by others could be the underlying neuronal substrate for imitation or/and understanding of the movements observed. Considering the functional diversity in Broca's area, the concept of a task set which is established –resonates– before the task is actually performed might be an attractive explanation for the nature of its contribution to motor as well as language tasks. Similar to Broca's area, Wernicke's area as well seems to participate in non-language functions. Indeed, it has been demonstrated that the left and right posterior superior temporal cortex including Wernicke's area and its right homologue support not only the processing of speech but as well the one of non-speech sounds (Binder et al., 2000). However recent studies clearly delimited speech from non-speech functions in this cortical region (Scott et al., 2000; Wise et al., 2001).

Figure 2.2 represents the anatomical localization of Broca's area and of Wernicke's area in the left inferior frontal gyrus and in the left posterior superior temporal gyrus (pSTG) respectively.



**Fig. 2.2** Localization of Broca's area (B) and Wernicke's area (W), indicated in a 3D rendering of the left hemisphere of a subject who participated in the study.

## 2.3 Related Work

Previous neuroimaging studies investigating early and late second language learning in bilinguals yielded inconsistent findings with respect to the impact of early second language acquisition during an early period in life. Some studies found that both, bilinguals who learned the second language early in life -early bilinguals- and those who learned the second language in early adulthood -late bilinguals- process their two languages in highly overlapping brain areas (Chee et al., 1999c; Perani et al., 1998). Chee et al. (1999c) for example, showed similar patterns of overlapping activation in early (age of acquisition (AOA) of the second language  $<6$ ) and late (AOA of the second language  $>12$ ) bilinguals during cued word generation. On the other hand, evidence was also found for differences in language processing between early and late bilinguals (Kim et al., 1997; Mahendra et al., 2003; Wartenburger et al., 2003; Wattendorf et al., 2001): using an internal sentence generation task, Kim et al. reported similar activation in Broca's area for both languages of early bilinguals (the second language was acquired in early infancy), whereas in the late bilinguals (AOA of the second language  $\sim 11,2$ ), the early and the late acquired language was represented in spatially separated parts of Broca's area.

The divergent results could be related to methodological differences, e.g. the experimental task used (words versus sentence production) or to the formation of groups considering different onset of second language learning.

Previous studies emphasize also the influence of proficiency on language representation in bilinguals (Chee et al., 2001; Mahendra et al., 2003; Perani et al., 1998). Perani et al. tested comprehension of auditory presented sentences and found that highly proficient early and late bilinguals both show a similar neuronal activity for L1 and L2 (Perani et al., 1998). In contrast in a study investigating semantic judgment in early and late bilinguals Chee et al. (2001) demonstrated smaller BOLD signal in the participants more proficient language. It cannot be excluded that different degrees of proficiency influenced the test outcome in the study of Kim et al. either, since the methods of assessment of proficiency have not been specified.

However, the study of Mahendra et al. (2003) which tested word and sentence production in early and late bilinguals confirmed the findings of Kim and colleagues. The authors show that early and late bilinguals process already their first acquired language differentially. As this language is generally highly proficient, the influence of a different degree of proficiency seems to be excluded. Thus, as far as language production is concerned, the results of previous studies suggest that AOA is a crucial factor, determining the neural organization of languages in bilinguals and that tasks requiring sentence production reveal the influence of this factor.

Table 2.1 resumes the studies presented, that investigated effects of age of acquisition and proficiency on language representation in early and late multilinguals

<b><u>EFFECTS ON LANGUAGE REPRESENTATION IN BILINGUALS</u></b>	<b>EARLY VERSUS LATE SECOND LANGUAGE ACQUISITION</b>	<b>EARLY VERSUS LATER SECOND LANGUAGE ACQUISITION-CONTROL OF LANGUAGE PROFICIENCY</b>
<b>No effect:</b> Overlapping cortical representations of the bilinguals languages	Chee 1999c Perani 1998	Perani 1998 (high proficiency in both languages)
<b>Effect:</b> Separated cortical representations of the bilinguals languages	Kim 1997 Mahendra 2003 Wartenburger 2003 Wattendorf 2001	Mahendra 2003 (high proficiency) Chee 2001 (different proficiency)

**Tab 2.1 Effects on language representation in bilinguals:**

Influence of age of second language acquisition and of proficiency

In the present study, we investigated brain activation during a narrative task in proficient multilinguals with early (early multilinguals) or late (late multilinguals) onset of bilingual experience. Early multilinguals ( $n=8$ ) acquired the second language before the age of three years. Language acquisition during this period has been considered as early in language development since only after this age the lexical, grammatical and phonological bases can be considered as “settled down” (Bates et al., 1992). Late multilinguals ( $n=8$ ) acquired the second language after the age of 9 years. At this age, communicative language skills seem to be established (Bates et al., 1992) even though language development continues for years (Piaget, 1967). In addition, subjects of both groups learned a third language after age 9. The proficiency levels were assessed in all three languages of each tested subject by a self-evaluation test (North, 2000) and a detailed linguistic interview (Franceschini, 2002). Few previous neuroimaging studies tested more than two languages of multilingual subjects (Vingerhoets et al., 2003; Yetkin et al., 1996) but none controlled for subsequent later language learning in both, early and late multilinguals. In particular, as language learning later in life occurred in both tested groups of multilinguals, we could for the first time disregard the influence of this factor on potential differences in language processing between early and late multilinguals. As such, this study continues and extends previous neuroimaging studies investigating the influence of early second language acquisition on the cortical language representation.

### 3 Materials and Methods

#### 3.1 Subjects

The subjects investigated were right-handed (lateralization index > 90%) according to the Edinburgh Handedness Inventory (Oldfield, 1971), 22 to 35 years old and without any history of neurological disorders. Subjects were selected from a larger cohort of multilinguals who spoke at least three languages. Criteria for inclusion in this study were age of second language acquisition (early-before the age of three years or late-after the age of nine years) and proficiency in the three languages. Early multilinguals (n=8) acquired the second language before the age of three years. Late multilinguals (n=8) acquired the second language after the age of 9 years. All tested multilinguals learned at least a third language (L3) after the age of 9 years. The distribution of male and female participants was balanced (4 females and 4 males per group). All three languages in both groups were tested by fMRI (Table 3.1). Each language was tested twice, on different days to account for effects of variable performance. The study was approved by the ethics committee of the University Hospital of Basel and participants in the study gave written consent prior to their participation.

TIME OF ACQUISITION	EARLY MULTILINGUALS	LATE MULTILINGUALS
before three years	EL1, EL2	LL1
after nine years	EL3	LL2, LL3

**Tab. 3.1 Early and late multilinguals: age of acquisition of the three tested languages.**

All participants in the study were subjected to a detailed interview related to their language biography (Franceschini, 2002) and a proficiency self-evaluation test based on the European Language Portfolio (North, 2000). Both tests were carried out and evaluated by Daniela Zappatore in the context of her PhD thesis prepared at the Romanistic Seminar, University of Basel. Further support came from John Wäfler and Patrick Deslarzes which contributed to the transcription of the language interviews. The evaluation of the language biographies showed that in early multilinguals the second early language was acquired successively in 2 subjects and almost simultaneously in 6 subjects. The successively learned languages were classified into the first learned L1 and the second learned L2 and the simultaneously acquired languages into L1 and L2 according to their importance during the acquisition process. In late multilinguals, the late learned languages were classified into an earlier learned L2 and a later learned L3. In addition, the language biographies allowed to assess how the languages were learned so as to differentiate spontaneous not directed learning (informal learning) from learning at school (Table 3.2 and 3.3).

**Early multilinguals**

SUBJECT	L1	L2	L3
14, M/ a=27	German Informal and at school	French Informal and at school	English At school
24, F/ a=25	German Informal and at school	English Informal and at school	French At school
30, M/ a=27	Italian Informal and at school	Swiss German Informal	English At school
32, M/ a=22	English Informal and at school	German Informal and at school	Italian Informal and at school
34, F/ a=34	Catalan Informal and at school	Spanish Informal and at school	English At school
43, M/ a=22	Indonesian Informal	German Informal and at school	English At school
64, F/ a=31	Swiss german Informal	Italian Informal and at school	English At school
69, F/ a=23	German Informal and at school	Italian Informal and at school	French At school

**Tab. 3.2 Early multilinguals: acquisition mode (informal, at school or both) of the two early (L1 and L2) and the late (L3) acquired languages (the numbers were attributed for identification during the process of data acquisition, M=male, F=female, a= age of the subject).**

**Late multilinguals**

SUBJECT	L1	L2	L3
13, F/ a=31	French Informal and at school	German At school	English At school
15, F/ a=31	Czech Informal and at school	German At school	English At school
18, M/ a=35	Swiss german Informal	French At school	English At school
21, M/ a=28	French Informal and at school	German At school	English At school
23, F/ a=27	Italian Informal and at school	German At school	English At school
53, F/ a=32	French Informal and at school	German At school	English At school
57, M/ a=30	French Informal and at school	German At school	English At school
62, M/ a=22	Italian Informal and at school	German At school	French At school

**Tab. 3.3 Late multilinguals: acquisition mode (informal, at school or both) of the early (L1) and the two late (L2 and L3) acquired languages (numbers were attributed for identification during the process of data acquisition, M=male, F=female, a= age of the subject).**

Table 3.2 and 3.3 indicate whether the languages have been first learned informal (spontaneously) or first informal and later at school or first at school (and later of course informal, but this occurs to all languages that are actively spoken and has not been considered as “acquisition mode” in the presentation). The tables show that the early acquired languages have all been learned informal (spontaneously) and later at school, except the L1 of two (Swiss German and Indonesian) and the L2 of one (Swiss German) early multilingual subject(s) as well the L1 (Swiss German) of a late multilingual subject, which were learned informal only. The late learned languages have all been learned at school first, only one subject in the group of early multilinguals learned the late learned language (L3) first informal and later at school.

Table 3.4 reveals the following proportion of the main represented language groups, German (G) and Roman (R) languages for further discussion on the influence of typological differences on the results (see discussion, Chapter 5.4)

Early multilinguals	L1: G5/R2	L2: G4/R4	L3: G5/R3
Late multilinguals	L1: G1/R6	L2: G7/R1	L3: G7/R1

**Tab 3.4 Early and late multilinguals: proportion of German (G) to Roman (R) languages.**

In the self-evaluation test on language proficiency (North, 2000), the subjects were requested to indicate their competence according to five different language skills; oral comprehension, reading comprehension, conversation, oral expression and writing. The self-evaluation was guided by a detailed questionnaire on concrete language situations. The following situation for example has been described for the self-evaluation of conversational skills: “I can interact with a degree of fluency and spontaneity that makes regular interaction with native speakers quite possible. I can take an active part in discussion in familiar contexts, accounting for and sustaining my views”. Competence was judged on a 6 level scale. For each of the three languages of each subject (L1, L2 and L3), the mean score of the five language skills was calculated. Table 3.5 shows the mean group scores for L1, L2 and L3 for early and for late multilinguals.

PROFICIENCY			
	L1	L2	L3
Early multilinguals	5.28±0.37	5.14±0.32	4.14±0.48
Late multilinguals	6.00±0.00	4.41±0.15	4.33±0.21

**Tab. 3.5 Early and late multilinguals: mean proficiency levels of the three tested languages. (6 = very high proficiency; 1 = very low proficiency).**

The tests confirmed high language proficiency (Table 3.5) and permanent use of their languages. In both groups, however, self evaluated proficiency in the languages acquired after the age of nine was at least one level below the one of earlier acquired languages.

## 3.2 BOLD effect

Magnetic resonance imaging (MRI) allows characterizing structural- anatomical properties of human tissue. The basis of this technique is to measure properties of  $H^+$  protons after energy supply within a magnetic field. When returning to the original energetic state, they emit an electromagnetic signal whose decay can be characterized independent ( $T_1$ ), and dependent ( $T_2$ ,  $T_2^*$ ) from surrounding tissue qualities. This technique has set a new standard in anatomical imaging of the human body. Functional magnetic resonance imaging (fMRI) uses the MRI technique to give insight in neuronal activity of a tissue. This is of particular interest for the observation of neuronal brain activity.

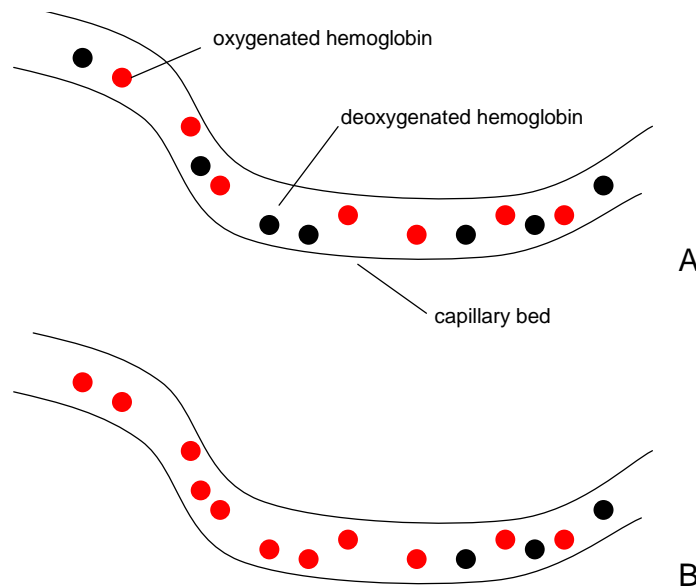
The physiological basis of fMRI is the coupling between regional neuronal activity on the one hand and changes in regional cerebral blood flow (rCBF) and regional cerebral blood volume (rCBV) on the other hand. Changes in blood flow and blood volume alter the proportion and content of oxy-/ deoxy-hemoglobin in the supplying blood vessels. Hemoglobin shows different magnetic characteristics, dependent on its oxygenation. By assessing the electromagnetic emission at relaxation times ( $T_2^*$ ) sensitive to the magnetic characteristics of the surrounding tissue, fMRI captures these changes. Consequently, in fMRI, blood oxygenation level is responsible for MR signal changes. This effect has been first recognized by Ogawa and colleagues (Ogawa and Lee, 1990) and described as blood oxygenation level dependent (BOLD) effect.

The processes accompanying changes in hemoglobin oxygenation related to neuronal activity are complex and not fully understood. However, there is evidence that regional induced neuronal activity and resulting metabolic activity, per example after sensory stimulation, leads to increase of rCBF and rCBV. During transient stimulation this effect surpasses oxygen consumption in the neuronal tissue and results in a higher oxyhemoglobin concentration in venous blood supplying vessels (Fox and Raichle, 1986). Increase of oxyhemoglobin leads to a signal increase in  $T_2^*$  weighted images. Consequently, a higher regional fMRI signal indicates a higher regional neuronal activity. FMRI thus measures electrical or metabolic activity in neuronal tissue only indirectly, as hemodynamic correlates. Recent studies however clarified the neuronal processes that determine the higher rCBF and rCBV after transient stimulation. In particular, it could be shown, that it is the functional signal of synaptic activity which



acts on the blood vessels because it precedes the metabolic signal of energy consumption. (Magistretti and Pellerin, 1996). Such an increase in blood flow without an immediate corresponding increase in oxygen consumption leads to the change in the ratio between oxy- and deoxy- hemoglobin and thus explains the signal detectable by fMRI. Moreover, a recent study allowed to attribute the BOLD effect to input and intracortical neuronal processing rather than to the spiking output (Logothetis et al., 2001).

Fig 3.1 is a resuming representation of the content in blood vessels before and after a neuronal stimulation.



**Fig. 3.1 BOLD effect.**

(A) Before neuronal stimulation: oxygenated hemoglobin is converted into deoxygenated hemoglobin at a constant rate. (B) After neuronal stimulation: Increase of the ratio oxygenated/ deoxygenated hemoglobin results in increase of the T2\* effect.

### 3.3 Task

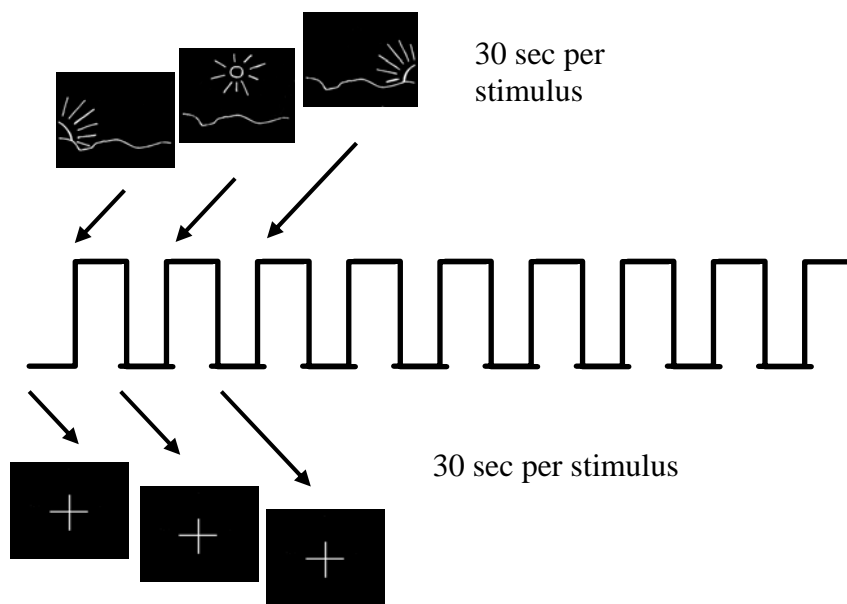
#### Test conditions

Two experimental conditions, a language and control task, were designed to test all three languages in both groups. The language task was a narrative language production task (adapted from Kim et al. (Kim et al., 1997), in which subjects were requested to covertly (without articulation) formulate the routine of the previous day and to relate this to an imagined person. In the control task, a perceptual non-speech task, subjects performed a motor action (finger tapping) in response to silent periods of the scanning sound (approx. every 6 sec.).

In contrast to language tests that consider only the processing of words, the language task applied in this study was a “holistic” task that was expected to reveal more language relevant processes in the brain. Moreover, we opted for a covert execution of the language task since here, scanning artifacts due to head movements are minimized (Yetkin et al., 1996). Further support for the choice of a covert language task has been provided by Palmer and colleagues (Palmer et al., 2001) which demonstrated that covert and overt stem completion elicited similar brain activation even in brain areas thought to be devoted to motor aspects of speech planning and execution. To ensure a monolingual mode (Grosjean, 2001), i.e. suppression of all other languages except the one currently being tested, subjects choose as an imagined interlocutor a person to whom they are used to speak only in the target language.

During the control task, the subjects had to react to changes of an audible stimulus. The main purpose of this control condition was to attract and maintain attention rather than to execute the motor act. In addition, such reference tasks engage attention processes but do not implicate any language processing (Binder et al., 1999). Stimuli for each task were presented visually in a block design. In a block design, stimuli are displayed for longer time periods. This allows analyzing a steady state response to stimuli, thereby showing regions with a robust activation, i.e. continuously involved in task management. In our experimental design, both stimuli were displayed alternatively for periods of 30 seconds and repeated 9 times. The language task was indicated symbolically by showing a sun at different positions for morning, noon and evening. The subjects were requested to formulate the routine of the morning of the previous day in response to the “morning” representation respectively give the corresponding response to the “noon” and “evening” condition. For the control task a simple cross was used (Figure 3.2).

To control for effects of variability, subjects were scanned in all three languages on two different days. The order of languages during the runs was randomized. To minimize effects of caffeine and nicotine on the tested neuronal language activity (see Chapter 5.5), participants were instructed to avoid drinking coffee and to refrain from smoking during the hours prior to the fMRI session. After the scanning session, the subjects were questioned to assess whether the language and control condition were managed according to the given instructions. Notably, one subject could not be included in the study because she did not perform the control task correctly in the first session and refused to come for a third session to replace the data from the session which failed.



**Fig. 3.2 Language task during fMRI.**

The order of presentation of the language (pictures representing morning, noon and evening) and of the control condition (pictures representing a cross) is indicated.

### 3.4 Data acquisition and Data analysis (SPM)

#### 3.4.1 MRI data acquisition

Imaging was performed on a 1.5 T Magnetom Vision MRI scanner (Siemens, Germany). Functional images were obtained by using an T2\*-weighted EPI sequence (repetition time: 6 s, echo time: 60 ms, flip angle: 90°) covering the entire brain with 48 contiguous axial slices (resolution: 3x3x3 mm). In each functional image session, 90 scans were collected comprising 9 blocks per condition. T1-weighted (resolution: 1x1x1 mm) anatomical images were acquired at the end of the functional imaging session using a MP-RAGE (magnetization prepared rapid acquisition gradient echo) sequence.

#### 3.4.2 Data analysis

Processing and analysis of data was performed using SPM99 (Friston et al., 1995). On the basis of SPM99, a specific procedure of processing and statistical analysis of the functional data was developed in order to assess language specific brain activity. Establishment of the protocol was supervised by Birgit Westermann (expertise in Medical Image Processing and Analysis). In addition, the procedure has been adapted to the guidelines and recommendations of the SPM developers group.

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#### **Preprocessing**

To create comparable conditions for statistical data analysis of the different subjects, images were preprocessed according to guidelines recommended by SPM99. This includes mainly the following steps:

1. Functional images of each session (T2\* images) were realigned to correct for movements.
2. Functional images of each session (T2\* images) were co-registered to the high-resolution structural image (T1-image), which serves as anatomical reference.
3. The T1-image and T2\* images were normalized to the space defined by the standard MNI brain template (Montreal Neurological Institute average brain template, which is an average of 152 young, normal subjects of both sexes without history of neurological disorders) using non-linear transformation.
4. The functional images were smoothed by an 8 mm isotropic Gaussian kernel to account for inter-subject variability expected in the group analysis.

## Statistical model

### Main effect

Statistical modeling and inference is based on a design that predicts the time course of the BOLD (blood oxygen level dependent) signal change as a hemodynamic function in response to the tasks. Differences in task related demands, i.e. between language and control condition (main effect), manifest as condition related effects for each subject. The statistical significance of these condition related effects (t-value) is described for the entire brain as statistical parametric map (SPM).

*This evaluation allowed to assess the main effect of the language conditions (L1, L2, L3) for each tested subject.*

### Fixed and random effect analysis

At the group level, condition related effects can be assessed by evaluation of the statistical parametric maps with a fixed effect model or random effect model.

Fixed effects analysis reveals the average of condition related effects within a group. The statistical significance is determined by the ratio of the group average to the average error (remaining error between the real and predicted signal change for all subjects). This provides a t-statistics for the group. In contrast, the random effects analysis considers additionally the variability of this error between subjects. This provides the t-statistics for the whole population. In our analysis, we opted for a fixed effects model for the following reasons: within language regions a high anatomical variability has been observed (Amunts et al., 1999) and different language regions may contribute variably to language processing in different subjects (Paradis, 2000). A random effect model would tend to reject activated language regions, and seems therefore too conservative for the assessment of language functions. It was suggested that 'in many instances first-level inferences (fixed effects model) are quite appropriate and more useful, e.g. to characterize inter-subject variability' (Karl Friston, Wellcome Department of Imaging Neuroscience, FIL, SPM mailing list, 18.07.2001). Variable language activation has been also observed between repeated imaging sessions and could be attributed to changing attention (Mahendra et al., 2003). By considering in the fixed effect model analysis the two runs of the tested language task, we were able to account for this variability inherent to language processing. More specifically, the variability was controlled for by inclusive masking the group average of the two runs with a conjunction of both runs. Indeed, the conjunction analysis excludes those regions as being activated, where significant differences between both runs occur, i.e. regions which exhibit a high variability in activation (Perani et al., 1996; Price and Friston, 1997). The procedure adopted ensured that the voxels being revealed as significant in activation were not only significant in the average group activation of both runs but also significant in the conjunction analysis of both runs.

*This evaluation was used to assess the condition (language or control condition) related neuronal activity (main effect).*

### Interaction effect

Differences in neuronal activity between different tasks are revealed by the interaction effect (Price et al., 1997). This effect has been defined as “the size of the influence of two or more main effects together” (Kinney, 2002).

*This analysis allowed to define task related differences of L1, L2 and L3 within and between both tested groups of multilinguals.*

Table 3.6 shows the defined main and interaction effects at the single subject and at the group level with the corresponding statistical thresholds.

STATISTICAL THRESHOLD			
	Main effect (at group and single subject* level)	Interaction effect between groups	Interaction effect Within groups
test contrast (average effect across both runs)	$P < 0.05$ , 5 voxel corrected	$P < 0.0001$ , 10 voxel uncorrected	$P < 0.001$ , 5 voxel uncorrected
conjunction contrast (conjunction of both runs)	$P < 0.001$ uncorrected only group level	$P < 0.001$ uncorrected	$P < 0.005$ uncorrected

**Tab. 3.6 Statistical thresholds (p-value), extended threshold (cluster voxel size) and the correction applied for multiple comparisons for the different effects analyzed.**

\*Each run was analyzed separately in single subjects.

### T-value

The statistical significance of the main effect and the interaction effect are both assessed by a t-test. The t-value reported for each effect is constraint by the underlying evaluation hypotheses.

### Analysis of the BOLD signal change

To show the condition related neuronal activity independent from the statistical model; i.e. independent from a tested reference condition, the neuronal signal was compared to the mean brain signal separately for each condition (Donaldson et al., 2001).

This is implemented in SPM99 by determining the signal intensity of a given effect in a particular voxel with respect to the global mean brain intensity. The global mean intensity was scaled to 100 and in consequence the height of the effect is indicated in % signal change.

The global mean intensity is an average of all intracortical voxels computed from all functional images of a session from which voxels with a value less than 1/8 of the whole image intensity were disregarded (Stefan Kiebel, Wellcome Department of Imaging Neuroscience, FIL, SPM mailing list, 30.11.2000).

$$\text{BOLD signal change} = (\text{signal intensity}) \times 100 / (\text{global mean intensity})$$

The mean signal change in a voxel of interest is obtained by averaging the signal across subjects and sessions of the corresponding condition and group.

*In this study we analyzed the BOLD signal change in regions of highest differential activation (activation maxima) within and between groups as revealed by the interaction effect. This allowed to assess separately the contribution of the language and the control condition to the tested effect.*

### Identification of activated regions

SPM provides the coordinates of highest activated voxels in MNI coordinates. This standard template does not match completely to the Talairach brain. To correctly identify Brodmann Areas and to report the localization of areas according to the Talairach Atlas, the MNI coordinates have been converted into Talairach coordinates using an additional non-linear transformation (Matthew Brett, The MNI Brain and the Talairach Atlas, <http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml>). In this study, all coordinates of activated regions are given in the Talairach space. For the identification of anatomical regions we referred to the Talairach atlas (Talairach and Tournoux, 1988). This allows in addition relating our results to other studies.

## 4 Results

Early multilinguals as well as late multilinguals were selected according to their ability to communicate in at least three languages. Early multilinguals acquired two languages (L1, L2) early in life, before the age of three years and learned at least one language (L3) after the age of nine years. In contrast, late multilinguals acquired only one language during early childhood (L1) but learned at least two languages (L2, L3) after their early adolescence. L1, L2 and L3 of both groups are described in more detail in Chapter 3.1.

TIME OF ACQUISITION	EARLY MULTILINGUALS	LATE MULTILINGUALS
before three years	L1, L2	L1
after nine years	L3	L2, L3

**Tab. 4.1 Early and late multilinguals: time of acquisition of the three tested languages.**

In all subjects of both groups we tested L1, L2 and L3 with fMRI according to the procedures described in 3.3. Each language has been tested twice.

### 4.1 Language related neuronal activity in early and late multilinguals

#### 4.1.1 Individual analysis of the first acquired language

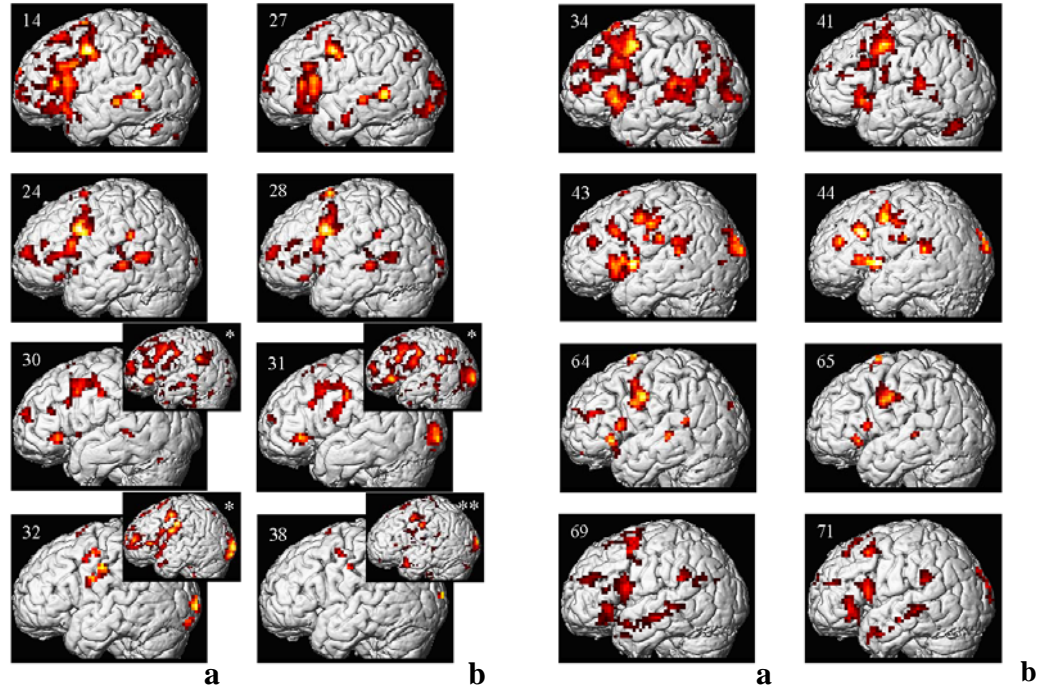
The first acquired language (L1) was analyzed in each early or late multilingual subject. Regions with language related neuronal activity are projected on a 3D rendering of the individual brain (Fig 4.1 and 4.2). The brain activations of both tested runs are shown separately.



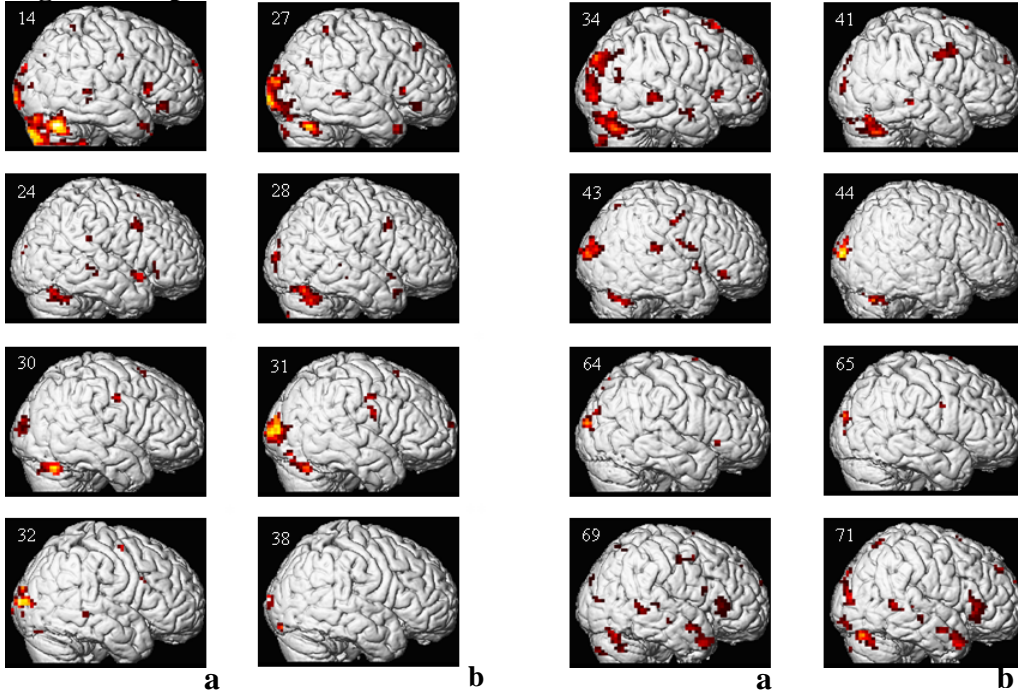
## Figures

### Individual activation in the first acquired language of early multilinguals

#### Left hemisphere



#### Right hemisphere

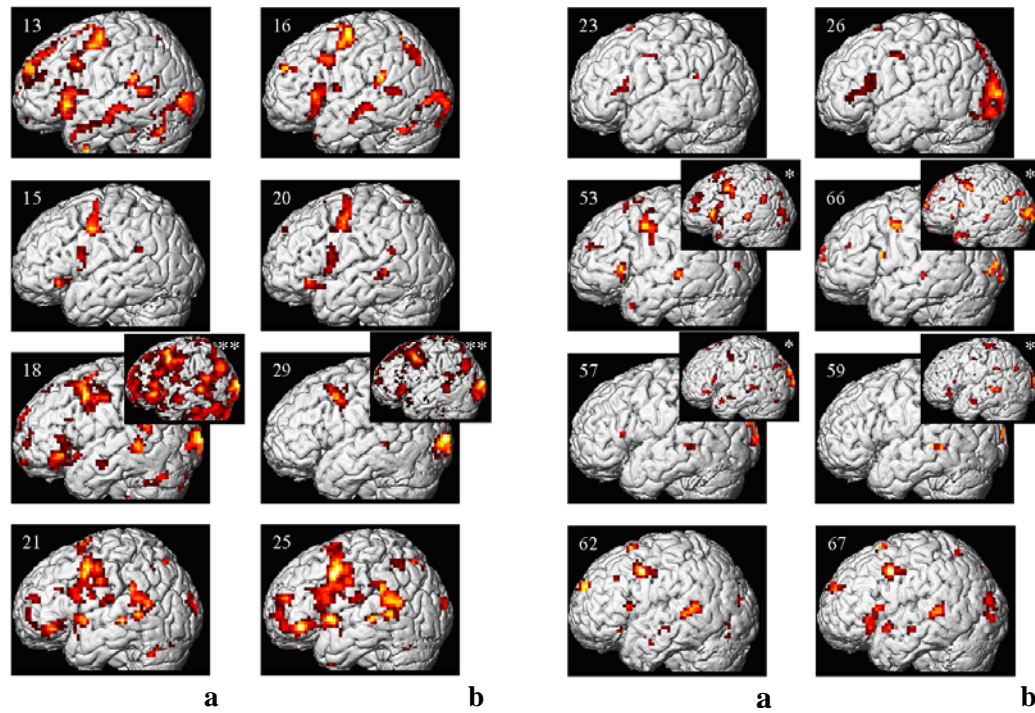


**Fig. 4.1 Early multilinguals: Neuronal activity in L1 of each tested subject.**

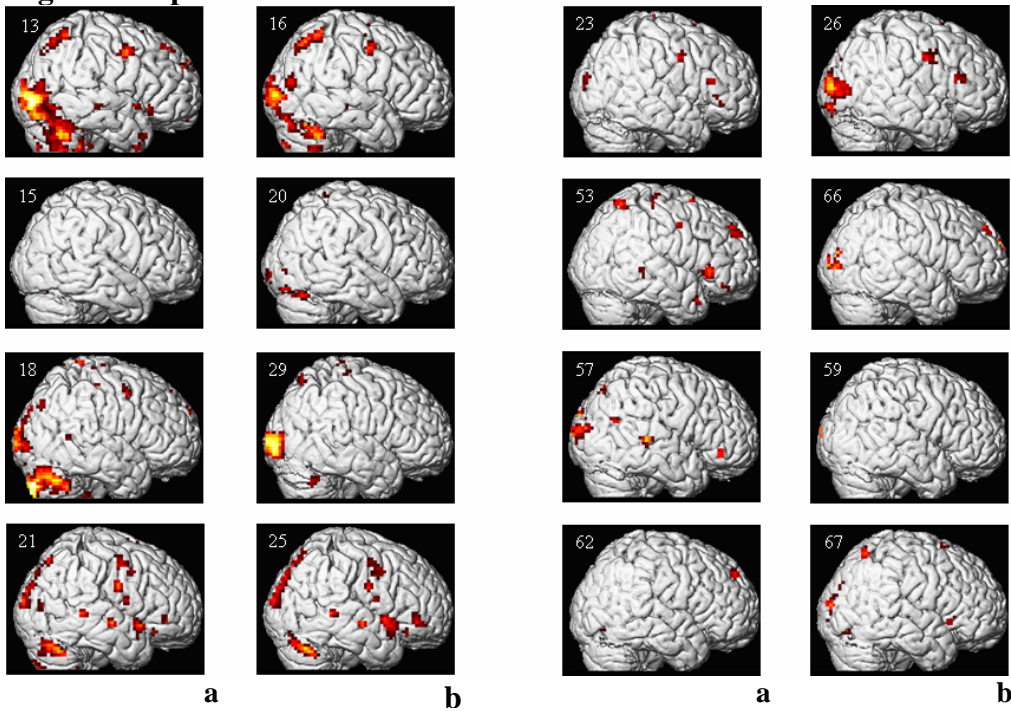
Statistically relevant neuronal activation has been projected on the normalized 3D rendering of the individual brain (a: first run, b: second run). The statistical threshold was set at  $P < 0.05$  with a spatial extent of 5 voxels (corrected). The threshold has been adapted to visualize activation in left Broca's area in all subjects. The corresponding representations are shown in additional images (\*:  $P < 0.01$  uncorrected with a spatial extent of 5 voxels, \*\*:  $P < 0.05$  uncorrected with a spatial extent of 0 voxels).

## Individual activation in the first acquired language of late multilinguals

### Left hemisphere



### Right hemisphere



**Fig. 4.2 Late multilinguals: Neuronal activity in L1 of each tested subject.**

Statistically relevant neuronal activation has been projected on the normalized 3D rendering of the individual brain (a: first run, b: second run). The statistical threshold was set at  $P < 0.05$  with a spatial extent of 5 voxels (corrected). The threshold has been adapted to visualize activation in left Broca's area in all subjects. The corresponding representations are shown in additional images (\*:  $P < 0.01$  uncorrected with a spatial extent of 5 voxels, \*\*:  $P < 0.05$  uncorrected with a spatial extent of 0 voxels).

## Findings

Figures 4.1 and 4.2 show that in all tested subjects the tested language related brain activity in left prefrontal and premotor regions and in the occipital lobe was statistically relevant. When considering lower statistical thresholds, participation of left Broca's area in the language task can also be confirmed for all tested multilinguals. In numerous subjects, cortical regions in the left superior temporal lobe could be revealed as well. In contrast, in structures of the right hemisphere, neuronal activity during the language condition was significant only in a few subjects.

The pattern of brain activity associated with the language condition was similar in both tested runs of each subject. However, in most multilinguals, neuronal activity during the first tested run was more extensive than during the second run. To allow a systematic comparison of language related brain activity between early and late multilinguals further analysis of the data was carried out at the group level.

### 4.1.2 Group analysis of first, second and third acquired languages

In early and late multilinguals, the group averages of the L1, the L2 and the L3 language condition were compared to their corresponding auditory control condition. In both groups the two tests of each language were included in the statistical analysis (see 3.4).

## Table

To evaluate the language specific neuronal response, brain regions in which neuronal activity during the language condition increased were identified. Within each activated region, the brain coordinates (in Talairach coordinates, see 3.4) and t-values (see 3.4) of the activation maximas (voxels that present a regional maximum of difference with the control condition) were assessed. Table 4.2 shows the most consistent findings, i.e. all brain regions where activation maxima were found in at least the two early acquired languages of early multilinguals and the two late acquired languages of late multilinguals. Within each region, only the activation maximum which presented the highest t-value is shown.

EARLY MULTILINGUALS - LATE MULTILINGUALS						
ANATOMICAL REGION	EL1	EL2	EL3	LL1	LL2	LL3
Language related neuronal response- left hemisphere						
<b>Frontal region</b>						
L. medial frontal gyrus, (SMA, BA 6)	<b>t:34.47</b> T:-3 17 49	<b>34.72</b> -3 17 49	<b>34.71</b> -3 17 49	<b>22.57</b> -6 17 54	<b>23.33</b> -6 17 52	<b>24.51</b> -6 17 52
L. middle frontal gyrus, precentral gyrus (BA 6)	<b>t:32.18</b> T:-48 5 41	<b>31.08</b> -48 5 41	<b>30.30</b> -48 5 41	<b>24.14</b> -50 -1 41	<b>28.88</b> -50 -1 41	<b>28.02</b> -50 -1 41
L. inferior frontal gyrus (BA 47)	<b>t:12.91</b> T:-53 23 -6	<b>13.33</b> -53 23 -6	<b>13.96</b> -53 23 -6	-	<b>14.38</b> -48 26 -11	<b>12.66</b> 48 26 -11
L. inferior and middle frontal gyrus (Broca's area and adjacent prefrontal region, BA 44/45/46)	<b>t:11.80</b> T:-59 12 10	<b>10.68</b> -59 9 11	<b>14.39</b> -56 12 13	<b>6.33</b> -45 10 16	<b>13.67</b> -56 23 2	<b>12.20</b> -56 18 10
<b>Temporal regions</b>						
L. superior temporal sulcus, (STS, BA 21/22)	<b>t:17.27</b> T:-48 -44 2	<b>17.17</b> -50 -32 -1	<b>20.70</b> -62 -29 1	<b>16.79</b> -48-44 2	<b>20.3</b> -50 -41 5	<b>18.59</b> -50 -41 5
<b>Parietal regions</b>						
L. posterior cingulate gyrus BA (23/30/31)	<b>t:13.43</b> T:-15 -58 14	<b>10.29</b> -12-58 11	<b>12.50</b> -12-60 12	<b>13.69</b> -12-55 17	<b>11.04</b> -12-52 14	<b>10.82</b> -6-55 11
L. inferior parietal lobe (BA 40 /7)	<b>t:10.92</b> T:-18-65 50	<b>11.06</b> -15-65 50	<b>11.72</b> -27-68 45	<b>9.18</b> -9-73 51	<b>10.17</b> -6-73 51	<b>8.73</b> -9-73 48
<b>Occipital regions</b>						
L. occipital lobe (BA 17, 18, 19)	<b>t:14.24</b> T:-9-96 8	<b>17.29</b> -9-96 8	<b>15.10</b> -9-96 8	<b>18.12</b> -3-93 5	<b>19.73</b> -3-93 5	<b>15.71</b> -3-93 5
<b>Subcortical structures</b>						
L. corpus striatum	<b>t:12.99</b> T:-18 3 11	<b>13.12</b> -21 3 11	<b>14.88</b> -21 3 8	-	<b>8.57</b> -18 3 5	<b>7.52</b> -18 3 8
Language related neuronal response- right hemisphere						
<b>Frontal regions</b>						
R. medial frontal gyrus (SMA, BA 6)	<b>t:15.69</b> T:6 17 52	<b>19.06</b> 6 17 52	<b>17.87</b> 6 17 52	<b>10.03</b> 6 15 60	<b>9.83</b> 6 15 60	<b>8.11</b> 6 15 57
<b>Parietal regions</b>						
R. posterior cingulate gyrus (BA 23/30/31)	<b>t:11.03</b> T :6-46 8	<b>8.33</b> 6 -46 8	<b>9.68</b> 9 -47 2	<b>9.19</b> 9 -52 11	<b>7.60</b> 9 -55 11	<b>8.04</b> 6-52 8
<b>Occipital regions</b>						
R. occipital lobe (BA 17, 18, 19)	<b>t:17.18</b> T:15-99 9	<b>14.40</b> 9-90 1	<b>13.33</b> 12-92 24	<b>17.34</b> 9-87 4	<b>18.86</b> 9-87 2	<b>15.61</b> 9 -87 4
<b>Subcortical structures</b>						
R. cerebellum	<b>t:13.85</b> T:39-65 -19	<b>13.83</b> 36 -68 -19	<b>13.60</b> 36-68 -19	<b>9.17</b> 53 -57 -27	<b>9.37</b> 36-71 -17	<b>8.42</b> 53 -57 -27

**Tab. 4.2 Early and late multilinguals: Main effect.**

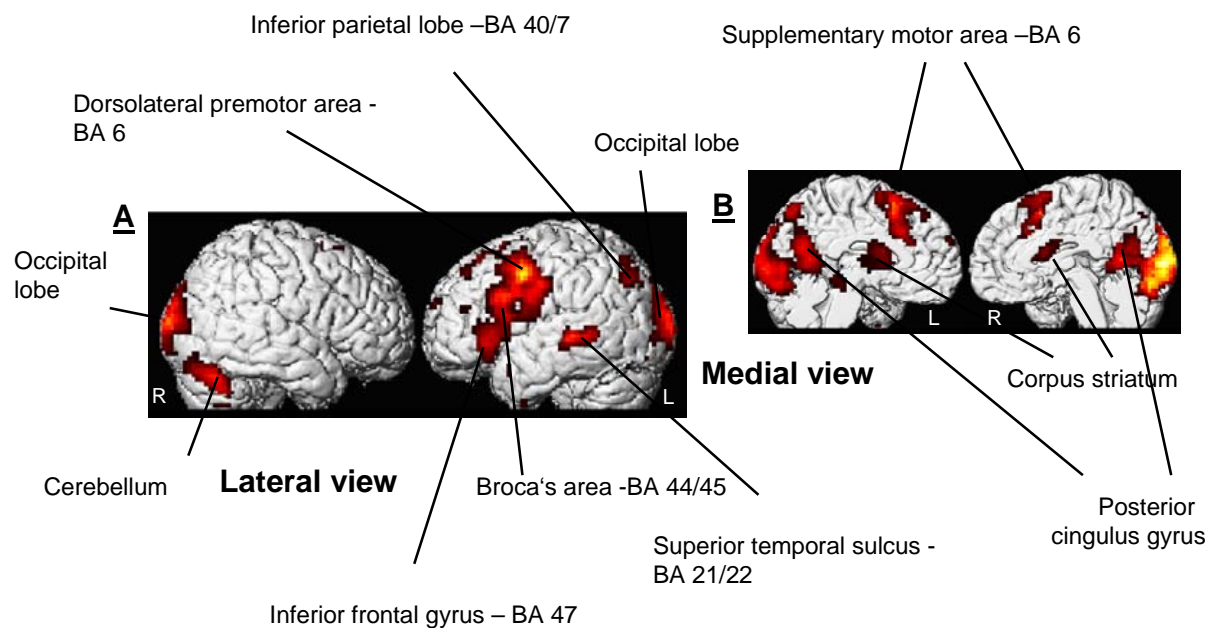
In brain regions of higher neuronal activity during the language condition, t-value (t) and localization (in Talairach coordinates, T=x y z) of regional highest activation (activation maxima) are shown for the group average of the three tested languages (L1, L2 and L3) in early (E) and in late multilinguals (L).

## Figures

The regional higher neuronal activity during processing of each tested language (L1, L2, and L3) is illustrated by Figure 4.3 for early multilinguals and by Figure 4.4 for late multilinguals. The results are projected on a brain from a subject of the study (male, early multilingual subject). Almost all brain regions described in Table 4.2 can be identified on the lateral view of the 3D rendering of the brain (Figures 4.3 A and Figures 4.4 A). The right and left supplementary motor area, the posterior cingulate gyrus and the striatum are shown on a medial view of the brain (B). For overview, the average activation of all three tested languages together is shown for early and late multilinguals in Figure 4.5.

### Main language effect in each of the three tested languages of early multilinguals

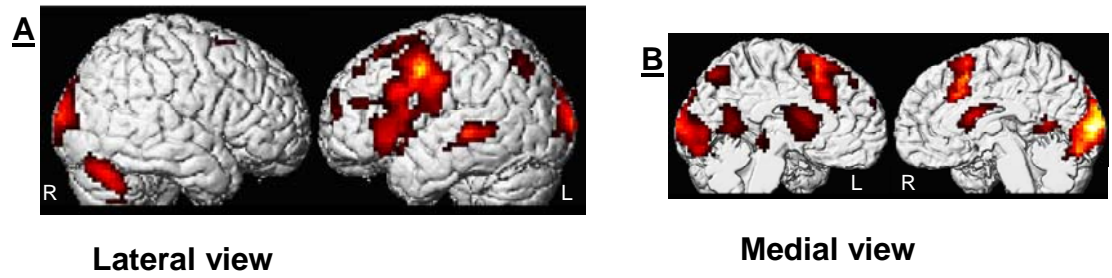
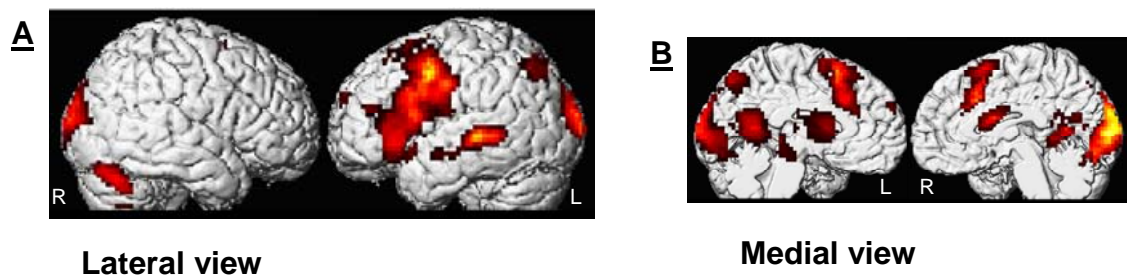
#### Early acquired L1



**Fig. 4.3 Early multilinguals: Main language effect of L1. (first and second part)**

The results are projected on a 3D brain representation from a subject of the study. The most significant results are indicated for L1. A: lateral view (R=right, L=left). B: medial view (R=right, L=left). The evaluation was set at  $p < 0.05$  (corrected). All activated regions  $>5$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).



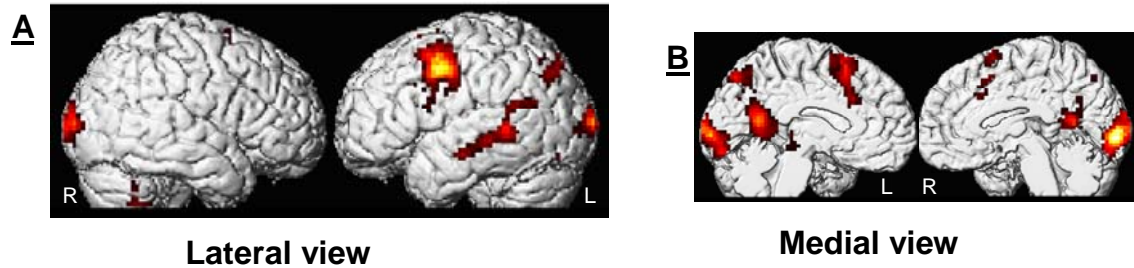
**Early acquired L2****Late acquired L3**

**Fig. 4.3 (continued) Early multilinguals: Main language effect of L2 (upper panel) and L3 (lower panel).**

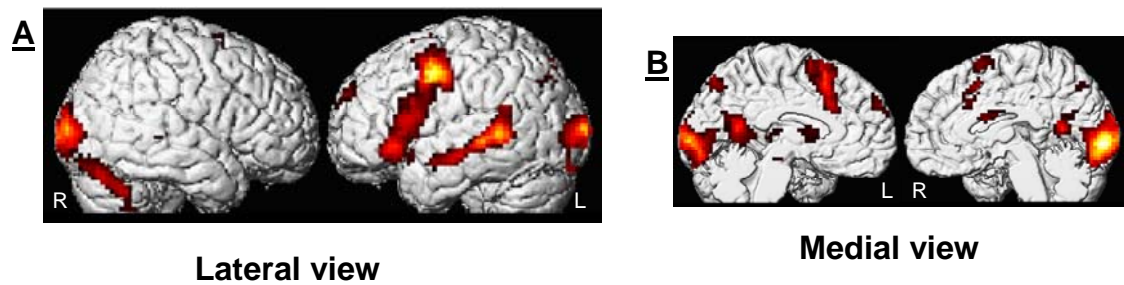
The results are projected on a 3D brain representation from a subject of the study. The most significant results are indicated for L1. A: lateral view (R=right, L=left). B: medial view (R=right, L=left). The evaluation was set at  $p < 0.05$  (corrected). All activated regions  $>5$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

## Main language effect in each of the three tested languages of late multilinguals

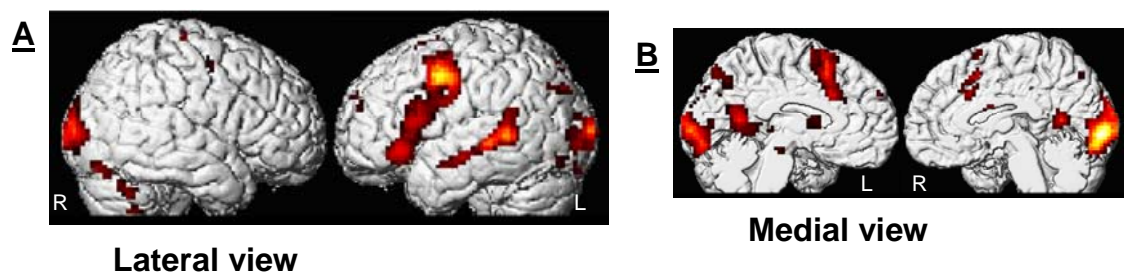
### Early acquired L1



### Late acquired L2



### Late acquired L3

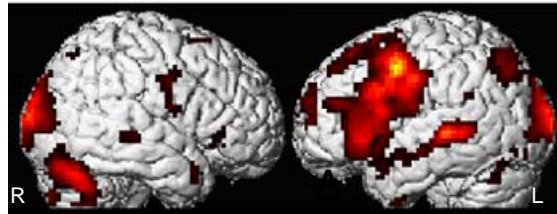


**Fig. 4.4 Late multilinguals: Main language effect of L1 (upper panel), L2 (middle panel) and L3 (lower panel).**

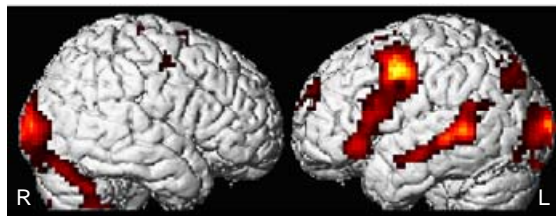
The results are projected on a 3D brain representation from a subject of the study. A: Lateral view (R=right L=left), B: Medial view (R=right L=left). The evaluation was set at  $p < 0.05$  (corrected). All activated regions  $> 5$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

## Main language effect in all three tested languages of early and late multilinguals

### Early multilinguals (L1, L2 and L3)



### Late multilinguals (L1, L2 and L3)



**Fig. 4.5 Early and late multilinguals: Main language effect of the three tested languages (L1, L2 and L3).**

Early multilinguals are shown in the upper panel and late multilinguals in the lower panel. The results are projected on a 3D brain representation from a subject of the study. A: Lateral view (R=right L=left), B: Medial view (R=right L=left). The evaluation was set at  $p < 0.05$  (corrected). All activated regions  $> 5$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

## Findings

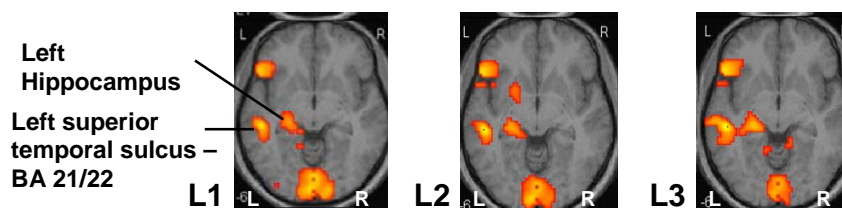
### General findings

As shown in Table 4.2 and Figures 4.3AB, 4.4 AB and 4.5, in both groups, higher neuronal activity during the language condition was mainly found in regions of the left hemisphere. In the frontal lobe, regions activated during the language condition were the medial frontal gyrus bilaterally (supplementary motor area, BA 6), the left middle frontal gyrus and adjacent precentral gyrus (dorsolateral premotor area, BA 6) and the left inferior frontal gyrus (Broca's area- BA 44/45 and BA 47) with -in early multilinguals only- the adjacent middle frontal gyrus (dorsolateral prefrontal areas, BA 46). Neuronal activity in BA 47 however could not be confirmed for the first



language of late multilinguals. More posteriorly, neuronal activity was evidenced in the left superior temporal sulcus (BA 21/22), the left inferior parietal lobe (BA 40/7), the posterior cingulate gyrus bilaterally (BA 30/31/23) and the occipital lobe (BA 17, 18, 19). The neuronal activity in the left superior temporal sulcus extended also into the hippocampus (Figure 4.6). However, since activation maxima were not consistently found in the hippocampus, the localization of this region is not listed in the Table 4.2.

### Early multilinguals



### Late multilinguals



**Fig. 4.6 Early and late multilinguals: Main language effect of L1, L2 and L3 in a selected cortical region.**

The Figures show the activation in an axial slice through the STS and the Hippocampus (R=right L=left). The evaluation was set at  $p < 0.05$  (corrected). All activated regions  $>5$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

Evidence was found for the involvement of subcortical structures during the performing of the language task: neuronal activity was found in the left striatum and in the right cerebellum in all tested languages (Figures 4.3B and 4.4B), excepted from this was the first language (L1) of late multilinguals in which neuronal activity was not statistically relevant in the striatum. According to Table 4.2, two regions of the left hemisphere, the left dorsolateral premotor area (BA 6), the right and left supplementary motor area (BA 6) and the left superior temporal sulcus (BA 21/22) exhibit the most significant neuronal activity in all languages of both groups. In

contrast, activation in Broca's area (BA 44/45) was always significant, but was less pronounced.

### **Group specific findings**

In general, early and late acquired languages of early multilinguals (Figure 4.3 and Table 4.2) elicited a higher neuronal response than the corresponding languages of late multilinguals (Figure 4.4 and Table 4.2). In particular, regions in the left frontal lobe, including the left dorsolateral premotor area (BA 6), the right and left supplementary motor area (BA 6), left Broca's area (BA 44/45) with the adjacent left dorsolateral prefrontal cortex (BA 46), the right and left striatum and the right cerebellum were clearly more involved in the languages of early than the one of late multilinguals. In late multilinguals only one brain region seems to be more activated than in early multilinguals: Figure 4.4 shows that in all three tested languages of late multilinguals, neuronal activity in the left superior temporal sulcus (BA 21/22) is more widespread and, in the first acquired language, extends even into the supramarginal gyrus (Figure 4.4 A). However, this observation could not be confirmed by the data (t-values of the activation maxima) reported in Table 4.2. Further analysis of these results in Chapter 4.2 allows specifying the group differences in language processing.

### **Specific findings for the multilinguals early and late acquired languages**

The early respectively the late multilinguals early and late acquired languages showed variable activation: in both groups later acquired languages show higher neuronal activity in and in proximity to left Broca's area (BA 44, 45, 46), in the left superior temporal sulcus (BA 21/22) and in the left striatum. Higher significance of the neuronal activity was as well found for later acquired languages in the left dorsolateral premotor area (BA 6) and in the left orbitofrontal cortex (BA 47), but only in the group of late multilinguals. However, a further analysis of the data did not allow confirming this group specific processing of late learned languages in late multilinguals (Chapter 4.3).

## 4.2 Group specific language processing: comparison of early and late multilinguals

The statistical comparison (interaction effect, see Chapter 3.4.2) of the language test between early and late multilinguals allowed further defining cortical regions with a group specific language processing. In this analysis we compared languages similar in age of acquisition and proficiency (**EL1/LL1**, **EL3/LL3**, **EL2/LL1** comparisons, see Table 4.3). Languages different in age of acquisition and proficiency were not systematically compared; however, to allow estimation of the influence of these variables on the group specific language processing, the **EL2/LL2** (see Table 4.3) comparison was assessed. In brain regions which exhibited differential activation between both groups the Talairach coordinates (see Methods, Chapter 3.4) and the t-values for the highest local difference (activation maximum) were reported. In addition, in all cortical regions with group specific language processing the neuronal signal (BOLD signal) of the language condition and of the auditory control condition were assessed separately, on the basis of the main group effect (see Methods, Chapter 3.4) and were reported for both languages that were compared. This procedure allowed revealing the BOLD signal of the language condition in regions with group specific activations.

COMPARISON	COMPETENCE	TIME OF ACQUISITION	EARLY MULTILING. (E)	LATE MULTILING. (L)
early languages	similar	similar: early acquired < 3 years	<b>EL 1</b> <b>EL 2</b>	<b>LL 1</b>
late languages	similar	similar: late acquired > 9 years	<b>EL 3</b>	<b>LL 3</b>
early and late languages	not similar early>late	not similar: late-early acquisition	<b>EL 2</b>	<b>LL 2</b>

**Tab. 4.3 Comparisons of languages between groups.**

Compared are early acquired languages similar in proficiency (**EL1/LL1**, **EL2/LL1**), late acquired languages similar in proficiency (**EL3/LL3**), and early or late acquired language different in proficiency (**EL2/LL2**).

## Tables

Table 4.4 and 4.5 show the brain regions which exhibited differential activation between both groups. For each region, the Talairach coordinates, t-value and BOLD signal of the voxel with the highest differential activation are shown. In addition, for each activation maxima, the BOLD signal of the language condition is indicated for both languages compared. Table 4.4 shows the results for the brain regions where the

group differences were originating mainly from the language condition. Cortical regions where the t- value of the group differences was mainly determined by the auditory control condition are reported in Table 4.5. Notably this concerned the left superior temporal gyrus (BA 22), the left parietal operculum (PO, BA 43), the left insula, the right supramarginal gyrus (BA 40) and the right superior parietal lobe (BA 7). These regions will not be further discussed. Brain regions within the left middle and superior frontal gyrus (BA 8 and BA 10) exhibited a substantial variability of the localization of differential activation and are not listed in the Tables.

EARLY MULTILINGUALS (E) /LATE MULTILINGUALS (L)				
ANATOMICAL REGION	EL1/LL1 t-value Talairach Coord. BOLD signal lang.cond.	EL2/LL1 t-value Talairach Coord. BOLD signal lang.cond.	EL2/LL2 t-value Talairach Coord. BOLD signal lang.cond.	EL3/LL3 t-value Talairach Coord. BOLD signal lang.cond.
Language related neuronal response- left (L) and right (R) hemisphere				
<b>Frontal regions</b>				
L. inferior frontal gyrus, Broca's area (BA 44/45)	t=15 T=-59 9 11 B: E 0.5 L 0.02	15.1 -59 9 11 E: 0.91 L: 0.02	11.12 -59 9 11 E: 0.91 L: 0.01	12.38 -59 9 13 E: 0.71 L: -0.36
L. inferior frontal gyrus, Broca's area (BA 44/6)	t=11.98 T=-59 1 25 B: E 0.52 L -0.19	11.98 -53 2 30 E: 1.21 L: 0.01	9.87 -59 1 25 E: 0.67 L: 0.16	10.72 -59 4 27 E: 0.52 L: -0.06
L. inferior frontal gyrus, Broca's area (BA 44/9)	t=12.2 T=-50 19 29 B: E 2.11 L 0.28	11.51 -50 19 29 E: 1.79 L: 0.28	9.4 -50 19 29 E: 1.79 L: 0.5	9.84 -48 16 30 E: 2.08 L: 0.46
R. inferior frontal gyrus, (BA 44/45)	t=7.56 T=59 15 19 B: E -0.1 L -0.59	7.56 59 15 19 E: -0.1 L: -0.59	8.49 59 21 18 E: 0.37 L: -0.12	5.94 59 16 21 E: 0.31 L: -0.72
R. inferior frontal gyrus, (BA 44/9)	t=7.54 56 24 24 B: E 0.15 L -1.11	7.54 56 24 24 E: 0.61 L: -0.56	8.45 -15 20 48 E: 0.61 L: -0.56	-
L. supplementary motor area- SMA (BA 6)	t=11.22 T=-3 32 48 B: E 1.37 L 0.54	8.49 -3 32 48 E: 0.9 L: 0.54	9.55 -15 20 48 E: 1.37 L: 0.2	8.8 -3 20 49 E: 1.89 L: 1.19
R. supplementary motor area -SMA (BA 6)	t=9.68 T=6 32 48 B: E 1.24 L 0.35	9.68 6 32 48 E: 1.24 L: 0.35	10.02 9 26 54 E: 0.62 L: -0.26	9.71 6 23 51 E: 0.72 L: 0.17
L. dorsolateral premotor area (BA 6)	-	-	-	-
L. precentral/postcentral gyrus (BA 4,1,2,3)	t=8.52 T=-53 -13 37 B: E 0.59 L -0.22	10.11 -56 -10 36 E: 1.46 L: 0.15	9.02 -48 -16 37 E: 1.49 L: 0.26	8.88 -56 -10 34 E: 1.17 L: 0.03
L. anterior cingulate gyrus (BA 32)	t=7.9 T=-6 25 32 B: E 1.27 L 0.2	8.89 -6 25 32 E: 0.85 L: 0.2	6.94 -6 28 32 E: 0.56 L: 0.75	7.37 -9 28 32 E: 0.9 L: -0.17
L. middle frontal gyrus (BA 46)	t=9.22 T=-45 42 17 B: E 1.05 L -0.04	10.38 -45 42 17 E: 1.26 L: -0.04	9.52 -45 42 17 E: 1.26 L: -0.24	-
L. inferior frontal gyrus (BA 47)	t=6.3 T=-45 17 -1 B: E 0.94 L 0.47	-	-	-

**Tab. 4.4 Early and late multilinguals: Interaction effect. Language activity is shown in cortical regions of differential activation which is mainly due to the language condition (first and second part).**

The voxels with regional highest difference between early and late multilinguals are listed (t=t-value, T=Talairach coordinates, B=BOLD signal of the language condition – E=early multilinguals, L=late multilinguals). The t-value of voxels with a higher response in early multilinguals is shown on the left part of each column, that of voxels higher activated in late multilinguals is shown on the right part.

EARLY MULTILINGUALS (E) /LATE MULTILINGUALS (L)				
ANATOMICAL REGION	EL1/LL1 t-value Talairach Coord. BOLD signal lang.cond.	EL2/LL1 t-value Talairach Coord. BOLD signal lang.cond.	EL2/LL2 t-value Talairach Coord. BOLD signal lang.cond.	EL3/LL3 t-value Talairach Coord. BOLD signal lang.cond.
Language related neuronal response- left (L) and right (R) hemisphere				
<b>Temporal regions</b>				
L. fusiform gyrus/lingual gyrus (BA 19/37)	t=8.25 T=-15 -73 -6 B: E 0.5 L -0.02	7.26 -12 -73 -6 E:1.16 L: 0.03	6.12 -27 -9 -11 E: 0.37 L:2.02	-
R.fusiform gyrus/lingual gyrus	-	-	5.59 36 -88 -11 E:1.14 L:2.26	-
L. superior temporal sulcus (BA 21/22)	t=5.89 T=-62 -26 -4 B: E 0.14 L 0.02	8.88 -62 -29 4 E:1.73 L: 0.19	11.06 -56 -40 8 E: 0.84 L:1.44	10.47 -65 -26 4 E:1.61 L: 0.18
R. middle temporal gyrus (BA 21/22)	t=6.85 T=62 -52 8 B: E 0.03 L -0.96	7.84 62 -55 8 E:0.06 L:-1.19	-	-
L. supramarginal gyrus/posterior superior temporal gyrus -pSTG (BA 40/22)	t=8.15 T=-59 -43 19 B: E -0.53 L 1.21	7.24 -59 -46 19 E: 0.58 L:1.21	8.04 -59 -46 19 E: 0.58 L:1.15	8.42 -59 -46 19 E: 0.02L:-0.87
<b>Parietal regions</b>				
L. anterior supramarginal gyrus (BA 40)	t=10.65 T=-59 -34 24 B: E-0.17 L-0.4	13.11 -59 -34 24 E: 0.47 L:-0.4	9.8 -59 -31 24 E: 0.28 L-0.88	8.96 -59 -31 24 E:-0.01L:-1.12
L. inferior parietal lobe (BA 40/7 )	-	7.49 -36 -24 54 E:-0.59L:-0.74	6.91 -39 -26 54 E: -0.36L: -0.81	-
<b>Occipital regions</b>				
L. cuneus (BA 19)	t=10.29 T=-12 -86 35 B: E 1.49 L 0.48	8.21 -12 -86 35 E:1.52 L:0.48	6.82 -12 -89 32 E: 1.27 L:-0.21	7.74 -12 -89 32 E: 1.43 L:-0.08
R. cuneus (BA 19)	t=5.76 T=33 -89 18 B: E 1.43 L 0.3	6.76 24 -92 24 E: 1.41 L:0.27	-	-
<b>Subcortical structures</b>				
L. striatum	t=5.54 T=-18 12 -1 B: E 0.6 L 0.4	7.27 -27 -3 -5 E: 0.4 L: 0.02	7.06 -24 -3 3 E: 0.44 L:0.24	7.05 -24 0 6 E: 0.8 L:0.23
R. cerebellum	t=7.88 T=39 -62 -20 B: E 1.55 L 1.02	7.13 24 -69 -39 B: E 0.51 L 0.48	-	-

**Tab 4.4 (continued) Early and late multilinguals: Interaction effect.**

Language activity is shown in cortical regions of differential activation which is mainly due to the language condition. The voxels with regional highest difference between early and late multilinguals are listed (t=t-value, T=Talairach coordinates, B=BOLD signal of the language condition- E=early multilinguals, L=late multilinguals). The t-value of voxels with a higher response in early multilinguals is shown on the left part of each column; that of voxels higher activated in late multilinguals is shown on the right part.

EARLY MULTILINGUALS (E) /LATE MULTILINGUALS (L)				
ANATOMICAL REGION	EL1/LL1 t-value Talairach Coord. BOLD signal lang.cond.	EL2/LL1 t-value Talairach Coord. BOLD signal lang.cond.	EL2/LL2 t-value Talairach Coord. BOLD signal lang.cond.	EL3/LL3 t-value Talairach Coord. BOLD signal lang.cond.
Language related neuronal response- left (L) and right (R) hemisphere				
L. superior temporal gyrus (BA 22)	t=10.57 T=-59 -25 15 B: E -52 L -0.49	11.37 -59 -25 15 E: 0.09 L:-0.49	-	6.33 -50 -29 10 E:0.2 L:-0.81
L. parietal operculum (BA 43)	t=9.68 T=-59 -22 23 B: E 0.1 L -0.28	10.57 -59 -22 23 E:0.57 L:-0.28	10.81 -62 -22 23 E:0.46 L:-1.05	10.88 -59 -22 23 E:0.38 L:-0.78
L. insula	t=8.72 T=-36 0 8 B: E -0.19 L 0.04	9.57 -33 0 8 E: 0.36 L:0.2	8.8 -33 0 8 E:0.36 L:-0.31	7.65 -36 -2 11 E:-0.02 L:-0.41
R. anterior supramarginal gyrus (BA 40)	t=5.52 T=56 -36 32 B: E-0.88 L -0.78	-	-	-
R. superior parietal lobe (BA 7)	-	-	6.47 39 -55 58 E:0.3 L:-0.1	6.54 33 -55 58 E:-1 L:0.34

**Tab. 4.5 Early and late multilinguals: Interaction effect. Language activity is shown in cortical regions of differential activation which are determined by the auditory control condition.**

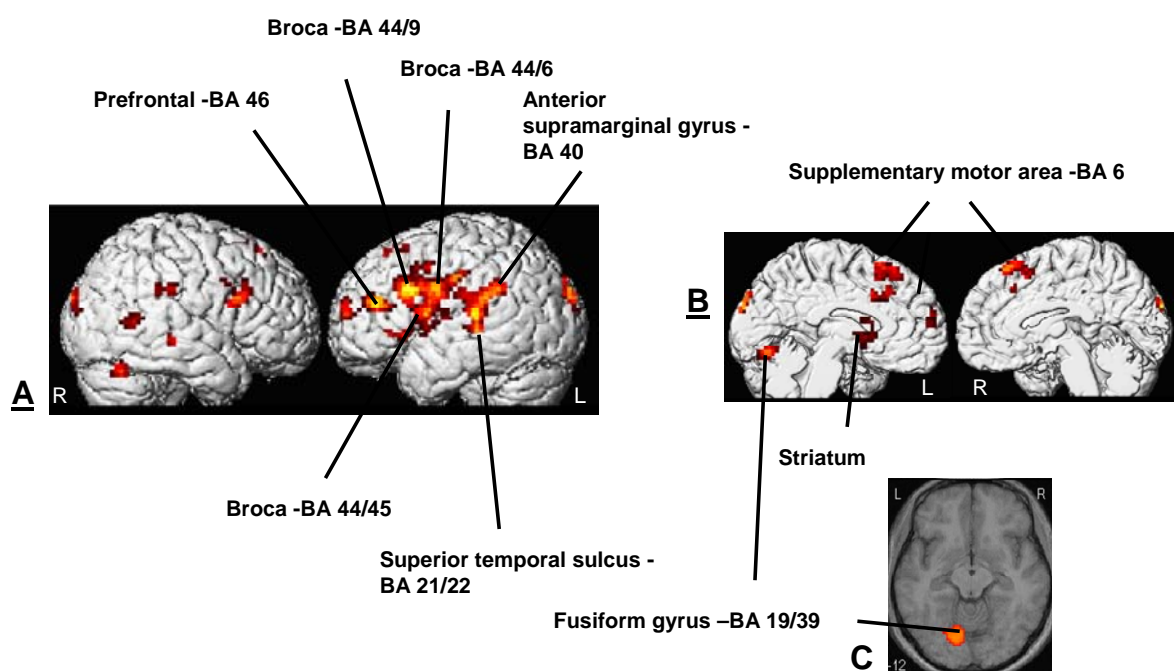
The voxels with regional highest difference between early and late multilinguals are listed (t=t-value, T=Talairach coordinates, B=BOLD signal of the language condition E=early multilinguals, L=late multilinguals). The t-value of voxels with a higher response in early multilinguals is shown on the left part of each column; that of voxels higher activated in late multilinguals is shown on the right part.

## Figures

Figures 4.7-4.14 illustrate the group specific language responses for all language comparisons defined in Tab 4.3. Regions of differential activation have been projected for each language comparison on brain from a subject which has participated in the study (early multilingual, male).

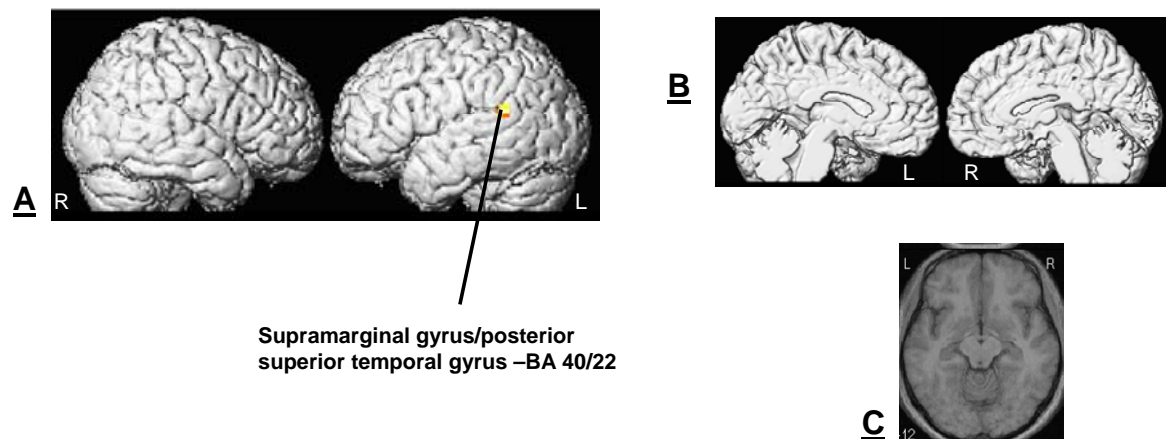
### Comparison of early acquired languages between early and late multilinguals (EL1/LL1 and EL2/LL1)

Contrast EL1>LL1



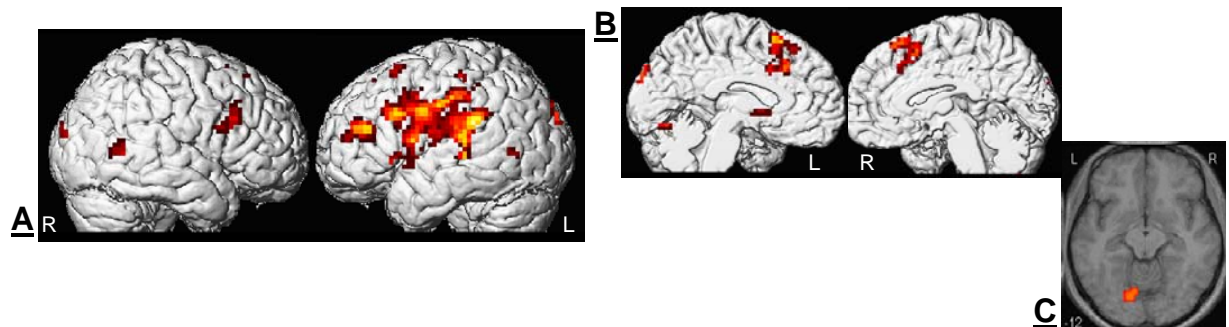
**Fig. 4.7 Early multilinguals>Late multilinguals (EL1 >LL1): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The regions with the most significant results are indicated. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions >10 voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

Contrast **LL1>EL1**

**Fig. 4.8 Late multilinguals > Early multilinguals (LL1 > EL1): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. Regions with significant activation are indicated. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions  $>10$  voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

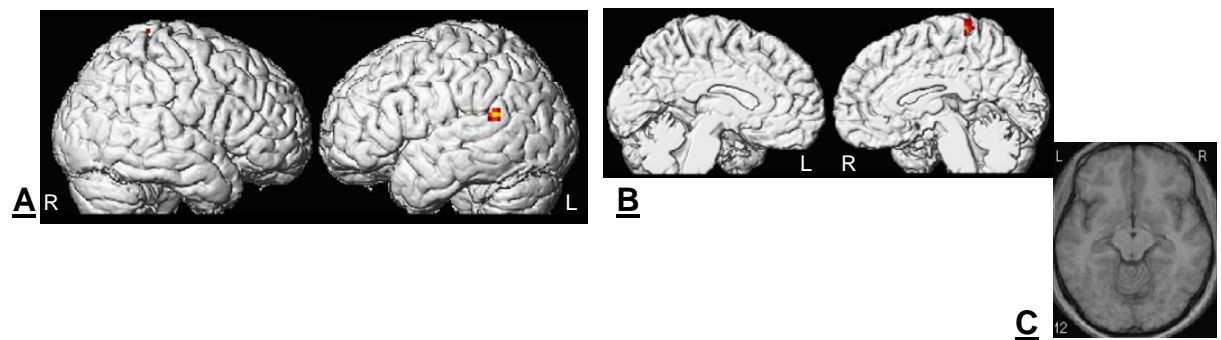
Contrast **EL2>LL1**

**Fig. 4.9 Early multilinguals > late multilinguals (EL2 > LL1): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions  $>10$  voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).



### Contrast LL1>EL2

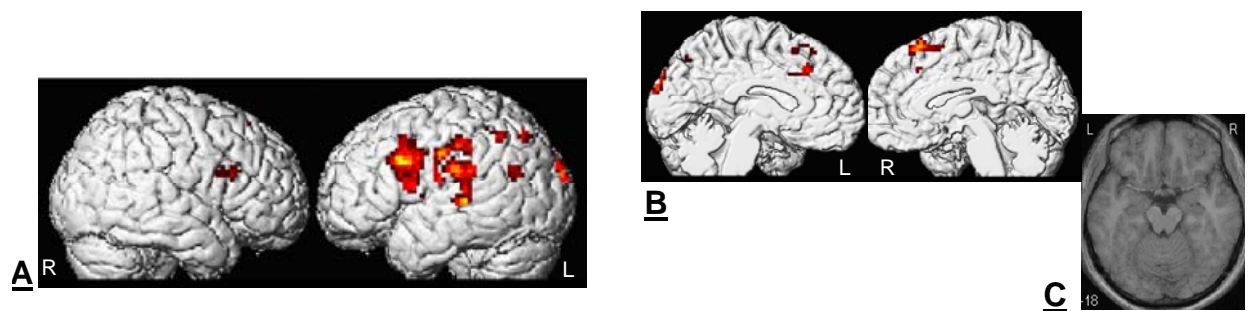


**Fig. 4.10 Late multilinguals> late multilinguals (LL1 > EL2): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions >10 voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

### Comparison of late learned languages between early and late multilinguals (EL3/LL3)

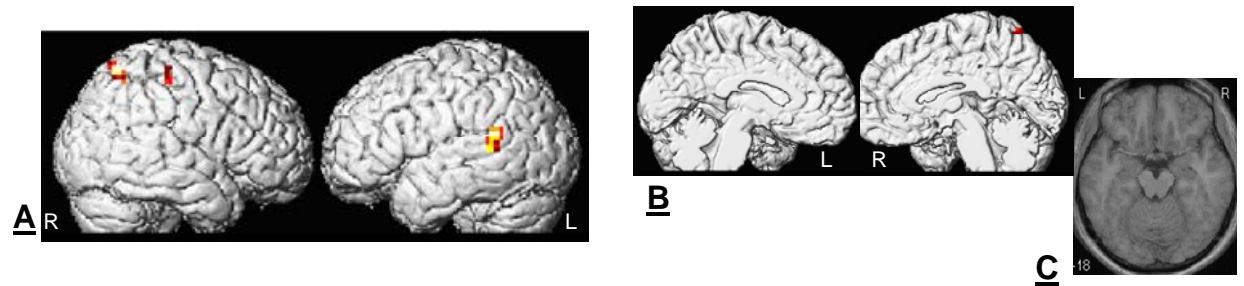
#### Contrast EL3>LL3



**Fig. 4.11 Early multilinguals>late multilinguals (EL3 > LL3): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions >10 voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

## Contrast LL3&gt;EL3

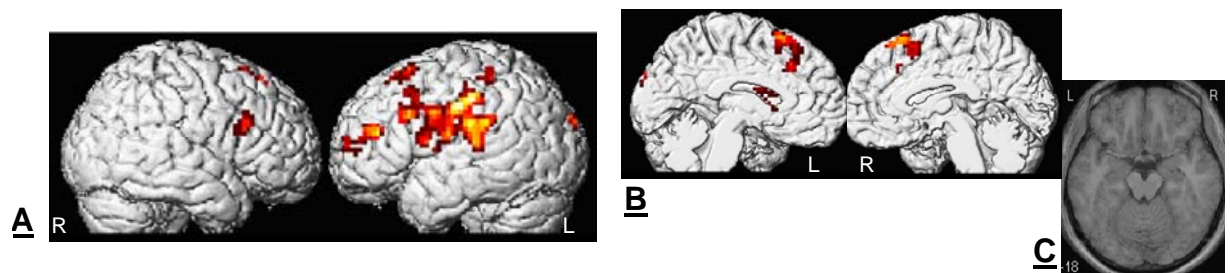


**Fig. 4.12 Late multilinguals>late multilinguals (LL3 > EL3): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions >10 voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

### Comparison of languages with different age of acquisition between early and late multilinguals (EL2/LL2)

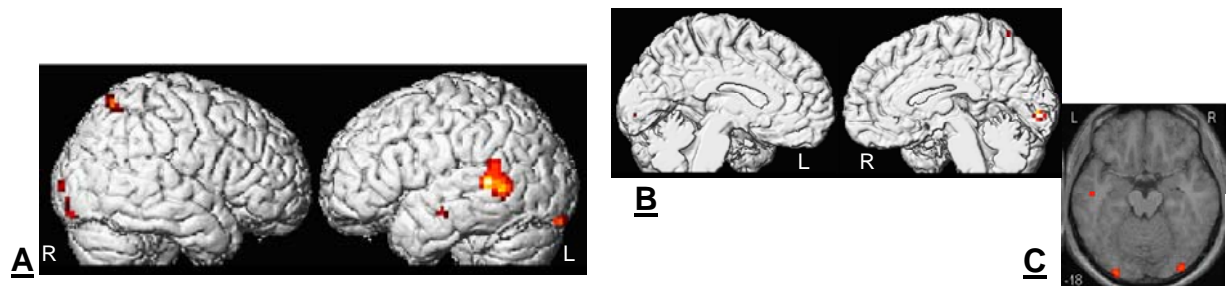
## Contrast EL2&gt;LL2



**Fig. 4.13 Early multilinguals> late multilinguals (EL2 > LL2): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions >10 voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

## Contrast LL2&gt;EL2

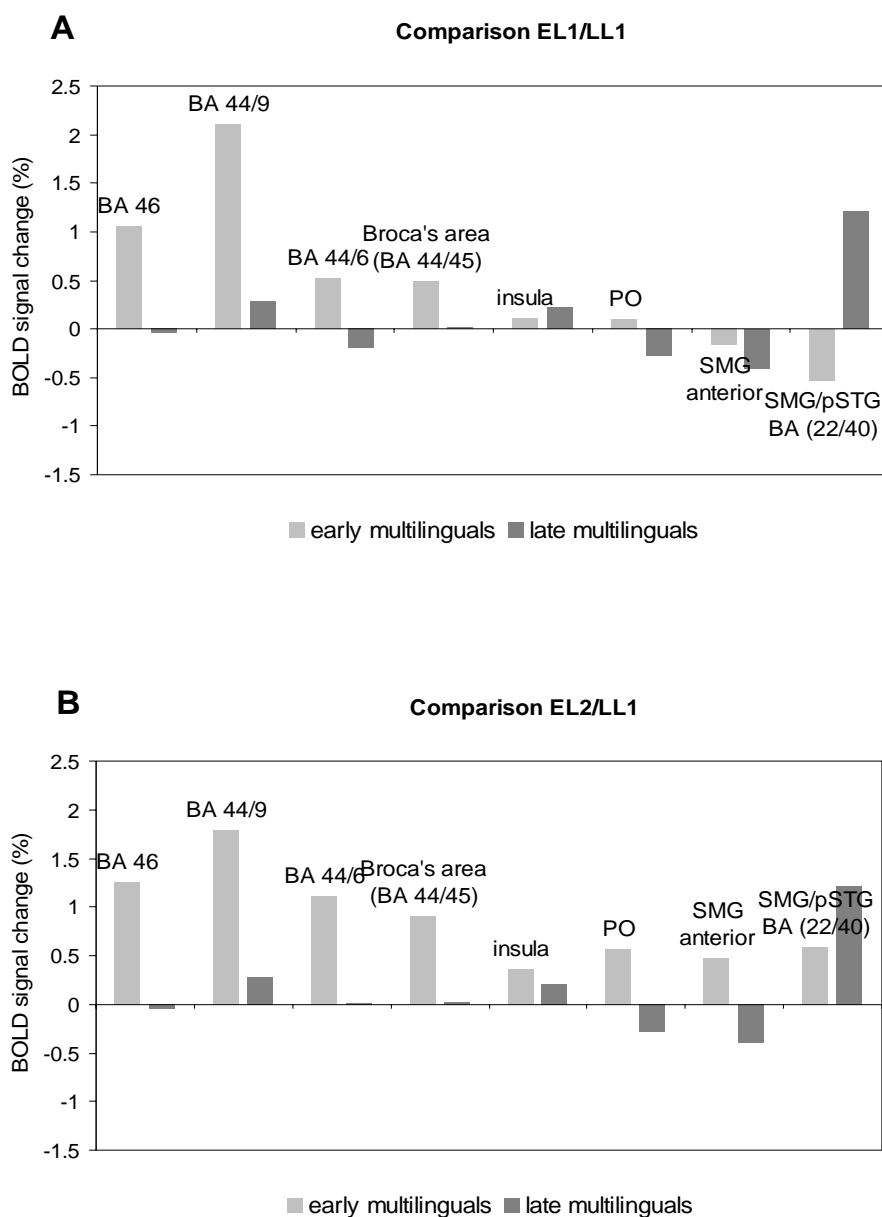


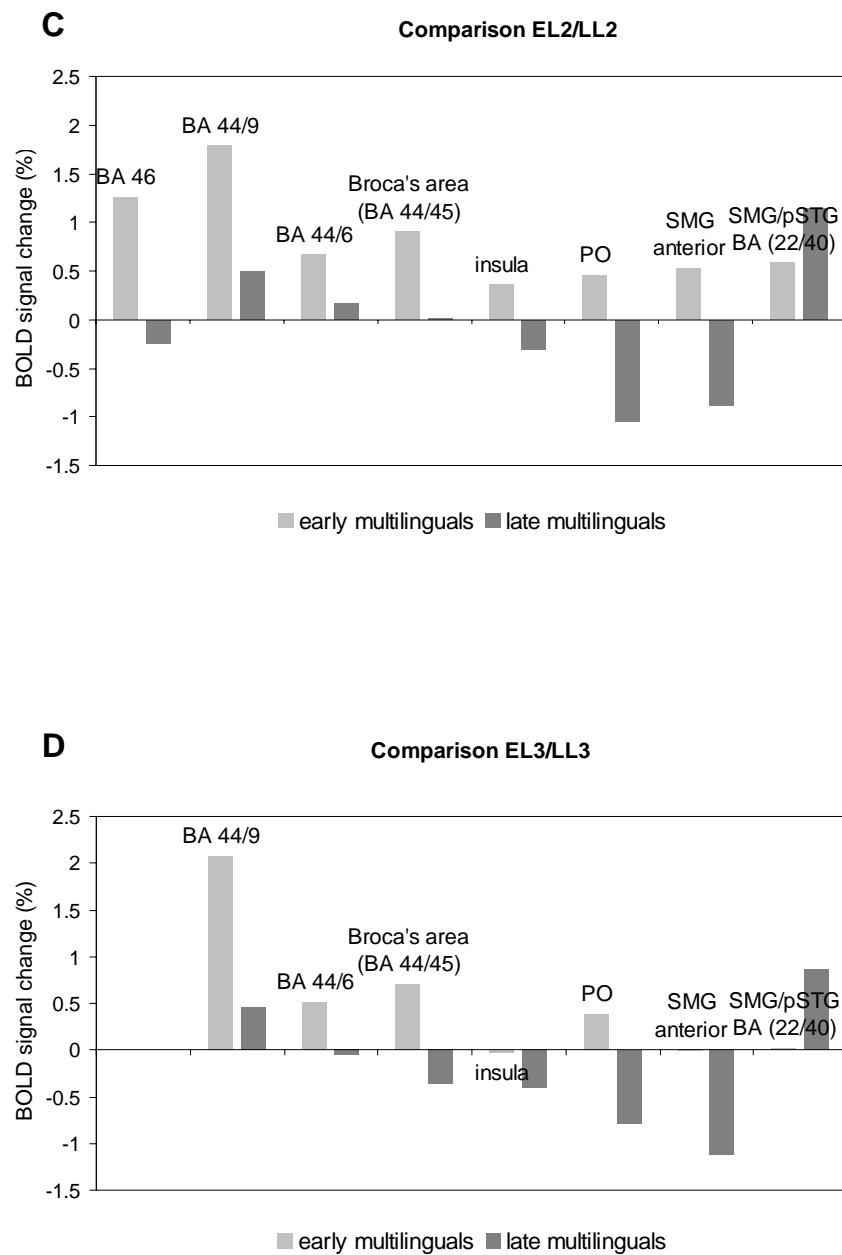
**Fig. 4.14 Late multilinguals>early multilinguals (LL2 > EL2): Interaction effect.**

The results are projected on a brain from a subject of the study. A: lateral view (R=right, L=left) on the 3D brain representation. B: medial view (R=right, L=left) on the 3D brain representation. C: neuronal activity in an axial slice through the fusiform gyrus. The interaction evaluation was set at  $p < 0.0001$  (uncorrected). All activated regions >10 voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.001$  (uncorrected).

## Early and late multilinguals: BOLD signal change in left frontal and perisylvian areas

To provide further insights to these results, we represented the % BOLD signal change (see Methods, Chapter 3.4.2) for all language comparisons in the left frontal and perisylvian regions with group specific task management (Figure 4.15 A, B, C, D). In these Figures, the regions evaluated are represented successively along the anterior-posterior axis corresponding to the direction of the arcuate fasciculus.





**Fig. 4.15 Early and late multilinguals: BOLD signal change. Contrast of A) EL1/LL1, B) EL2/LL1, C) EL2/LL2 and D) EL3/LL3.**

Values of the BOLD signal change (% change in activity compared to average brain activity during language and control task) in left frontal and perisylvian areas of group specific activation, represented along an anterior-posterior axis.

## Findings

### The language comparisons between early and late multilinguals reveal differences between both groups

#### *Comparisons of languages similar in age of acquisition and proficiency*

Early multilinguals. Comparisons of languages similar in age of acquisition and proficiency between the groups of early and late multilinguals (contrasts **EL1>LL1**, **EL2>LL1** and **EL3>LL3**) showed a substantially higher neuronal activity in early as well as late acquired languages of early multilinguals than in the corresponding languages of late multilinguals (Figures 4.7, 4.9 and 4.11).

Notably, the three tested languages of early multilinguals (**EL1**, **EL2** and **EL3**) showed higher neuronal activity in motor related regions of the left hemisphere; the inferior frontal gyrus (Broca's area: BA 44/45, BA 44/6, BA 44/9), the precentral/postcentral gyrus (BA 4/1/2/3), the medial frontal gyrus (supplementary motor area BA 6), the anterior cingulate gyrus (BA 32) and the striatum. In addition, during processing of early acquired languages (Figures 4.7 and 4.9) early multilinguals also showed a higher participation of additional regions in the left middle frontal gyrus (prefrontal BA 46), in the left inferior frontal gyrus (BA 47, only in **EL1**, Table 4.4) in the right cerebellum (only in **EL1**, Table 4.4) and in the left inferior parietal lobe (BA 40/7, only in **EL2**, Table 4.4). Right motor related areas with higher activation in early multilinguals were the right homologues to Broca's area (BA 44/45, BA 44/9) and the supplementary motor area (BA 6).

Sensory areas with higher activity in early multilinguals included in both hemispheres visual areas (BA 19, Figure 4.4) that are known to be involved in higher associative tasks. The left superior temporal sulcus (BA 21/22) exhibited higher activity too; the significance of differential activation was however variable across the different comparisons. In addition, in the early acquired languages of this group the left fusiform gyrus (BA 19/37) and the right middle temporal gyrus (BA 21/22) were also more activated.

Late multilinguals. The comparisons of languages similar in age of acquisition and proficiency between both groups (contrasts **LL1>EL1**, **LL1>EL2** and **LL3>EL3**) show that in late multilinguals brain activity was less important than in early multilinguals (Figures 4.8, 4.10, 4.12). Here, only in the part of the left supramarginal gyrus adjacent to the posterior superior temporal gyrus (SMG/pSTS, BA 22/40) did the neuronal activity reliably exceed that of early multilinguals in all languages being compared.

#### *Comparisons of languages different in age of acquisition and proficiency*

Comparisons of languages different in age of acquisition and proficiency (**EL2/LL2** comparison, Figures 4.13 and 4.14) showed higher brain activity for the early acquired more proficient languages of early multilinguals as compared to the late learned and less proficient languages of late multilinguals. The pattern of differential activation was similar to the one of the comparison of languages similar in age of

acquisition and proficiency. Only the left superior temporal gyrus (BA 21/22) and the left fusiform gyrus (BA 19/37) showed a different result (Table 4.4). Here, the higher activation of the **LL2** as compared to the **EL2** suggests that higher neuronal activity in these areas might also be correlated to later acquisition and/or lower proficiency.

### **The results for left frontal and perisylvian regions are reviewed by the analysis of language related BOLD signal change**

Figure 4.15 represents the result of the language related BOLD signal analysis for each language comparison between early and late multilinguals (**EL1/LL1**, **EL2/LL1**, **EL2/LL2** and **EL3/LL3**). The value of the language signal is shown for left perisylvian and dorsolateral prefrontal regions. In general the representation confirms that the result of the language comparisons reveals above all differences in language related neuronal activity: early multilinguals show a higher language signal in frontal regions and late multilinguals only in the posterior part of the left supramarginal gyrus. In addition, the representation of the BOLD signal change demonstrates that, within each group, the neuronal response during processing of L1, L2 and L3 is highly consistent. Notably, in all three languages of early multilinguals, the BOLD signal cumulates in premotor/prefrontal regions, with a maximum in BA 44/9. In contrast, in the three tested languages of late multilinguals a high language related BOLD signal could only be observed in the SMG/pSTG, dissociating from the activation in more anterior areas. However, the analysis of the BOLD signal also signalizes that in early multilinguals, BA 44/9 and not BA 44/45, as might be deduced from the corresponding t-value (Table 4.4), is the region with the most relevant language activation within Broca's area.

### **Some cortical regions are not influenced uniformly by early mono- or bilingual language experience**

The language comparisons between early and late multilinguals and the analysis of the BOLD signal change in perisylvian regions of differential activation revealed that the function of some cortical regions has not uniformly been determined by the effect of early respectively late second language acquisition: on the one hand, in some brain regions an effect was revealed for the early, but not for the late acquired languages, on the other hand, subfields within some brain regions showed a marked specificity to the effect of early mono- respectively bilingual language acquisition.

#### *Left prefrontal/frontal cortex*

Left Broca's area (BA 44/45, 44/9 and 44/6) is higher activated in all three languages of subjects with early second language experience- early multilinguals. Further analysis of the BOLD signal change revealed that here, a subfield of Broca's area (BA 44/9) exhibits a particular prominent activation during the language condition. Another brain region localized in the frontal cortex shows the effect of early second language acquisition in early acquired languages only: in early multilinguals the dorsolateral prefrontal cortex (BA 46) is only more activated in their early acquired languages (**EL1** and **EL2**).

*Supplementary motor area*

As revealed by the main language effect (Chapter 4.1, Table 4.2) early and late multilinguals activate two subfields of the premotor area (BA 6) during processing of their languages; the left dorsolateral premotor region (on the left side) and the supplementary motor area (bilaterally). The language comparisons between the two groups (Chapter 4.3, Table 4.4) revealed differences in activation, however only in the subfield of the supplementary motor area. Here, all three languages of early multilinguals are more activated than those of late multilinguals (Table 4.4).

*Left supramarginal gyrus*

The part of the left supramarginal gyrus which is adjacent to the posterior portion of the superior temporal gyrus (BA 40/22) exhibits in all three languages of late multilinguals a higher activation than in those of early multilinguals. In contrast, in a more anterior part of the left supramarginal gyrus the situation is opposite; here, all three languages of early multilinguals are higher activated than those of late multilinguals.

*Right middle temporal gyrus*

The right middle temporal gyrus shows higher activation in early multilinguals as compared to late multilinguals but only in their early acquired languages (EL1 and EL2).

*Left fusiform gyrus*

The left fusiform gyrus evidences a higher activation in early multilinguals, but only in their early acquired languages (EL1 and EL2).

### 4.3 Comparison of the multilinguals early and late acquired languages

To further specify language processing in early and late multilinguals the early and late learned languages were compared within each group (interaction evaluation, see methods, Chapter 3.4.2). Accordingly, in early multilinguals **EL1** was compared with **EL3** and **EL2** with **EL3** and in late multilinguals **LL1** with **LL2** and **LL1** with **LL3**.

In brain regions with differential activation between early and late acquired languages, the Talairach coordinates (see Methods, Chapter 3.4) and the t-values for the highest local difference (activation maximum) were reported. In addition, in all cortical regions with group specific language processing the neuronal signal (BOLD signal) of the language condition and of the auditory control condition was assessed separately, on the basis of the main group effect (see Methods, Chapter 3.4), and reported for the languages that were compared. This procedure allowed showing the BOLD signal of the language condition in regions with group specific activations.



## Table

In Table 4.6 brain regions with language specific neuronal response are shown. Here, the number of activated voxels, the t-value and coordinates (in Talairach space) of the activation maxima and the BOLD signal of the languages that were compared are reported for each region.

It has to be noted, that the comparison of the two early acquired languages in early multilinguals (EL1 and EL2) and of the two late learned languages (LL2 and LL3) in late multilinguals shows no difference and is not listed.

ANATOMICAL LOCALIZATIONS	EARLY MULTILINGUALS				LATE MULTILINGUALS			
	EARLY>LATE		LATE>EARLY		EARLY>LATE		LATE>EARLY	
	EL1>EL3	EL2>EL3	EL3>EL1	EL3>EL2	LL1>LL2	LL1>LL3	LL2>LL1	LL3>LL1
L. angular gyrus (BA 39)	<b>t=5.49</b> <u>v=17 vox</u> -50 -54 36 <b>L1 : -0.4</b> <b>L3 : -0.53</b>					<b>t=4.58</b> <u>14 vox</u> -45 -65 42 <b>L1 : -0.09</b> <b>L3 : -0.57</b>		
L. supramarginal gyrus (BA 40)	<b>t=5.46</b> <u>v=10 vox</u> -59 -45 33 <b>L1 : -0.02</b> <b>L3 : -0.39</b>				<b>t=4.75</b> <u>16 vox</u> -48 -59 39 <b>L1 : -0.07</b> <b>L2 : -0.05</b>	<b>t=4.64</b> <u>19 vox</u> -50 -60 28 <b>L1 : 0.06</b> <b>L3 : -0.11</b>		
L. middle/anterior superior temporal sulcus (BA 21/22)			<b>t=5.84</b> <u>16 vox</u> -62 -9 -5 <b>L3 : 0.63</b> <b>L1 : -0.39</b>	<b>t=5.96</b> <u>9 vox</u> -65 -23 1 <b>L3 : 1.23</b> <b>L1 : 0.62</b>			<b>t=6.25</b> <u>18 vox</u> -59 0 -10 <b>L2 : 0.92</b> <b>L1 : 0.2</b>	<b>t=6.09</b> <u>64 vox</u> -56 -9 -7 <b>L3 : 0.35</b> <b>L1 : 0.42</b>
L. posterior superior temporal sulcus (BA 21/22)							<b>t=6.61</b> <u>118 vox</u> -56 -40 8 <b>L2 : 1.44</b> <b>L1 : 0.95</b>	<b>t=5.68</b> <u>12 vox</u> -56 -40 8 <b>L3 : 1.05</b> <b>L1 : 0.95</b>
L. anterior supramarginal gyrus (BA 40)								<b>t=5.78</b> <u>31 vox</u> -53 -37 24 <b>L3 : 0.16</b> <b>L1 : 0.15</b>
L. precentral gyrus (BA 4)								<b>t=5.03</b> <u>34 vox</u> -53 -2 28 <b>L3 : 0.18</b> <b>L1 : 0.17</b>

**Tab. 4.6 Early and late multilinguals: comparison of early and late acquired languages within each group.**

The interaction evaluation was set at  $p < 0.001$  (uncorrected). Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.005$  (uncorrected). In activated regions with a number of voxels higher than eight, v= number of activated voxels, t= t- values, T= Talairach coordinates indicated as x, y, z in anatomical localizations of the activation maximas and B=BOLD signal of the language conditions are shown.

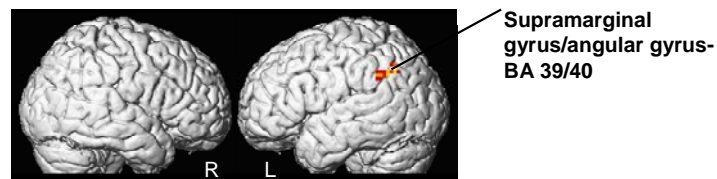
## Figures

Figures 4.16-4.19 demonstrate the differential activation for each language comparison. In these representations the differential activation is projected on a 3D rendering of a brain from one of the subjects of the study (male, early multilingual subject).

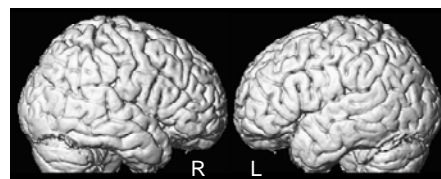
### Early multilinguals: comparison of early with late acquired languages (EL1/EL3, EL2/EL3)

Figure 4.16 shows higher activation of early as compared to late acquired languages in early multilinguals (contrasts **EL1>EL3** and **EL2>EL3**)

#### Contrast **EL1>EL3**



#### Contrast **EL2>EL3**

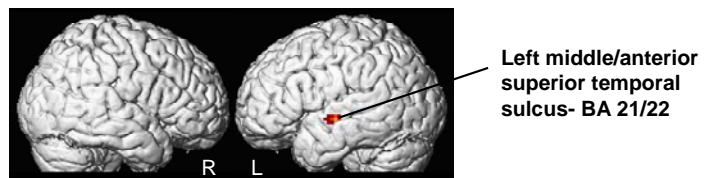


**Fig. 4.16 Early multilinguals: language comparisons (interaction effect). Higher activation in early as compared to late acquired languages.**

The contrast **EL1>EL3** is shown in the upper panel and the contrast **EL2>EL3** in the lower panel. The interaction evaluation was set at  $p < 0.001$  (uncorrected). All activated regions  $>8$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.005$  (uncorrected).

Figure 4.17 shows higher activation of late as compared to early acquired languages in early multilinguals (contrasts **EL3>EL1** and **EL3>EL2**)

Contrast **EL3>EL1**



Contrast **EL3>EL2**



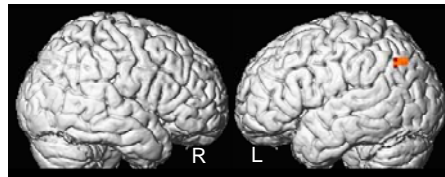
**Fig. 4.17 Early multilinguals: language comparisons (interaction effect). Higher activation in late as compared to early acquired languages.**

The contrast **EL3>EL1** is shown in the upper panel and the contrast **EL3>EL2** in the lower panel. The interaction evaluation was set at  $p < 0.001$  (uncorrected). All activated regions  $>8$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.005$  (uncorrected)

### Late multilinguals: comparison of early with late acquired languages (LL1/LL2, LL1/LL3)

Figure 4.18 shows higher activation of early as compared to late acquired languages in late multilinguals (contrasts LL1>LL2 and LL1>LL3)

Contrast LL1>LL2



Contrast LL1>LL3

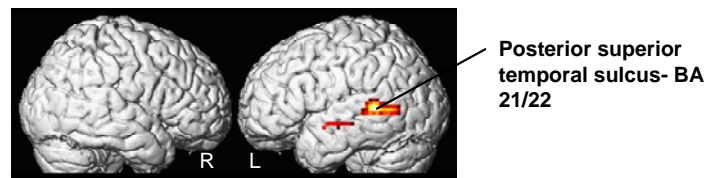


**Fig. 4.18 Late multilinguals: language comparisons (interaction effect). Higher activation in early as compared to late acquired languages.**

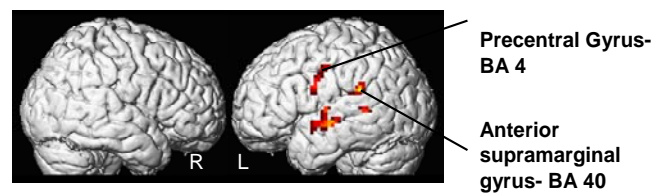
The contrast LL1>LL2 is shown in the upper panel and the contrast LL1>LL3 in the lower panel. The interaction evaluation was set at  $p < 0.001$  (uncorrected). All activated regions  $>8$  voxel are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.005$  (uncorrected).

Figure 4.19 shows higher activation of late as compared to early acquired languages in late multilinguals (contrasts **LL2>LL1** and **LL3>LL1**)

Contrast **LL2>LL1**



Contrast **LL3>LL1**



**Fig. 4.19 Late multilinguals: language comparisons (interaction effect). Higher activation in late as compared to early acquired languages.**

The contrast **LL2>LL1** is shown in the upper panel and the contrast **LL3>LL1** in the lower panel. The interaction evaluation was set at  $p < 0.001$  (uncorrected). All activated regions  $>8$  voxels are shown. Run 1 and run 2 were masked inclusively with the conjunction of run 1 and run 2 at  $p < 0.005$  (uncorrected).

## Findings

### **In a few cortical regions, the comparison of the multilinguals early and late acquired languages evidence differential activation**

In general, the comparison of the multilinguals early and late acquired languages revealed in early and in late multilinguals only a few regions with differential activation, although the evaluation was performed at a lower threshold than the comparison of languages between groups (Table 4.6, Figures 4.16 to 4.19).

#### *Early acquired languages*

The early and the late multilinguals first, early acquired language evidences higher activation in the left supramarginal/angular gyrus as compared to its language(s) learned after the age of nine years (contrasts **EL1>EL3** resp. **LL1>LL2** and **LL1>LL3**) (Figures 4.16 (upper panel) and 4.18). In contrast, in this brain region a second early acquired language as experienced by early multilinguals shows no difference to the late learned language (contrast **EL2>EL3**) (Figure 4.16, lower panel).

#### *Late acquired languages*

The early and the late multilinguals later learned languages evidence higher activity in the left superior temporal sulcus (BA 21/22) as compared to its early acquired language(s) (contrasts **EL3>EL1** and **EL3>EL2** resp. **LL2/LL1** and **LL3/LL1** contrasts) (Figures 4.17 and 4.19). This confirmed the findings of the main language effect which revealed in both groups a higher neuronal response of the later learned language(s) (Table 4.2). The late multilinguals third learned language shows in addition a higher neuronal activity in the left precentral gyrus (BA 4) and in the anterior part of the left supramarginal gyrus (BA 40) (contrast **LL3>LL1**, Figure 4.19 lower panel).

### **The results of the multilinguals language comparisons are reviewed by the analysis of the language related BOLD signal change**

The analysis of the condition related BOLD signal change in regions of differential activation confirmed that in early multilinguals, the results were mainly due to differences of the language conditions. In contrast, in late multilinguals the results of the language comparisons had to be reviewed. Here, almost no difference was found in the supramarginal/angular gyrus between the language condition of the early acquired and the one of the first language that was learned after age nine (contrast **LL1>LL2**). Similarly, in the left superior temporal sulcus the difference between the language condition of the first acquired language and the one of the second language that was acquired after age nine (contrast **LL3>LL1**) was also very small. Here, the anterior part of the left superior temporal sulcus evidenced even a higher activation in the early acquired language. It is possible that similar to the other languages being compared in late multilinguals, differences between the language conditions indeed exist in subfields of the temporal lobe but that they have been masked by the high activation during the auditory control condition (see Chapter 4.4). However, taking

into account the present results we excluded the results which have not been confirmed by the BOLD signal analysis from further discussions. This also applies to the findings of the LL2/LL3 comparison which according to the analysis of the BOLD signal also results from a different auditory activation of the two languages that were compared.

**In some cortical regions the multilinguals early and late acquired languages do not show clear-cut differences.**

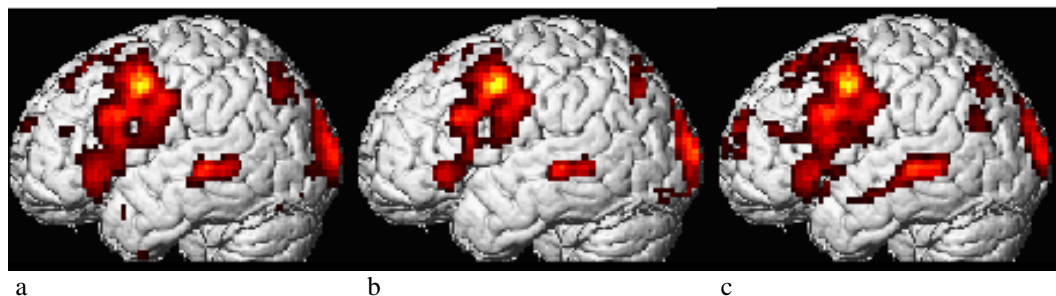
*Superior temporal sulcus*

The present analysis shows that early and late multilinguals use regions within the left superior temporal sulcus (BA 21/22) differently; late multilinguals exhibit more important differences between their early and late acquired languages than early multilinguals. This shows in particular by the more extensive activation of the late learned languages; notably in the posterior part of the left superior temporal sulcus the first late learned language of late multilinguals (LL2) exhibits an important difference to their first early acquired language (contrast LL2>LL1) (Figure 4.19, upper panel).

## 4.4 Influence of variables on the results

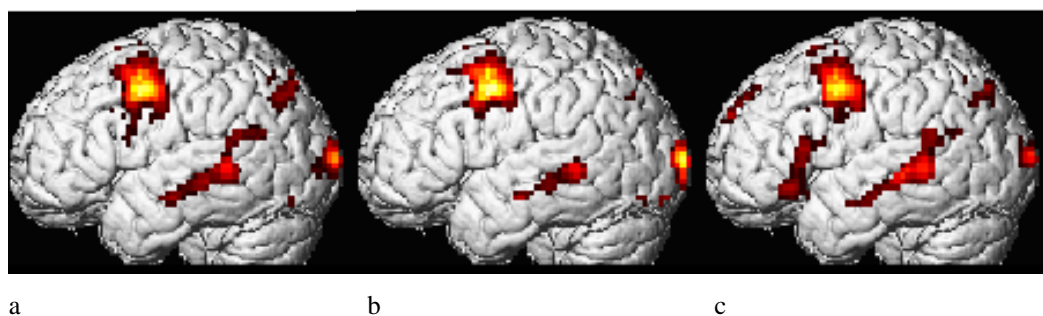
### 4.4.1 Reproducibility

Each language of early and late multilinguals (**EL1**, **EL2** and **EL3** resp. **LL1**, **LL2** and **LL3**) was tested twice, on different days. This allowed examining the reproducibility of the neuronal activity associated with the performance of the language task. Here, it is exemplified by the language activation of the first acquired language (**EL1** resp. **LL1**) in the left hemisphere. The activation related to the first and the second tested sessions is shown separately for the groups of early (Figure 4.20 a and b) and late (Figure 4.21 a and b) multilinguals (**EL1** resp. **LL1**). The analysis was performed according to the procedure established for the analysis of the main language effect (see Chapter 3.4). The representation of the first and second run has been contrasted to that of the analysis of the group average including both sessions (Figures 4.20 c and 4.21 c). In contrast to the analysis of the main group effect (Chapter 4.1.2) in the present analysis the group average was not masked inclusively with the results of the conjunction analysis of both groups. These representations demonstrate that the first and the second test of the first acquired language elicited similar activation. Activation varied only slightly in extent; the first tested run eliciting higher neuronal activity than the second. This finding was true for both, early and late multilinguals.



**Fig. 4.20 Early multilinguals (EL1): Main language effect shown for the left hemisphere.**

a) main effect of run 1, b) main effect of run 2, c) main effect including run1 and run2. The evaluation was set at  $p > 0.05$  (corrected). All activated regions  $> 5$  voxels are shown.



**Fig. 4.21 Late multilinguals (LL1): Main language effect shown for the left hemisphere.**

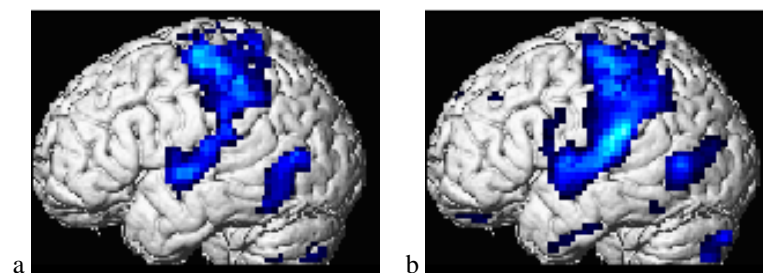
a) main effect of run 1, b) main effect of run 2, c) main effects composed of run1 and run2. The evaluation was set at  $p > 0.05$  (corrected). All activated regions  $> 5$  voxels are shown



#### 4.4.2 Neuronal activity during the auditory control condition

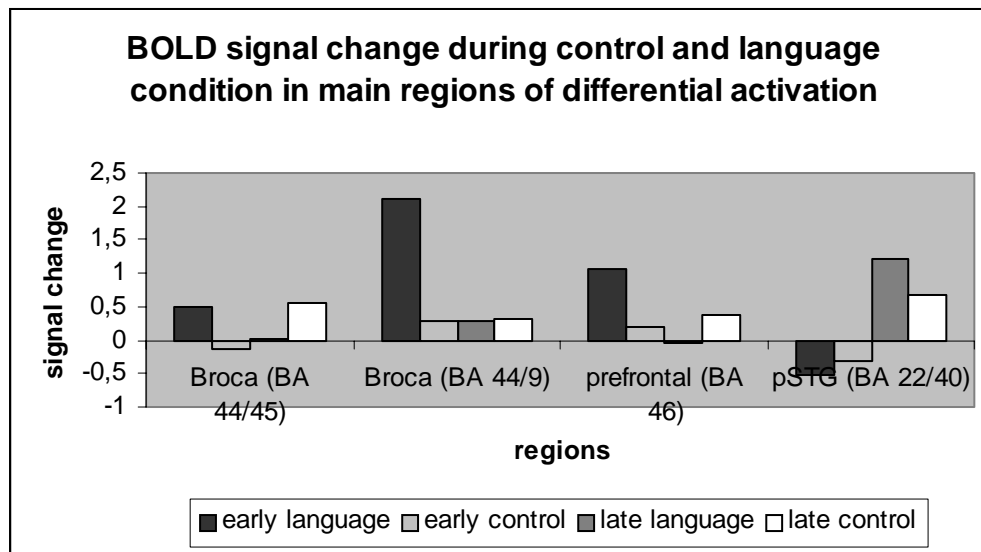
To estimate a possible influence of the auditory control condition on the results, the auditory condition was considered. First, the main effect of the auditory condition as compared to the language condition was analyzed according to the procedure described in Chapter 3.4. Here, the result was exemplified for the first acquired language of early and of late multilinguals (EL1 resp. LL1) and shown for the left hemisphere (Figure 4.22).

Second, in four main regions of group specific language processing revealed by the language comparisons between the groups of early and late multilinguals (see results Chapter 4.2), the BOLD signal change during the auditory condition was analyzed for the first acquired language (EL1 resp. LL1), according to the procedure described in Chapter 3.4. The regions evaluated were two subfields within Broca's area (BA 44/45 and BA 44/9), the left dorsolateral prefrontal cortex (BA 46) and the left pSTG (BA 22/40). Figure 4.23 shows the BOLD signal change of the auditory condition, contrasted with the one of the language condition.



**Fig. 4.22 Early and late multilinguals (EL1 resp LL1): Main effect of the auditory control condition.**

(conjunction analysis of run 1 and run 2), a) early multilinguals and b) late multilinguals. The evaluation was set at  $p > 0.05$  (corrected). All activated regions  $> 5$  voxels are shown



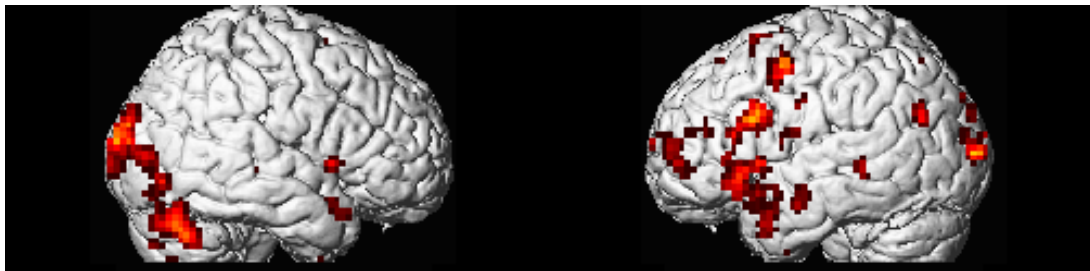
**Fig. 4.23 Early and late multilinguals: BOLD signal change of language and control condition in the first acquired language.**

Activation is shown for selected regions (Broca's area (44/45 and 44/9), the dorsolateral prefrontal cortex and the posterior superior temporal gyrus (pSTG) with differential activation in the group comparison (early language- language condition in early multilinguals, late language-language condition in late multilinguals, early control- auditory control condition in early multilinguals, late control- auditory control condition in late multilinguals).

Figure 4.22 shows, that the auditory condition elicits higher activation than the language condition in the left primary and secondary auditory cortex and in left primary motor and sensory areas. In addition, a major focus of activation can be observed in the left posterior middle and inferior temporal gyrus. The activation pattern was similar in the right hemisphere which has not been shown. Figure 4.22 also demonstrates that regions of main interest for our study, i.e. Broca's and Wernicke's area were not activated, and thus exhibited no higher neuronal activity during the auditory condition than during the language condition. Further, Figure 4.23 shows that in four main regions with differential activation between both groups the results were mainly determined by language specific differences. Only in one subfield of Broca's area (BA 44/45) is the result also substantially influenced by the auditory condition.

### 4.4.3 Random effect analysis

Figures 4.24, 4.25, 4.26 and 4.27 represent the results of the random-effect analysis (see Methods, Chapter 3.4) for a comparison with the results of the fixed-effect analysis (see Chapter 4.1 and 4.2). The findings are exemplified by means of the results obtained for the first acquired language of early and of late multilinguals (**EL1** resp. **LL1**), and comprise data from the first run only. The main language effect is shown for early and late multilinguals in Figures 4.24 and 4.25 respectively; group differences are shown in Figures 4.26 and 4.27.



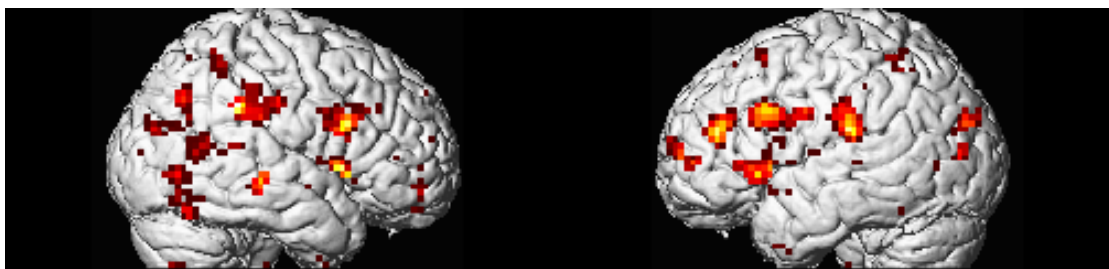
**Fig. 4.24 Early multilinguals (EL1): Main effect first run..**

Random effect analysis,  $p < 0.008$  uncorrected, 0 voxels. R= right hemisphere L=left hemisphere



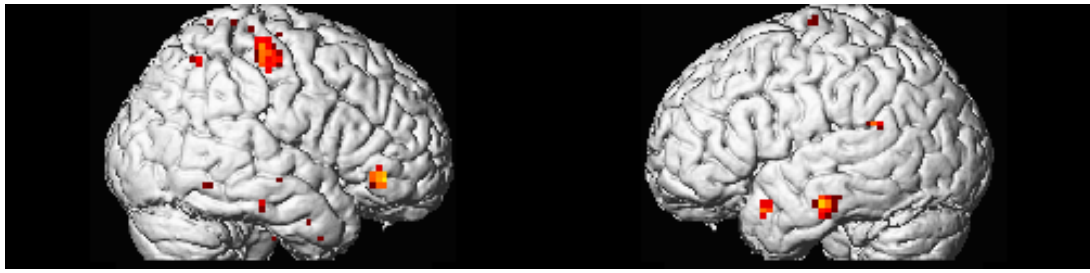
**Fig. 4.25 Late multilinguals (LL1): Main effect first run.**

Random effect analysis,  $p < 0.008$  uncorrected, 0 voxels. R= right hemisphere L=left hemisphere



**Fig. 4.26 Early multilinguals > late multilinguals (Contrast EL1/LL1).**

Interaction effect first run. Random effect analysis,  $p < 0.008$  uncorrected, 0 voxels. R= right hemisphere L=left hemisphere



**Fig. 4.27 Late multilinguals>early multilinguals (contrast EL1/LL1).**

Interaction effect first run. Random effect analysis,  $p < 0.008$  uncorrected, 0 voxels. R= right hemisphere L=left hemisphere

In general, the activation pattern related to the tested language condition as revealed by the random-effect analysis did not contradict the findings of the fixed-effect analysis (Chapter 4, Figures 4.3, 4.4, 4.7 and 4.8). Indeed, similar to the main effect obtained by the fixed-effect analysis, the main effect of the random-effect analysis reveals activation in Broca's area and in left dorsolateral premotor regions (Fig 4.24 and 4.25). Furthermore, the group comparison (interaction effect) performed by the random-effect analysis also confirms the pattern of activation indicated by the fixed-effect analysis i.e. higher neuronal activity of Broca's area (BA 44/9, 44/45), the left dorsolateral prefrontal cortex (BA 46) and the anterior portion of the supramarginal gyrus in early multilinguals (Fig. 4.26). In addition, it reaffirms the higher neuronal activity observed in the left posterior inferior supramarginal gyrus (pSTG) of late multilinguals (Figure 4.27). In contrast, in the group comparisons other brain regions, notably the right dorsolateral prefrontal cortex and the anterior portion of the supramarginal gyrus, reach the predefined threshold only in the random-effect analysis. Here, early multilinguals show the same pattern of activation as in the left homologues. In late multilinguals as well, the random-effect analysis evidences cortical regions with higher activation that have not been revealed by the fixed-effect analysis, i.e. the right orbitofrontal cortex and a region in the left inferior temporal lobe.

## 5 Discussion

### 5.1 Main language effect in early and late multilinguals

#### 5.1.1 Main language effect in the first acquired language of each subject

In each subject we assessed the brain regions engaged in the narrative task by comparing the BOLD signal change of the language condition with the one of the auditory control condition. In early as well as late multilingual subjects, brain regions revealed by this procedure were localized mainly in the left hemisphere. Brain structures of the right hemisphere could only be revealed in a few subjects. These findings confirm previous studies of cortical lesions, showing that language processing in right handed subjects is almost exclusively supported by the left hemisphere. Processing of some specific linguistic aspects, however, are a function of the right hemisphere; for example processing of prosodic features (Dogil et al., 2002). Since our study was not specifically designed to assess right lateralized language processes, we did not expect to reliably reveal brain regions in the right hemisphere in all subjects. Pierre Broca (Broca MP, 1861) has postulated that left Broca's area is essential during language production. His idea has been confirmed by the results of previous imaging studies (Chee et al., 1999b; Kim et al., 1997). In line with these findings, our results show increased neuronal activity in left Broca's area during the language task for each tested subject (Figure 4.1 and 4.2). Surprisingly, the results provided no evidence for a consistent participation of left Wernicke's area in the language task. Indeed, the contribution of this region is assumed to be essential, not only during language comprehension but as well during language production tasks (Wernicke, 1874). This has also been confirmed by neuroimaging studies (Price et al., 1996; Wise et al., 2001). Thus, our results apparently are contradictory to previous findings. However, considering that the neuronal activity elicited by the auditory control condition in the superior temporal gyrus extends into Wernicke's area (see Chapter 5.5), it seems likely that activation in Wernicke's area has been masked by the control task. Neuronal activity during the language task also increased in subfields of the left prefrontal cortex not belonging to Broca's area and in regions of the left superior temporal lobe outside of Wernicke's area. This result confirms previous studies that showed the participation of these regions in tasks requiring language production (Price, 2000; Wagner et al., 2001). In each subject, the first and the second test of the first language (L1) revealed similar language related brain regions. This result indicates that the brain activation elicited by the narrative task tested in this study is reproducible (see Chapter 5.5.1).

### 5.1.1 Group activation in all three tested languages of early and late multilinguals

#### **Main language effect**

The comparison of the language condition with the control condition in early and late multilinguals at the group level revealed a similar set of activated regions in all tested languages of both groups (Chapter 4.2). The group evaluation allowed determining regions which could not be recognized as statistically relevant by the analysis of individual brain activation. In accordance to the lateralization of language processing to the left in right handed subjects (Pujol et al., 1999), the language condition mainly activated cortical and subcortical structures in the left hemisphere. These cortical regions are known to support specific language processes:

#### *Frontal lobe*

Neuronal activity in the left frontal lobe was observed in Broca's area (BA 44/45) involving the adjacent dorsolateral (BA 46) and ventrolateral (BA 47) prefrontal cortex and in supplementary (bilaterally) and dorsolateral premotor areas (BA 6).

Broca's area and the ventrolateral prefrontal region are localized in the inferior frontal gyrus. This cortical region, in particular Broca's area is essential during language production tasks (Wernicke, 1874). It has been revealed in imaging studies testing as diverse linguistic aspects as semantics (Illes et al., 1999), phonology (Fiez, 2001; Poldrack et al., 1999) and syntax (Caplan et al., 2000; Dapretto and Bookheimer, 1999). In line with its importance during various language tasks, its role has been resumed as providing access to stored linguistic information to plan the production of words and sentences (Fletcher and Henson, 2001). In contrast, the dorsolateral prefrontal cortex which comprises BA 46, is involved in tasks requiring coordination of diverse memory contents in order to plan tasks in a meaningful context (Fletcher and Henson, 2001). This function is also necessary during language production (Fuster, 2001).

Both premotor areas (dorsolateral and supplementary motor area, BA 6) hold an important role during the selection and preparation of a movement plan according to a given goal (Kawashima et al., 1994). In line with our results, a participation of these areas has been demonstrated in previous language production tasks (Chee et al., 1999b; Chee et al., 1999a; Vingerhoets et al., 2003), demonstrating that premotor regions also intervene in the planning of language output. The engagement of these regions occurs apparently independently from real language production. In fact, previous studies as well as the present study tested inner speech, thus did not consider audible language production.

Our results indicate that during a narrative language task neuronal activity is less significant in Broca's area than in premotor areas (Table 4.4). Apparently, this is contradictory to the prominent role attributed to Broca's area during language production. However crucial regions for particular cognitive processes might not necessarily require high neuronal activity to be efficient. It is imaginable that the

function of Broca's area consists in passively adopting an equilibrium with other language areas rather than actively directing language processes (Paradis, 2000).

#### *Temporal and parietal lobe*

The language network revealed in this study does not only include the network of frontal cortical regions traditionally associated to language production tasks, but also of regions in posterior lobes, i.e. the left superior temporal sulcus (BA 21/22), the left hippocampus, the left inferior parietal lobe (BA 40/7) and the posterior cingulate gyrus (BA23/39/31). The participation of sensory related functions, i.e. Wernicke's area in any language process has been proposed since early studies of symptoms in aphasic patients (Wernicke, 1874). More recent imaging studies revealed additional regions in the temporal and parietal lobes whose function could be relevant during language tasks. Accordingly, contribution of the middle and anterior temporal lobe (including the superior temporal sulcus BA 21/22) seems necessary to access semantic knowledge (Price, 2000). Activity in the hippocampus is related to retrieval of declarative knowledge (Opitz and Friederici, 2004). Our results show that the function in these regions is relevant during the production of narratives. Neuronal activity in the posterior cingulate gyrus and in the left inferior parietal lobe has been observed in cognitive tasks which require attention to retrieval of specific sensory targets (Snyder et al., 1995). Referring to the results of our study, it seems that retrieval of sensory related language information involve these areas too.

#### *Occipital lobe*

In primary and secondary visual areas (cuneus and lingual gyrus (BA 17, 18, 19)), the language condition elicited higher neuronal activity than the auditory control condition. This could result from differences in the load of the visually presented stimuli between both conditions. Indeed, the language condition required analysis of complex visual stimuli (representation of morning, noon and evening) whereas the control condition only required observation of a cross. In addition, higher neuronal activity in occipital regions supporting visual associations, i.e. in Brodmann area 19 could be shown. It is possible that during the narrative task visually related concepts are activated, for example when the morning scene is imagined. Furthermore, neuronal activity during the language task was also significant in the left fusiform gyrus (BA 37). Engagement of this temporal/occipital region has been observed in studies which investigated semantic word representation related to visual conceptions (Buchel et al., 1998; Moore and Price, 1999). This indicates that in the occipital lobe the language task activates visually related concepts which might represent as well linguistic aspects of the task.

#### *Cerebellum and Striatum*

Neuronal activity during the language task was also high in the right cerebellum and the left striatum (activity was also observable in the right striatum, but was less significant). The cerebellum and the basal ganglia traditionally have been viewed for their involvement during execution of learned motor tasks. Both structures ensure that selected movements are executed efficiently (Berridge and Whishaw, 1992; Perrett et al., 1993). Researchers have recently become also interested in potential non motor functions of the cerebellum and the basal ganglia. Involvement of these structures

during cognitive tasks, including language (Gabrieli et al., 1998; Ullman, 2001a) have been discussed. In this study the lateralization of the observed neuronal activity to the left in the striatum and to the right in the cerebellum is consistent with the left lateralized function of Broca's and Wernicke's areas during language tasks. Thus, our results support the idea that the striatum and the cerebellum are specifically engaged in the linguistic aspect of the planned language output.

#### *Non dominant hemisphere*

The comparison of the linguistic task with the auditory control condition revealed neuronal activity in the supplementary motor area (BA 6), the striatum and the posterior cingulate gyrus (BA 23/30/31) in both hemispheres. The activated regions are involved in selecting (supplementary motor area) and executing (striatum, posterior cingulate gyrus) motor plans. The bilateral activation of these structures indicate the role of these structures as part of a more general neuronal network devoted to motor aspects of language planning and execution. It has to be noted that our data revealed no activation in the right homologues of Broca's and Wernicke's area. This finding seem to contradict the results of other studies testing language production tasks which demonstrated predominately left lateralized activation but also in the right homologues of Broca's and Wernicke's area (Mahendra et al., 2003; Vingerhoets et al., 2003). It is possible that the auditory cued performance of fingertapping as required for the control task of our study engages functions in the right homologues of Broca's and Wernicke's area, comparable to those of the language condition and therefore masks language processes in the right hemisphere.

Altogether, it seems that the production of narratives tested in our study is close to the natural language situation in that it reveals brain regions which are complementary during language production: On one side, left perisylvian and motor related cortical and subcortical structures are involved in the transient reconstruction of words and sentences for subsequent language output (Damasio et al., 1996). On the other side, the left superior temporal lobe and the left fusiform gyrus support semantic access to words and thus mediate between conceptual knowledge and transient reconstruction of words (Damasio et al., 1996).

#### **Between group differences**

Comparison of the language task with the auditory control task at the group level revealed similar regions in all tested languages of early and late multilinguals. However, the neuronal systems in these regions showed variable activity, presumably indicating group differences in language processing (Figures 4.3-4.6, Table 4.4). In languages similar in age of acquisition, early multilinguals exhibit more language related brain activity than late multilinguals in particular in the frontal lobe, the cerebellum and the striatum. In line with these results, two previous studies (Kim et al., 1997; Mahendra et al., 2003) comparing language activity in early and late bilinguals, reported group specific language processing in Broca's area. Very similar to our results, Mahendra and colleagues (2003) found higher neural activity for both languages of early bilinguals as compared to those of late bilinguals in the inferior frontal gyrus.



Group differences have been assessed by statistical comparison of task related neuronal activity between early and late multilinguals (see Results, Chapter 4.2) and will be discussed in Chapter 5.2.

### **Within group differences**

Previous studies comparing early and late acquired languages demonstrated higher neuronal activity in left inferior frontal and posterior temporal regions for a less proficient late learned language (Vingerhoets et al., 2003; Yetkin et al., 1996). Similarly, our results revealed a more extensive recruitment of Broca's area and the superior temporal lobe for the later acquired and less proficient language(s), suggesting that additional neural activity is necessary in these regions to compensate for the lack of proficiency. In addition, this tendency seems to hold for both, multilinguals with and without early bilingual experience.

The results of the statistical comparison of the early and the late multilinguals early and late acquired languages are shown in Chapter 4.3 and will be discussed in Chapter 5.3.

## 5.2 Comparison of language processing between the groups of early and late multilinguals

The statistical evaluation of differences in task related neuronal activity between early and late multilinguals (interaction effect, see Methods, Chapter 3.4.2) allowed to confirm and specify the group differences observed in the main effect (Chapter 4.1): In all three tested languages, early multilinguals use the neural language network more intensively, in particular frontal and subcortical regions related to aspects of motor programming. In only one cortical region, the part of the posterior superior temporal lobe which is adjacent to the supramarginal gyrus, neuronal activity has been higher in all three languages of late multilinguals. Analysis of the BOLD signal in brain regions of differential activation confirmed that the differences found between early and late multilinguals are mainly due to differences in language processing (Figure 4.15).

Our findings extend the results of previous studies in the field of bilingual language acquisition which found differences in first and second language processing between subjects exposed to a second language early in life and those learning a second language only in early adulthood (Kim et al., 1997; Mahendra et al., 2003): we demonstrate for the first time, that early second language acquisition affects neural organization of languages learned as adolescents or young adults. In addition, since early and late acquired languages were tested in both groups, we were able to compare languages between early and late multilinguals similar in acquisition / learning conditions and proficiency (Chapter 4.2) thereby minimizing the possible influence of these variables on the results. Moreover, since late language learning occurred in both tested groups, we could clearly attribute the observed group differences to influence of second language learning early in life. These specifications have not been possible so far, because no previous study comparing early and late bilinguals controlled for late language learning. Overall, the differences between subjects with early versus late second language acquisition demonstrate that late second language learning is not able to modify the language system to the early multilingual mode. Thus, our data support the idea of a critical time period for the development of the language network (Lenneberg, 1969). We are however not able to determine an exact time limit from the present data, since we assessed only second language learning before age three and after age nine. In the following sections the results will be discussed in more detail.

### 5.2.1 Comparison of early acquired languages

Our study was designed to show the influence of early bilingual (early multilinguals) as compared to early monolingual language acquisition (late multilinguals) on the development of the cortical language network. Thus, group specific processing of early acquired languages as discussed in this chapter indicates differences in early

language development. In contrast, group specific processing of late acquired languages show how languages learned later in life rely on early established procedures. This aspect will be discussed in Chapter 5.2.2.

### **5.2.1.1 Language network related to executive functions: the role of procedural memory**

The influence of early second language experience on the maturing left frontal and subcortical neuronal network was particularly notable: Broca's area (BA 44/9, BA 44/45, BA 44/6), regions in the dorsolateral prefrontal cortex (BA 46), the anterior cingulate gyrus (BA 32), the striatum and the cerebellum (the only structure which was activated on the right) showed higher neuronal activity in both early acquired languages of early multilinguals as compared to the early acquired language of late multilinguals.

The prefrontal cortex holds an important role in executive functions. Here, lower level sensory representations, memory or motor operations are controlled for goal-directed behaviour (Miller, 2000). Specifically, the function of the inferior frontal gyrus with Broca's area during cognitive tasks and language seems to consist in retrieving and sustaining transient representations for a response. The functions of anterior portions of the dorsolateral prefrontal cortex (BA 46) have been described as operating on information that is currently retrieved to support higher level planning (Fletcher and Henson, 2001). It has been shown that neuronal activity in prefrontal cortical regions increases, when relevant information requires selection of different response alternatives (Sakai et al., 2002; Zysset et al., 2001). Higher involvement of the left middle and inferior frontal gyrus becomes also apparent when it is necessary to guide controlled semantic retrieval or to prevent interferences at a linguistic level (Moss et al., 2005; Thompson-Schill et al., 1997; Wagner et al., 2001). Notably, Thompson-Schill et al. (1997) and Wagner et al. (2001) investigated a similar task in which subjects were required to compare a target word to several probe words and had to decide which probe was most similar. Thompson Schill and colleagues (1997) found higher activation in conditions, where the comparisons between items were based on specific attributes or features and not on global similarity. In the study of Wagner et al. (2001), differences were related to the associative strength between the cue and the correct target, with the weaker associated target eliciting a higher response.

Mixing and switching phenomena indicate that multilinguals may have simultaneously elements of the other language present (Grosjean, 2001; Marian and Spivey, 2003) thus may continuously need to prevent cross-linguistic interference. Neurolinguistic models of bilingualism postulated that processing in the target language may be facilitated or by inhibiting the non-target language (Green, 1998) or by increasing the level of activation of the target language (de Bot, 1992). The results of previous fMRI and PET studies investigating bilinguals during mixed-language tasks confirmed the role of the left prefrontal cortex including Broca's area also in cross-linguistic control mechanisms (Price et al., 1999; Rodriguez-Fornells et al., 2002). Indeed, in a PET study investigating bilingual subjects, Price and collaborators (1999) revealed higher neuronal activity in the left inferior frontal gyrus (BA 44) during a mixed language naming task relative to naming in only one language. The authors explained the results in terms of higher cognitive control of the language

processes engaged. Higher engagement of neuronal systems in left dorsolateral prefrontal and inferior frontal regions was also revealed by the group of Rodriguez-Fornells (2002) which investigated bilinguals during a task that required ignoring stimuli from the non-target language.

Our results show that during the build-up of meaningful sequences of spoken language (during the narrative task), early multilinguals engage more left prefrontal neuronal resources, including those in Broca's area, than late multilinguals. Thus, differences between early and late multilinguals in the prefrontal cortex could be the correlate of control functions, differently engaged to prevent cross-linguistic interference. Processes related to establishment of procedural memory during the early language acquisition period give support to this proposition: Up to the age of three years the child learns primarily implicitly (Parkin and Streete, 1988) establishing thereby procedural memory. Procedural memory includes functions of the prefrontal cortex (Squire and Zola, 1996). It is relegated to other cortical structures as soon as routine operation is in place (Fuster, 2001) and this is possible when the use of the cognitive item is unequivocal in the communicative situation. The two groups of multilinguals tested in this study had all mastered three languages; however, only early multilinguals acquired two languages early in life, before age three. In early multilinguals, establishment of qualitatively different control functions in the left prefrontal cortex could therefore indeed have been required to resolve the cross-linguistic interference experienced during the early period of preferential procedural language acquisition.

Tasks which require cognitive control also associate the anterior cingulate gyrus to the activated network (Duncan and Owen, 2000). It seems that this cortical region signalizes conflict or interference detected for subsequent control in the dorsolateral prefrontal cortex (Carter et al., 1998). This could explain the higher neuronal activity of this region, as reported in our results, of early multilinguals. Further evidence of the importance of control functions in early multilinguals can be derived from the higher activation in the striatum, characteristic for this group. Indeed, in bilinguals increased demands on selective access to linguistic representations engage cortical-subcortical circuits including the fronto-striatal loop (Abutalebi et al., 2001).

Since only adults were included in this study, the present results indicate that early multilinguals not only engage additional frontal and subcortical control functions early in life but also integrate them permanently into their language processing. One could however argue that the higher activation in early multilinguals does not signalize a different establishment of cross-linguistic control functions early in life but rather the effect of their longer period of language experience. However, if the later assumption was true, the effect of early bilingual language acquisition would be uniformly present in the cortical language network, particularly in those regions which allow management of the different languages. However, contrary to early multilinguals, late multilinguals rely substantially on the function of neuronal systems in the left posterior superior temporal gyrus (pSTG), see Chapter 4.2. The pSTG, together with left prefrontal regions, is involved in inhibition of irrelevant items held in verbal working memory (Baddeley et al., 1998). Thus, some control functions necessary to prevent cross-linguistic interference could be established diametrically differently in early and late multilinguals. This would be contradictory to the idea of a linear influence of second language experience on the development of language

functions. The different activation of early and late multilinguals in the pSTG will be discussed in more detail below.

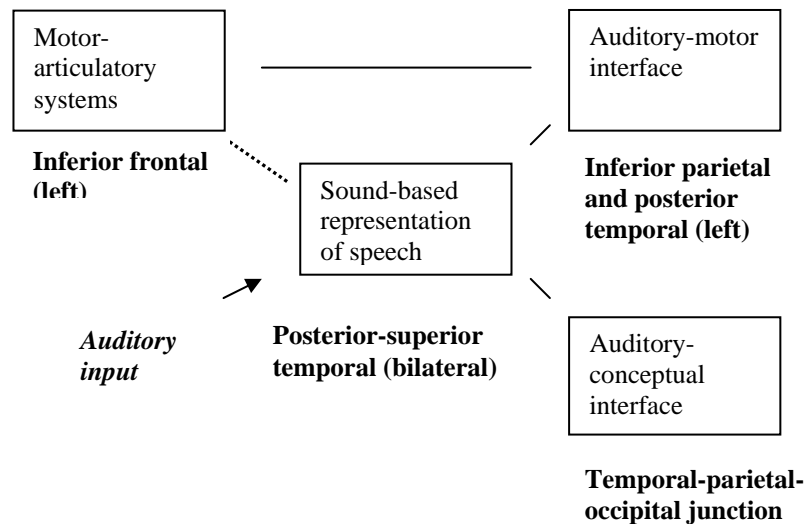
### 5.2.1.2 Language network related to sensory related functions

#### Sensory-motor integration of verbal material

In comparison to early multilinguals, late multilinguals activate only one region more intensely during processing of the first language (Chapter 4.2). This region is localized within the left posterior language network at the junction of the posterior superior temporal gyrus with the supramarginal gyrus. In our results we refer to this region as pSTG (Table 4.4), which can be considered as Wernicke's area (Chapter 2.2).

In Wernicke's model of language processing (Wernicke, 1874), Broca's area and Wernicke's area are viewed as homogenous cortical regions, representing sensory (Wernicke's area) respective motor (Broca's area) language aspects (Chapter 2.1). According to this model, pronounced neuronal activity of late multilinguals in Wernicke's area suggest that during the production of narratives, they preferentially activate the auditory representation of the word, -'das Klangbild'- . High neuronal activity of early multilinguals in inferior frontal regions, Broca's area, in contrast indicates that in these subjects the motor representation of words is important. The quantitative analysis of the BOLD signal change in regions along the left posterior-anterior axis interconnecting Wernicke's area (pSTG) with Broca's area (corresponding to the arcuate fasciculus) revealed differences between early and late multilinguals in detail (Figure 4.15): in late multilinguals, the activation of the pSTG is dissociated from the one in the anterior supramarginal gyrus and frontal regions. In early multilinguals in contrast, activation increases from the pSTG to anterior regions to cumulate in Broca's area (BA 44/9). Wernicke's model postulates a direct connection of Broca's and Wernicke's area (Chapter 2.1). It is not sufficient to explain why influences in relation to early second language learning as experienced by early multilinguals do not affect neuronal activity in both regions similarly. However, although their anatomical localizations of Broca's and Wernicke's area are still not clearly delimited (see Chapter 2.2), at present, there is ample evidence for the subdivision of Broca's area (Amunts et al., 1999) and Wernicke's area (Morosan P et al., 2005) into distinct cytoarchitectonic areas. Recent neuroimaging studies evidenced also a functional heterogeneity of Wernicke's area during language processing and this could account for the result of our study. In fact, not only the participation of the pSTG in speech production tasks as claimed by Wernicke is now established, but also its different contribution to speech perception respective speech production tasks (Buchsbaum et al., 2001; Price et al., 1996; Wise et al., 2001). Referring to these results and taking into account different manifestations of aphasia, Hickok and Poeppel presented a model of the network for speech perception and related language functions which considers the functional heterogeneity in the pSTG (Hickok and Poeppel, 2000). They propose that on one hand acoustic-phonetic speech codes, represented bilaterally in the pSTG, connect via an auditory-conceptual

interface with a widely distributed conceptual knowledge. This process is important during speech comprehension. On the other hand they suggest that acoustic phonetic speech codes also contact via a left lateralized sensory-motor interface network in posterior temporal and inferior parietal regions the motor articulatory systems in the frontal lobe (Hickok and Poeppel, 2000; Hickok and Poeppel, 2004). This pathway supports phonological encoding which is relevant during speech production (Figure 5.1).



**Fig. 5.1 Model of the cortical network supporting speech perception and related language functions proposed by Hickok and Poeppel.**

The dashed line indicates the possibility of additional, non-parietal auditory-motor interface networks (Hickok and Poeppel, 2000)

The most important supplement to Wernicke's model of language processing is the postulation of interface systems, which allow the connection of the sound based representations with motor or conceptual representations. It seems evident that the large set of possible associations in such a network may be adjusted according to the demands and lead to regional effects during neuronal processing of a language item. Our results show that the effect of early second language learning in early multilinguals results in higher neuronal activity in Broca's area but not in Wernicke's area. In contrast, the higher engagement of Wernicke's area in late multilinguals is not associated to a higher activity in Broca's area. The presented model of Hickok and Poeppel could explain the observed dissociation in neuronal activity of these two cortical regions. Indeed, our findings may indicate a functional modulation of the network connecting sound based representations with motor representations. The establishment of this network for sensory- motor integration of phonological aspects of speech could be dependent on early mono- or bilingual language experience.

Which processes representing sensory-motor integration of phonological language aspects are differently modulated in early and late multilinguals?

### **Maintenance of transient representation of speech codes in the posterior superior temporal gyrus**

Testing language processes at a phonemic level it could be shown that the pSTG, Wernicke's area, holds a specific role within the posterior language network. In fact, its role has been proposed as transiently representing sequences of phonemes in auditory space (Wise et al., 2001). This function would support on one side the connection of heard speech sounds with their mental representations to be recognized and on the other side the phonological encoding of mental representations for motor related language tasks (Wise et al., 2001). This assumption is consistent with the finding that activity in different subfields of this region is present not only during verbal retrieval and speech perception tasks but also during verbal fluency tasks (Buchsbaum et al., 2001; Price et al., 1996; Wise et al., 2001). It gives support to the hypothesis that the pSTG acts as interface between speech perception or lexical recall and speech production. Accordingly, the role of the pSTG has also been proposed to be central during the process of language acquisition, whereby the transient representation of sequences of phonemes and their rehearsal, ultimately results in long-term lexical memories (Wise et al., 2001).

In the present study it could be shown that during language production, late multilinguals exhibit a more pronounced neuronal activity in the pSTG, Wernicke's area, than early multilinguals. These findings show that the functional establishment of the network for sensory-motor integration of phonological language aspects is dependent on early mono- or bilingual language acquisition (see previous paragraph). Here we consider the specialization of the pSTG within a left sensory-motor integration network for phonological encoding to specify the functional differences between early and late multilinguals. While early multilinguals use the sensory-motor integration of phonological language aspects into motor articulatory systems, in late multilinguals, the transient phonological representation in auditory space prevails.

What is the role of the network for sensory-motor integration of phonological language aspects during language production?

### **The function of the sensory-motor integration network for phonological language aspects explained by the verbal working memory model**

According to Baddeley, "working memory" is the short-term memory system used in all sorts of daily activities, among which language comprehension and production (Baddeley, 2003). Verbal working memory is fundamental during on-line processing of verbal material (Wilson, 2001). In addition it supports early language acquisition (Baddeley et al., 1998; Kuhl, 2000).

Baddeley's model of verbal short term memory proposes that verbal material can be temporarily retained in a phonological store, which is subject to rapid decay. However, the activation of the elements in the phonological store can be maintained through a process of subvocal articulatory rehearsal, via the so-called "phonological loop". The phonological memory system is localized in the SMG. The subvocal

rehearsal system has been attributed to Broca's area and the left inferior parietal lobe (Paulesu et al., 1993). Apparently, the two systems comprise the substrate of the sensory-motor network engaged in phonological encoding. Indeed, brain imaging studies have yielded evidence that brain activity pattern related to phonological processing are compatible with and thus support the model of a rehearsal loop as proposed by Baddeley and colleagues (Demonet et al., 1994; Poeppel, 1996; Price et al., 1996). These findings suggest that the function of the verbal working memory includes the network for phonological encoding.

An important result of the present study is that early and late multilinguals rely on different regions within this left lateralized network. In early multilinguals Broca's area is more activated whereas late multilinguals rely more on the left pSTG, i.e. Wernicke's area. These group differences in the left sensory-motor integration network could be related to the function of the two subsystems of the verbal working memory; the phonological memory and the phonological rehearsal system. In late multilinguals, the positive signal change in the pSTG, together with the low signal change in the anterior supramarginal gyrus and the frontal cortex point to the importance of the phonological memory aspect of verbal working memory. In these subjects, the transient access to phonological concepts of words seems to be the language processing strategy adopted. However, sound-related verbal material in the phonological store is vulnerable to interference and this can accelerate decay of information. This transient representation of the verbal information can be stabilized by use of subvocal rehearsal system (Baddeley, 2003; Fletcher and Henson, 2001). The higher neuronal activity in Broca's area of early multilinguals indicates, that in these subjects the subvocal rehearsal system is continuously involved, possibly as a consequence of cross-linguistic interference in the phonological store. This is plausible since in early multilinguals during the early period of life, two languages are at the disposal of the child and therefore phonological representations of two languages may be associated with the same concept. Here, it seems that the rehearsal function is adopting control to resolve cross-linguistic interference. Late second language acquisition as experienced by late multilinguals is not able to reorganize this system to the early bilingual mode. It seems that the function of verbal working memory system is substantially modifiable and accessible to language experience early in life, during the period of procedural learning. This proposition is corroborated by Ullmann (Ullman, 2004) who suggests that perisylvian regions represent procedural memory aspects of language.

### **Visual concepts in early multilinguals**

Our results show, that in early multilinguals access to sensory memory during language production is enhanced, too. In these subjects, activation in a cortical region which processes complex visual stimuli, i.e. the left fusiform gyrus, is important. This region in the inferior temporal cortex supports access to words as well as objects (Buchel et al., 1998; Moore and Price, 1999). The bilingual child, experiencing words in two languages, apparently learns to use visual concepts to facilitate language processing. This idea is supported by the study of Wagner et al. (Wagner et al., 2001) who showed that controlled verbal retrieval not only activates the left inferior ventrolateral prefrontal cortex but also the left fusiform gyrus.



Overall, during processing of their early acquired languages early multilinguals engage not only a left frontal motor related network but also the left sensory-motor integrative network for phonological language aspects and higher sensory association areas to avoid cross-linguistic interference.

## 5.2.2 Comparison of second and third learned languages

### 5.2.2.1 The role of procedural and declarative memory in late acquired languages

In this study not only early acquired languages were compared between early and late multilinguals (EL1/LL1, EL2/LL1 comparison) but also late acquired languages (EL3/LL3) and the second acquired language (EL2/LL2). This language was not acquired at similar time periods in the two groups of multilinguals: in early multilinguals it was acquired before the age of three years, in late multilinguals after the age of nine years (see Methods, Chapter 3.4). In addition, early multilinguals used this language with higher proficiency than late multilinguals (see Chapter 3.1).

In all comparisons, group specific effects clearly manifested in Broca's area and the pSTG, Wernicke's area: Early multilinguals exhibited a higher neuronal activity in Broca's area whereas in late multilinguals a prominent neuronal activity could be observed in the pSTG. These results seem to be independent from attained competence and age of acquisition since this finding is corroborated by the result of the comparison of L2 between early and late multilinguals. The function of early and late acquired languages in Broca's area and in the pSTG seems to depend on language procedures established early in life. To our knowledge, this is the first time that the impact of early second language acquisition on further language learning as adults or adolescents has been reported. As previously discussed, early acquired languages of early multilinguals exhibit higher activation in Broca's area and reduced neuronal activity in the left pSTG. The group specific activation seems to be the neuronal correlate of higher cross-linguistic interference in early multilinguals (Chapter 5.2.1.1 and 5.2.1.2). Late acquired languages of early multilinguals show the same regional activation pattern in Broca's area and in the left pSTG as early acquired languages. This finding indicates that late learned languages depend on strategies established during the early developmental period, i.e. strategies sensitive to cross-linguistic interference of verbal material.

In contrast, in the left dorsolateral prefrontal cortex (BA 46) higher neuronal activity was not observed in the late acquired languages of early multilinguals (shown by the EL3/LL3 comparison). Indeed, increased activity of this region became only apparent in the comparisons of the early acquired languages of both groups (EL1/LL1 and EL2/LL1) and in the comparison of the second early acquired language of early multilinguals with the second late acquired language of late multilinguals (EL2/LL2). We have proposed that, similar to Broca's area, increased activation of left BA 46 in the dorsolateral prefrontal cortex- as observed in the early acquired languages of early

multilinguals- could be the neuronal correlate of higher control of cross-linguistic interference. This function would be established during the early period in life when acquisition of procedural language aspects prevails (Chapter 5.2.1). Our results indicate that during processing of late learned languages (L3), early multilinguals do not need additional control in the left dorsolateral prefrontal cortex. In fact, languages learned later in life depend highly on declarative memory (Ullman, 2001b), which represents consciously-explicitly- learned knowledge. Memories of later learned languages therefore have different declarative/procedural attributes than those of early acquired languages. In particular this might have an effect on language processing in cortical areas in which both procedural and declarative language aspects are relevant. In a situational context for example, processing of complex language structures in the left dorsolateral prefrontal cortex (for a review (Miller, 2000), does not only require functions of the procedural but also of the declarative memory system (Ullman, 2001b). Our results indicate that in this cortical region later learned languages of early multilinguals do not need additional control of cross-linguistic interference. It seems that here (predominantly) declarative memory of the late acquired language does not interfere with (predominantly) procedural memory of the early acquired languages.

In the left fusiform gyrus languages acquired as adolescents or adults of late multilinguals exhibited a higher activation than languages of early multilinguals learned in early childhood (EL2/LL2 comparison). In addition, the late learned language of both, early and late multilinguals evidenced no differential activation (EL3/LL3). Apparently here, early second language acquisition (Chapter 5.2.1.2) is not the determining factor during processing of late learned languages. Predominantly explicit learning strategies of later acquired languages could explain the observed activation. Indeed, this region allows processing of visual concepts (Moore and Price, 1999) and thus provides supports to the establishment of declarative memories. The dominant role of this memory system for late learned languages could explain why here, the effect of explicit learning strategies overrides the one of early second language acquisition.

The language comparisons between early and late multilinguals (EL1/LL1, EL2/LL1, EL3/LL3 and EL2/LL2) also revealed group differences in the middle and anterior parts of the left temporal lobe. The observed differences varied in magnitude and anatomical localization. From this, no profile attributable to the effect of early second language learning or of the time period of language acquisition emerged (Table 4.4). Regions in the left temporal lobe support processing of semantic/conceptual language aspects (Price, 1998) and are involved in functions of the declarative memory system (Ullman, 2001b). In contrast to procedural memory, declarative memory is accessible to new experience throughout life (Ullman, 2001b). Related to this, we did not expect to reveal differences in this cortical region between any language of early and late multilinguals. Yet, one possible explanation for the inconsistent differences could be, that in the temporal lobe, anatomically segregated regions are specialized for different types of semantic attributes (Damasio et al., 1996). In particular, specific semantic information associated with biographical memories or complex sentence processing is processed in more anterior parts of the temporal lobe (Fletcher et al., 1995; Gorno-Tempini and Price, 2001). Thus, the variable language processing observed in this region could be related to the biographical or situational knowledge preferentially established in one particular language rather than to an explicit or implicit learning strategy. For instance, memories associated to the tested communicative situation

seemed to be variable across the different languages, independent from age of acquisition or proficiency level.

### 5.2.3 Effect of early second language acquisition discussed in the context of cortical systems not specifically related to language processing

#### 5.2.3.1 Intrinsic knowledge about the language plan

Our data reveal a higher language related neuronal activity of the left frontal cortex in early multilinguals as compared to late multilinguals. More specifically, a higher neuronal activity in the early multilinguals early and late acquired languages was reliably shown in Broca's area (BA 44/45 and 44/9). This could be the neuronal correlate of frontal control functions (see 5.2.1.1) and of the sensory-motor interface system for phonological language aspects (see 5.2.1.2) possibly both engaged to resolve specific cross-linguistic interference between the early multilinguals languages. The comparison of both groups also showed that the supplementary motor area (SMA), a subfield of BA 6, was higher activated in the group of early multilinguals (Chapter 4.2). In contrast, no group differences could be reported for the dorsolateral portion of BA 6 (Chapter 4.2). This finding is surprising, since the main language effect revealed that in early and in late multilinguals both regions were reliably activated (see main effect, Chapter 4.1.2). In addition, the participation of both cortical regions in similar aspects of motor planning has been demonstrated (Kawashima et al., 1994).

However, according to Goldberg's internal-external control hypothesis of complex movements (Goldberg, 1985), the SMA and the dorsolateral prefrontal cortex contribute specifically to the selection of motor plans. Indeed, when internal representations, the memory of task execution, are necessary to perform a complex motor task, the prefrontal cortex together with the SMA and the basal ganglia participate in the activated network. This is exemplified sequential finger movements according to a sequence instructed to the subject. The memory of this sequence would serve as "internal representation" to perform the task.

When an action is induced by external reference, neuronal activity in the dorsolateral premotor cortex (BA 6) is preponderant. External reference means, that movements are guided by visual, auditory or somatosensory signals, which can be real or imagined. For instance, a tennis player who adjusts his posture to return a shot depends on an external control of his movements.

Encouraged by recent propositions that suggest similarities between the planning of actions and of language (Greenfield, 1991), we reconsidered the early multilinguals' pattern of language related neuronal activity within BA 6 in its perspective of motor planning. Related to this, the higher neuronal activity in the SMA might evidence that early multilinguals as compared to late multilinguals rely more on internal representations –intrinsic knowledge- during planning of motor language aspects.

Thus, in more general terms the early multilinguals' higher activation in Broca's area which we previously explained as specific cross-linguistic control functions could indicate that they rely more on internal representations –intrinsic knowledge- of the language plan.

### **5.2.3.2 Coordinating language plans with articulatory gestures in area 44/9**

As described in Chapter 4.2, in all three languages of early multilinguals the frontal activation is particularly high in left BA 44/9 which is localized at the interface of prefrontal (BA 9), premotor (BA 44) and motor regions (BA 4).

Which functional specialization could justify the strong susceptibility of this cortical region (BA 44/9) to early second language acquisition?

Previous fMRI investigations testing comparable language tasks reported only one peak of activation in Broca's area (Kim et al., 1997; Mahendra et al., 2003). Our study however allowed us to differentiate two regions within Broca's area; a region localized in the inferior anterior part (BA 44/45) and one in the superior part (BA 44/9). Linguistic categories of language processing, related to retrieval of semantic knowledge, are processed in more inferior anterior regions of Broca's area and the prefrontal cortex (Poldrack et al., 1999; Thompson-Schill et al., 1997). In contrast, high-level aspects of programming speech production per se seems to involve rather posterior superior parts (BA 44) of Broca's area (Poldrack et al., 1999). The latter function was also claimed by P. Broca when he first described this region as concerned with memory for coordinating speech movements.

Brass and von Cramon showed by an fMRI experiment that during cognitive tasks, BA 44/9 serves as a crucial component of motor task preparation within a frontal network (Brass and von Cramon, 2002). During the experiment digits between 20 and 40 were presented. Subjects had to alternate between two tasks: judging whether a digit was odd or even or judging whether the digit was greater or smaller than 30. Activation in BA 44/9 was specific for a situation where the task could be prepared by a presentation of a frame indicating the task, in advance to the digits. The authors propose that in BA 44/9, the association between stimuli and relevant motor responses are configured in accordance to the meaning, i.e. the task-relevant intrinsic knowledge about the stimuli.

We previously discussed (Chapter 2.2) the concept of a task set which is established –resonates- before the task is actually performed and thereby would allow access to the intrinsic knowledge about the stimulus. This function could explain the nature of the contribution of Broca's area to motor as well as language tasks. In addition, we argued (Chapter 5.2.1.1 and 5.2.3.1) that the early multilinguals' higher engagement of neuronal function in more inferior portions of Broca's area (BA 44/45) could indicate that -to control for cross-linguistic interference-, they have additional access to –intrinsic- knowledge of language features necessary for language output. This could in turn have determined the function in BA 44/9 which consists in associating

the intrinsic knowledge about the (language) stimulus –the task set- to the motor action for a meaningful (language) output.

### **5.2.3.3 Early experience and the dorsal stream system**

Early second language acquisition affects specific aspects of early and subsequently later learned languages. In fact, early multilinguals show in the three tested languages a different neuronal activity in the left fronto/parietal and posterior superior temporal network as compared to late multilinguals. This left lateralized network seems to be involved in retrieval of verbal material for subsequent language production (Chapter 5.2.1.1 and 5.2.1.2). Its function could depend on procedural memory established early in life (Ullman, 2004). In contrast, declarative memory, supported preponderantly in middle and anterior portions of the left temporal lobe (Ullman, 2001b) does not seem to be affected by early mono- as opposed to bilingual language acquisition. The procedural/declarative memory system has been described as closely being related to the dorsal/ventral stream system (Ullman, 2001a). Thus, the concept of the dorsal/ventral stream might provide new perspectives on our results.

The classic definition of the dorsal and ventral stream system by Ungerleider and Mishkin (Ungerleider and Mishkin, 1982) is related to the dorsal/ventral portioning first identified in the visual system of primates by the authors. The ventral stream projects from the primary visual cortex to inferior temporal brain regions and is involved in processing object identity (the “what” pathway) whereas the dorsal stream projects to parietal regions and is involved in processing object location (the “where” pathway). These findings have been confirmed by functional imaging studies in humans (Haxby et al., 1990). Since the dorsal stream is strongly connected to frontal premotor regions, it has been proposed that the dorsal stream allows also visuo-motor integration, as required in visually guided reaching or orienting responses (Goodale, 2000; Rizzolatti et al., 1997). In the auditory system, a functional and anatomical segregation of the neural systems involved in processing auditory stimuli has also been shown (Clarke S et al., 2000). Similar to their role in the visual system, the ventral auditory stream identifies and the dorsal stream localises auditory stimuli. Both auditory streams converge to the same cortical regions as the dorsal/ventral visual system, i.e. the parietal cortex and dorsal frontal regions for the dorsal stream and inferior/anterior and inferior frontal regions for the ventral system (Alain et al., 2001). In addition, the auditory dorsal stream seems to be critical for sensory-motor integration as well (Hickok and Poeppel, 2000; Wise et al., 2001). These findings suggests that the segregation of information processing into “what” and “where” pathways may be a fundamental property of cortical organization. Both, the dorsal visual pathway and the dorsal auditory pathway seem to be particularly susceptible to early experience. Concretely, in situations of diminished integration of sensory information from other modalities, plastic changes enhance the function of the dorsal pathway in both systems (Bavelier et al., 2000; Roder et al., 1999).

According to Ullman (Ullman, 2004), the functional and anatomical properties of the ventral/dorsal stream system indicate their relation to the procedural/declarative

memory system. He proposes that the ventral stream, as a memory based system, feeds representations into long term (declarative) memory and compares those representations with new ones. On the other side, he suggests that the capacity of the dorsal stream to transform sensory information into an egocentric framework that enables the execution of motor programs, indicates its relation to the procedural system. Some authors compare the processing of language stimuli with the dorsal/ventral stream division during the analysis of visual and auditory percepts (Hickok and Poeppel, 2004). In analogy to the visual and auditory system, the “dorsal” language pathway would allow sensory-motor integration of verbal material and the “ventral” language stream the connection of sound-based verbal material with conceptual representations in the temporal lobe. Since the dorsal and ventral stream systems are related to procedural, respective declarative aspects of memory processing, it is possible that procedural language memories involve a dorsal stream system and declarative language memories a ventral stream system. Our results suggest that early second language acquisition has an effect on the organization of procedural language memory. Thus, in early multilinguals as compared to late multilinguals, the function of the “dorsal” language pathway could have been altered. In contrast, no effect of early bilingual language experience on the organization of declarative memories has been observed. Thus, the function of the “ventral” language pathway might not be changed. Our study, however, has not been designed to give evidence for such potential changes in the dorsal/ventral stream system. Future research could focus on comparisons of dorsal/ ventral stream aspects in early and late multilinguals.

### 5.3 Organization of early and late acquired languages: Comparison of the multilinguals' languages

Comparisons of the multilinguals' languages within groups showed predominantly overlapping brain representations for early and late acquired languages. In both groups significant higher activation was only found in the left superior temporal sulcus for later learned languages and in the left posterior inferior parietal lobe for early acquired languages.

The neural representation of languages in bilinguals and polyglots has been investigated in previous studies. Although the pattern emerging is far from being consistent, numerous results support the hypothesis that the different languages of the same subject may be represented in distinct brain regions (Chee et al., 2000; Dehaene et al., 1997; Kim et al., 1997; Perani et al., 1996; Vingerhoets et al., 2003; Wartenburger et al., 2003; Yetkin et al., 1996). Moreover, the pattern of activation associated with the different languages strongly indicates an involvement of additional brain regions and a higher neuronal activity of less proficient and/or later learned languages. More specifically, age of acquisition seems to affect the cortical representation of grammatical processes and proficiency level the pattern of brain activity related to semantic judgments (Wartenburger et al., 2003).

#### 5.3.1 Higher neuronal activity of later learned languages

In line with previous studies which described higher brain activation of later learned languages, our results show that in both groups, regions adjacent to the left middle temporal sulcus (BA 21/22) exhibit higher neuronal activity during processing of late learned languages. Activation of this region during word fluency tasks has been associated to lexico-semantic retrieval (Price, 1998). Although all participants in our study claimed a high fluency in all three tested languages, we presume that the linguistic task required increased retrieval effort for the late learned languages. Lower performance in the late learned languages could indeed be confirmed by the evaluation of the language proficiency tests (Chapter 3.1, Table 3.5). Thus, the higher neuronal activity during processing of later learned languages as reported in the present study seems to be related to linguistic processes dependent on proficiency. The language proficiency tests applied in our study were however not specific enough to account for the group specific pattern of later learned languages in regions related to proficiency level; i.e. in late multilinguals higher differences in the left BA 21/22 between early and late acquired languages than in early multilinguals (Chapter 4.3). Some studies described higher neuronal activity for later learned languages not only in left posterior (in particular temporal) brain regions but as well in the left frontal lobe (particularly in Broca's area); this finding has been proposed to indicate

processes related to syntax in later learned languages (Vingerhoets et al., 2003; Wartenburger et al., 2003). In the present study however, we do not confirm these results. In fact, the tasks traditionally used to test the bilinguals languages such as word generation (Chee et al., 1999b), picture naming (Vingerhoets et al., 2003) and grammatical or semantic judgment (Wartenburger et al., 2003) specifically test selective access to semantic, i.e. declarative knowledge. In contrast, the narrative language condition applied in this study did not specifically test this language aspect. Given that bilinguals are more likely to use declarative knowledge to carry out language tasks in a late learned language (Ullman, 2001b) and that Broca's area contributes to selective retrieval of declarative memory (Buckner et al., 2001; Thompson-Schill et al., 1997) it is possible that previous studies revealed processes in regions of the left frontal lobe related to specific access to declarative memories and not to syntax in late learned languages.

### 5.3.2 Higher neuronal activity of earlier learned languages

Previous studies testing comprehensive reading, revealed brain regions with higher neuronal activity during processing of earlier learned languages as compared to processing of later learned languages (Perani et al., 1996; Vingerhoets et al., 2003). The authors indeed reported higher neuronal activity for earlier learned languages in regions specialized in semantic aspect of language processing, i.e. in left lateral/anterior and medial occipito/temporal regions. During tasks requiring sentence comprehension, the first language seems to engage more neuronal substrate to analyze the sentence meaning than later learned and less proficient languages. Given these previous results, we did not expect to reveal a higher neural activity of early learned languages compared to later learned languages in other cortical structures, even if the tested language condition required language production. Interestingly, our study revealed higher neuronal activity in the left supramarginal and angular gyrus (BA 39/40) for the first early learned language (EL1 resp. LL1) of early and late multilinguals. This region integrates sensory information of different modalities, in particular visual and auditory stimuli (Mesulam, 1998) and has been described in Hickok and Poeppel's model of language processing as auditory-conceptual interface system (Chapter 5.2.1.2). Moreover, association of speech sounds with the corresponding object information accompanies the process of language acquisition and ensures a meaningful use of spoken words (Bates et al., 1992). Related to this, it has been shown that the left angular and supramarginal gyrus provide a link of visually presented inputs to their phonological representation, based on meaning understanding (Demonet et al., 1992b). This process is important during early childhood already. For example, when a small child utters "house" when it sees a house, he shows that he has learned to associate the meaning of a visually encoded object to a spoken word. The same region is also implicated in association of letter strings –visually encoded "objects" – to spoken words (Bookheimer et al., 1995; Horwitz et al., 1998). Establishment of the capacity of orthographic to phonological mapping is imperative when the child has to learn how to read (Pugh et al., 2000). In addition, studies investigating the effect of practice on word and object naming tasks found, that higher performance was associated with higher activation in this cortical region (Binder et al., 2003; Roland and Gulyas, 1995). In the present study, the first



language (EL1 resp. LL1) has not only been the most important language during the first years of language acquisition, but for the majority of subjects tested, it was the first language in which they were instructed to read (in all late multilinguals and in 6 out of 8 early multilinguals). Thus, both the transfer of visual information (object naming) or of letter strings (reading) to phonological representations could have been more established in the first acquired language of the early and late multilingual subjects tested in the present study.

Additional explanation for the nature of the specific language processing strategies in the first language of early and of late multilinguals (EL1 resp. LL1) may be derived from the activation pattern of the second early acquired language of early multilinguals as compared to their third late learned language (contrast EL2/EL3). Here, unlike to the first acquired language, no difference to the third late learned language could be shown in the left angular and supramarginal gyrus. Indeed, the second language of early multilinguals was acquired parallel to the first language, thus possibly developed similar object to spoken word associations. In contrast, it was not the language in which the subjects were instructed to read and therefore did not participate in the process of visually encoding letter strings to spoken words. Consequently, we propose that the changes of neuronal activity in the supramarginal/angular gyrus observed in the first acquired language of early and late multilinguals reflect their first reading experience.

It is surprising to discover differences between early and late acquired languages in brain regions which allow associating visually presented objects/letters to their corresponding sound in a task which requires production of narratives. However, the request for the language task occurred visually, by repetitive display of three different pictures (representing morning, noon and evening). Thus, the language task tested not only the production of narratives but as well as object recognition and the latter apparently revealed functional differences between early and late acquired languages in the left angular/supramarginal gyrus.

Taken together, the comparison of early and late learned languages within the groups of early and late multilinguals, revealed processes related to reading experience and proficiency. It did not allow finding a group specific processing of early and late languages.

## 5.4 Influence of variables on the results

Various factors may have an influence on the BOLD signal change. Thus, the results of this study might not be attributable solely to the influence of early monolingual as opposed to bilingual language acquisition. Some variables were controlled in advance. Since the responsiveness of blood vessels during neuronal stimulation changes with age (Aizenstein et al., 2004; Grossman et al., 2002) the subjects included in the study were not older than 35 years. In addition, there is a concern that the vascular effects of nicotine and caffeine (Mulderink et al., 2002) may change the coupling between the BOLD signal and neuronal activity. To minimize such effects of altered cerebrovascular dynamics, participants were instructed to avoid drinking coffee and to refrain from smoking during the hours prior to the fMRI session. Another factor which had to be considered was that basal brain activity varies between subjects and possibly reduces task related BOLD signal change. This factor has been taken into account by the subject-specific normalization of the data during the standardized SPM procedure (see Chapter 3.4).

Concerning language related brain activity, gender (Schirmer et al., 2004; Wildgruber et al., 2002) as well as language proficiency (Chee et al., 2001) are known to influence the outcome of functional imaging studies. Accordingly, the selection of the subjects aimed to balance these factors between the groups. Further, in this study we included only right handed subjects (see Methods, Chapter 3.1), since it is known that handedness determines language representation. Indeed, left hemispheric language lateralization is particularly characteristic for right handed subjects (Pujol et al., 1999). Another point we considered was the careful preparation of the subjects to the scanner session. We explained the planned experiment according to a standardized protocol established for this study. In addition, the language task was practiced immediately before the investigation to avoid active searching and remembering of the tested language situation (events of the day before) during the fMRI session. After the session the subjects were questioned to assess whether the language and control task had been managed according to the given instructions. The influence of other variables on the results could only be assessed by further data analysis as presented in the following paragraphs.

### 5.4.1 Reproducibility

The narrative task tested in this study was practiced immediately before each test. Actual task performance during the scanner session was not assessed. Indeed, management of such a control could cause additional, non-task related brain activation during the experiment. In consequence, the test procedure adopted did not clearly indicate that the observed neuronal activity was related to the performance of a

clear-cut task. Here we considered the brain activity elicited by the language condition for both tested runs independently. This analysis allowed assessment of whether the neuronal activity elicited by the language task was reproducible and, related to this, indicated whether the language task was unequivocal.

Regarding the first acquired language of each group (EL1 resp. LL1), the first and second tested run demonstrated a consistent pattern of activation (Figures 4.20 resp. 4.21). Activation varied only slightly in extent: in both groups the first tested run elicited higher neuronal activity than the second. The difference between the first and the second test could be explained by the effect of practice on task performance. Indeed, previous studies have shown that exercise reduces neuronal activity necessary for the performance of a task (Petersen et al., 1998). This effect might explain the lower brain activity during the second run.

Overall, the consistent brain activation pattern between the both language tests in the same subject indicates that the language strategy adopted in the test situation is reproducible. This finding gives support for the validity of the language test.

#### 5.4.2 Neuronal activity during the auditory control condition

During the auditory control task subjects performed a motor action (finger tapping) in response to periods when the scanner was silent. This auditory condition, which served as a reference condition for the language condition, seems not to implicate any language processing (Binder et al., 2003). Thus, contrasting language and auditory control conditions promises revealing a maximum of language related regions. However, the higher demands on auditory processing during the control condition could have masked language activity in proximity to primary and secondary auditory fields. In addition, the required motor action during the auditory task (finger tapping) is expected to engage the frontal executive network, which is also involved during the language condition. Thus, the auditory control task could have masked activity of the left frontal language network as well.

In Figures 4.22 and 4.23 (Chapter 4.4) we represented the neuronal activity during the reference condition to elucidate its possible impact on the observed pattern of language activity. Both hemispheres showed the same pattern of activation: here, only the left hemisphere has been shown. The main effect of the auditory condition as compared to the language condition (Figure 4.22) revealed that in the first tested language of both groups, the auditory condition, as expected, activated auditory related regions in a middle portion of the superior temporal gyrus. However, the results also demonstrate that in more posterior parts of the superior temporal gyrus, i.e. Wernicke's area, the auditory task did not elicit stronger activation than the language task. This result indicates that the results of the language comparisons (Chapter 4.2) were not determined by differences of the auditory condition alone. Figure 4.22 also shows that neuronal activity in primary motor and sensory regions of the pre/postcentral gyrus was relevant during the auditory condition. The observed activation seems to be related to the motor aspect of the auditory task- a finger tap each time the scanner noise stopped (see Methods, Chapter 3.3). Since this brain

region is not specifically involved in language processing a possible impact of this activation on the results will not be discussed further. A major focus of activation was also revealed in the posterior middle and inferior temporal gyri. Here also the activation was similar to that in the right hemisphere.

Another indication that the results are not confounded by the auditory condition comes from the separate analyses of the BOLD signal in regions of differential activation for the auditory condition and for the language condition (**EL1/LL1** comparison, Figure 4.23). Evidence of activity in two subfields of Broca's area (BA 44/45 and BA 44/9), the left dorsolateral prefrontal cortex (BA 46) and the left pSTG (BA 22/40) was crucial for the interpretation of the results. In general, the analysis showed higher signal differences between the language conditions than between the auditory conditions of the languages being compared. Only in one subfield of Broca's area (BA 44/45) was the result strongly determined by the auditory condition as well. In fact, in this portion of Broca's area, the language signal was reduced in **LL1**. Taken together, the comparison of the BOLD signal of both tested conditions confirmed that the main findings of the **EL1/LL1** comparison were not confounded by processes related to the auditory condition. Since the pattern of differential activation of the language condition was similar across the other language comparisons (contrasts **EL2/LL1**, **EL2/LL2**, **EL3/LL3**), we deduce that, here also, the results mainly reflects differences in the language conditions.

### 5.4.3 Intersubject variability: Random effect analysis

As explained in the methods (Chapter 3.4), for the data analysis the fixed-effect model was preferred to the random-effect model. This was motivated by the impact of inter-subject differences regarding anatomical localization or use of brain language regions on the results of a random-effect analysis. Indeed, in a random-effect analysis brain regions which exhibit inter-subject variability in activation tend to be excluded from the results. There are, however, also limitations to the evaluation method applied in our study. Indeed, since a fixed-effect analysis assesses the group average of activation without considering inter-subject variability, high activity in only a small sample of subjects may indicate a significant activation at the group level.

Figures 4.24-4.27 (Chapter 4.4) represent the results of the random-effect analysis of the early and late multilinguals' first acquired language for a comparison of the specific effect of the fixed-effect analysis on the results obtained. Here, the main effect showed, similarly to the fixed-effect analysis, language related activation in Broca's area and in left dorsolateral premotor regions. Interestingly, in late multilinguals, Broca's area showed high activation in the random-effect analysis, whereas activation revealed by the fixed-effect analysis was relatively small in this group. Considering the characteristics of the two models for group analysis, this finding could indicate that the signal is lower than in early multilinguals but that the anatomical localization and use of these language regions across the different subjects is relatively stable.

Other cortical regions that evidenced a specific effect of the evaluation method on the revelation of main language activation were localized in the left temporal lobe, in particular in its anterior part. Here, only the random-effect analysis revealed significant language related activation in early and late multilinguals. As discussed in Chapter 5.2.2, anterior portions of the left temporal lobe process specific semantic information such as those associated with episodic (autobiographical) memories. Here again, the specific impact of the evaluation method on the observed activation indicates, that individual language memories are invariably, though not strongly comprised in the tested communicative situation. It would be interesting to further investigate language processes related to the production of narratives in this cortical region. However, the hypotheses of the present study and the corresponding selection of groups were not appropriate to differentiate language processes related to this brain region.

Of major concern for this study was the question whether the results of the fixed-effect analysis showing the impact of early second language acquisition on the establishment of the left frontal and perisylvian language network could be replicated by the random-effect analysis. Indeed, the pattern of differential group activation revealed by the random-effect analysis (Figures 4.26 and 4.27) confirmed the findings from our study: the early multilinguals' languages showed more significant activation in left dorsolateral prefrontal brain regions whereas the late multilinguals' languages activated only a subfield within the left supramarginal gyrus more significantly. It has to be noted that the differential activation of late multilinguals in the supramarginal gyrus was reduced to only a few voxels. In fact, since this brain region distinguishes itself by an considerable functional heterogeneity (Howard et al., 1996), effects of inter-subject variability could have had a high impact on the result. Contrary to the fixed-effect analysis, the random-effect analysis revealed the same pattern of differential frontal activation for the right hemisphere as well. According to the specific characteristics of these two evaluations (see Methods, Chapter 3.4) this result could indicate that right prefrontal activation as well was consistently higher in all tested early multilingual subjects as compared to the late multilinguals. Thus, left frontal control functions engaged in early multilinguals (Chapter 5.2) also seem to comprise homologues in the right hemisphere. The group comparison by the random-effect analysis also allowed the determination of other brain regions not revealed in the fixed-effect analysis. Here, it could be shown that late multilinguals additionally involve functions of the right orbitofrontal cortex and of regions within the left inferior temporal lobe. Previous studies reported that right inferior prefrontal regions evaluate the emotional content of prosodic features of language (Ackermann H et al., 2004) and that inferior temporal regions store semantic information related to biographical experiences (Fletcher et al., 1995). This result indicates the strong potential of the narrative task applied in the present study. It would be interesting to test the same narrative task on other subjects to further evaluate effects of emotional implications or biographical relevance. However, it should be noted that those cortical regions revealed exclusively by the random-effect analysis represent language functions that could have been strongly influenced by current events. In contrast to the random effect analysis, the fixed-effect analysis of this study accounts for such effects of the present day condition by including two tests carried out on different days. This strongly suggests that in tasks related to language processing preference should be given to the fixed-effect analysis.

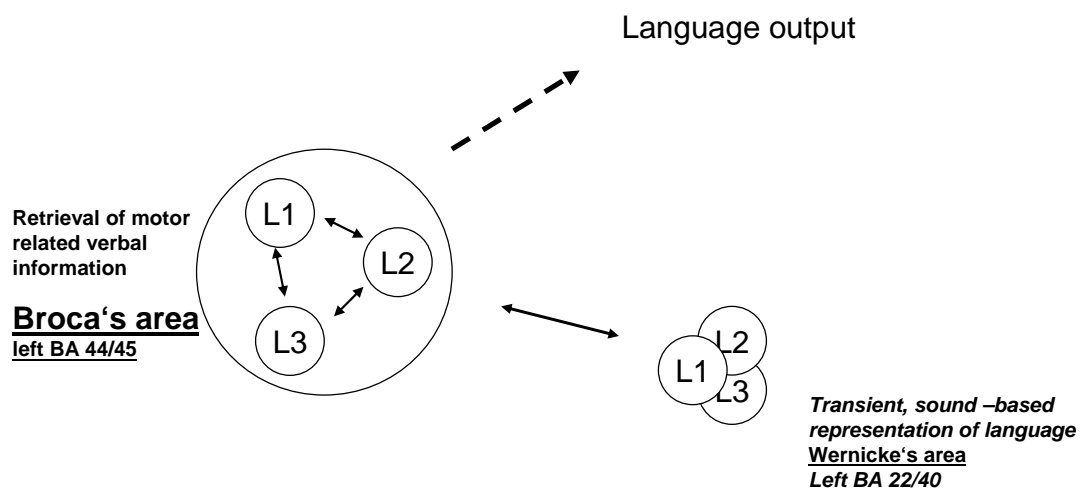
#### 5.4.4 Influence of typological differences

Structural differences between languages were not the focus of our study, but could potentially have an influence on language tasks. In fact, the impact of typological differences on reading strategies in English or Italian speaking subjects has been shown in a PET study (Paulesu et al., 2000): languages with an inconsistent orthography, such as English, do not allow direct mapping of letter to sound, while languages with a consistent orthography, such as Italian, do. Other brain imaging studies revealed that during a variety of linguistic tasks, native Chinese speakers rely more on the left middle frontal gyrus than do native English speakers (Tan et al., 2001). The underlying cognitive operation involved in Chinese language use was suspected to be related to visual spatial working memory, because this language requires processing of logographs. However, the same pattern of differences between Chinese and English speakers were observed for processing of speech sounds (Hsieh et al., 2001; Klein et al., 2001). This would argue for a pervasive strategy difference of groups with different reading strategies. Analogously, an effect of typological differences on the processing of the narrative task investigated in this study could not be excluded either. Indeed, in the first language of early multilinguals the proportion of Germanic to Romance languages was 5/2, while in the first language of late multilinguals this proportion was 4/4 (see Chapter 3.1). However, a similar pattern of differential activation revealed for the comparison of the first and the second language of early multilinguals (in which, for instance the proportion of Germanic to Romance languages was 4/4 in the second learned language) with the first language of late multilinguals (contrasts **EL1/LL1** and **EL2/LL1**) indicates that, here, typological differences are not influencing the tested language aspect.

## 5.5 Effect of early second language acquisition on the cortical language network exemplified by the language situation in early multilinguals: resuming representation

### Cortical regions which are possibly engaged to resolve specific cross-linguistic interference during processing of early and late acquired languages.

Cross-linguistic interference possibly manifests on one side in Broca's area during retrieval of motor related verbal information and on the other side in the network for sensory-motor integration of phonological language aspects which interconnects Wernicke's area with Broca's area. In early multilinguals both brain functions seem to be engaged to resolve higher cross-linguistic interference during processing of the early (EL1 and EL2) as well as the late (EL3) acquired languages. In Figure 5.2, processes related to resolution of interference are indicated by bidirectional arrows.



**Fig. 5.2 Early multilinguals: Resuming representation of early and late acquired languages (L1, L2 and L3).**

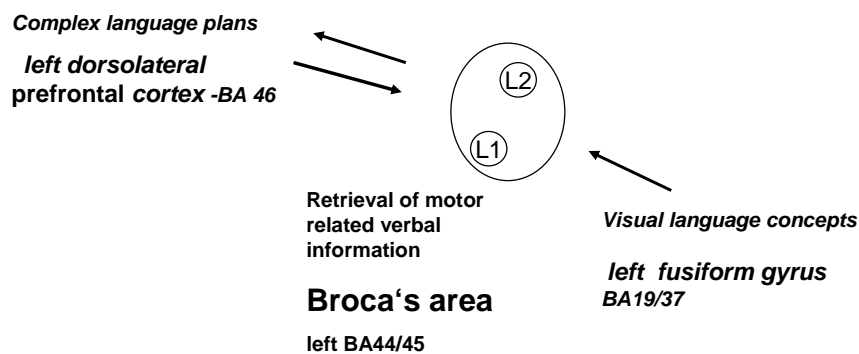
Cortical regions involved in resolving language interference consequently to early second language acquisition. The resolution of interference in Broca's area and by sensory- motor checking between Broca's and Wernicke's area is indicated by bidirectional arrows.

### **Cortical regions which seem to be involved in resolution of specific language interference in early acquired languages only**

In early acquired languages of early multilinguals (L1 and L2), the effect of early second language acquisition manifests not only in functions engaging Broca's area but also in the left fusiform gyrus and in the left dorsolateral prefrontal cortex (Figure 5.3).

The left fusiform gyrus processes visual language conceptions whereas the left dorsolateral prefrontal cortex allows planning of complex language structures.

The function in these two cortical regions could depend upon and/or support the resolution of cross-linguistic interference in Broca's area. This is indicated by the unidirectional arrows.



**Fig. 5.3 Early multilinguals: Resuming representation of early acquired languages (L1 and L2).**

Cortical regions involved in resolving language interference consequently to early second language acquisition. Influence on cortical areas related to resolution of cross-linguistic language interference is indicated by unidirectional arrows.



## 6 Conclusion

The data presented in this study confirm and extend the results of previous studies indicating that early exposure to one language as opposed to two languages has a permanent effect on language processing.

First, in line with previous work, our results reveal that at adult age, early multilinguals show different neuronal activity during language production than late multilinguals (Chapter 4.2 and 5.2). Late second language exposure, as experienced in late multilinguals, could not reorganize the brain function to an early bilingual mode. This indicates a critical time period for the organization of brain language functions relevant to the production of narratives.

Second, our data provide evidence for a specific effect of early bilingual language acquisition on language processes. Indeed, we show that early multilinguals as compared to late multilinguals recruit additional brain functions, particularly in regions of the left frontal lobe i.e. Broca's area and the adjacent prefrontal cortex. The higher engagement of this frontal neuronal network indicates the establishment of specific processes related to cross-linguistic interference resolution in early multilinguals (Chapter 5.2.1.1). Moreover, in this group the activation pattern in perisylvian regions indicates that the function of the network for sensory-motor integration of phonological language aspects might have been adjusted to resolve early experienced cross-linguistic interference (Chapter 5.2.1.2). Although previous fMRI studies showed regional effects of early second language acquisition on the cortical language network, none described the pattern of differential activation for a comprehensive interpretation of the effect of early second language acquisition on the language network.

Third, our data indicate that late learned languages of multilinguals mainly engage the language system developed in early childhood. In fact, similar to the early acquired languages, the early multilinguals' language which was learned in early adolescence or later shows a higher neuronal activity in Broca's area as compared to the corresponding language of late multilinguals (Chapter 5.2.2.1). To the author's knowledge, this is the first study to describe a difference between the activation patterns of early and late multilinguals' late learned languages.

In this study, we revealed the importance of early second language experience for the establishment of the brain language network. In particular, we were able to show that monolingual language experience shows effects on language learning in adults which differ significantly from those of bilingual learners. The specific activation patterns of early multilinguals indicates that the language processing strategy adopted for their early and subsequently learned languages reflects processes related to resolution of cross-linguistic interference. In his theoretical concept of language acquisition Chomsky introduced the idea of a "language acquisition device", to explain mechanisms of language acquisition in children. The findings of our study could initiate a debate whether the early establishment of processes to resolve language interference, including cross-linguistic interference, might be part of an innate mechanism for language acquisition. Although our results point to processes related to

the resolution of cross-linguistic interference to explain specific activation patterns in early multilinguals, further experimental work will be necessary to support and elaborate this hypothesis. One approach could be to investigate whether and how early and late multilinguals perform differently in experiments testing aspects of prefrontal control function that are independent from their bilingual situation such as controlled semantic retrieval, mechanism to select relevant from irrelevant semantic knowledge or non-specific executive control functions. Such tests could also indicate whether frontal control functions in monolinguals are different from those in multilinguals.

A question which remained unanswered in this study was whether brain mechanisms guiding language learning in adults are predetermined by early mono- or bilingual language acquisition. Concretely, our results did not clearly indicate whether early as compared to late multilinguals rely differently on the early established network to process languages learned as adults (Chapter 5.3). The current method to differentiate the languages of multilinguals should perhaps be critically reconsidered. In this context, it is important to recognize the potential for ongoing changes in language experience to influence cortical activation patterns. Languages learned at any age still function to transpose our sensory experiences of the world into internal representations. For instance, a change of one's place of work to another country is associated with more practice in one particular language and this generally results in higher proficiency in this language. In multilinguals, the resulting modifications in the cortical language system may be differently predetermined by early versus late bilingualism or by procedural versus declarative memory of the respectively early and late learned languages. In this sense, the fascinating perspective in multilingual research, made possible by brain imaging methods, is that it can not only reveal the influence of parameters determining language acquisition but also represent the permanent interplay between inherent norms and external reality.

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