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The age of second language acquisition determines the variability in activation elicited by narration in three languages in Broca's and Wernicke's area

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ABSTRACT

It is generally accepted that the presence of a second language (L2) has an impact on the neuronal substrates build up and used for language processing; the influence of the age of L2 exposure, however, is not established. We tested the hypothesis that the age of L2 acquisition has an effect on the cortical representation of a multilingual repertoire in 44 multilinguals with different age of exposure to a L2 (simultaneous or covert simultaneous exposure to L1 and L2, sequential acquisition of L1 and L2 between 1 and 5 years, late learning of L2 after 9 years of age) and all fluent in a late learned L3. Regional activation in a language production task showed a high in-between-subject variability, which was higher than within-subject variability between L1, L2, and L3. We, therefore, performed a single subject analysis and calculated the within-subject variance in the numbers of activated voxels in Broca's and Wernicke's area. Subjects with early exposure to L2 showed low variability in brain activation in all three languages, in the two early as well as the late learned language. In contrast, late multilinguals exhibited higher variability. Thus, cerebral representation of languages is linked to the age of L2 acquisition: early exposure to more than one language gives rise to a language processing network that is activated homogeneously by early and late learned languages, while the inhomogeneous activation in late multilinguals indicates more independent access to the multilingual repertoire. Early passive exposure to L2 results in the same low variance as active bilingual upbringing. Variability in local brain activity increases progressively from the simultaneous to late L2 exposure, indicating a gradual transition from the mode of early bilingual language representation to that of late ones.

1. Introduction

The organisation of languages in the bilingual or multilingual brain is of considerable interest to researchers in a variety of disciplines. The earliest attempts to investigate the neural basis of second language (L2) processing and its relationship to the first language (L1) suggested that different languages are represented in separate cerebral entities (Penfield & Roberts, 1959; see for review Paradis, 2000). With the introduction of neurofunctional imaging this notion has changed. PET- and fMRI-studies showed a very consistent regional pattern of activation in language relevant areas. First and second languages seem to share the same brain language system (Frenck-Mestre, Anton, Roth, Vaid, & Viallet, 2005; Hasegawa, Carpenter, & Just, 2002; Illes et al., 1999; Kovelman, Baler, & Petitto, 2008; Mahendra, Plante, Magloire, Milman, & Trouard, 2003). This is also the case in multilinguals: Vingerhoets et al. (2003) found predominantly overlapping regions of activation between three languages as did Briellmann et al. (2004) in quadrilingual subjects. These studies, thus, showed that all languages of an individual use a unitary language committed neural system, at any rate at the level of the BOLD-response (i.e. macroscopically and in a time frame of seconds).

Some studies reported at least partly separate representation of a bilingual speaker's languages. Differences in localisation between L1 and L2 were related to differences between languages with respect to proficiency and age of acquisition. Low proficiency in L2 resulted in variable activation of multiple additional brain regions (Chee, Hon, Lee, & Soon, 2001; Perani et al., 1998). With respect to the age of acquisition, Kim, Reklin, Lee, and Hirsch (1997) described

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that subjects who had learned their L2 in late adolescence activated spatially separated subfields in Broca's area but not in Wernicke's area, whereas early bilinguals showed overlapping activation for L1 and L2 in both areas. Segregated activation in late-onset L2-learners was also found in relation to differences in typology and prosody between the languages (Gandour et al., 2007; Jeong et al., 2007).

In bi- and multilingualism studies on the impact of the age of acquisition, the level of proficiency, the type of grammatical construction, and the amount of daily exposure to a language on regional brain activation, differences were generally detected in the *degree* but not in the regional localisation of activation in a consistent set of cortical areas (Perani & Abutalebi, 2005). Typically, in subjects with comparable levels of proficiency, late bilinguals had a higher amount of activation in L2 than L1 (Kovelman et al., 2008; Perani et al., 2003; Vingerhoets et al., 2003; Wartenburger et al., 2003). In contrast to most other studies, Mahendra et al. (2003) observed higher total activation in early bilinguals as compared to late bilinguals in both, word and sentence generation tasks. For subjects with low levels of proficiency, a larger BOLD-response was found (Briellmann et al., 2004; Hasegawa et al., 2002; Wartenburger et al., 2003). The higher workload needed for processing L2 seems to be responsible for the enhanced activation. Also, the amount of daily exposure to a language influences the extent of cerebral activation: the more extensive the exposure to the L2 was, the smaller were the differences between L1 and L2 (Perani et al., 2003).

Language development in the small child occurs in close association with the language varieties present in the environment and, thus, is open for several languages. It proceeds gradually (Kuhl, 2004) and in parallel with the development of the cerebral cortex (Sakai, 2005). Not yet settled is the issue whether and up to which age a critical time period for native-like acquisition of a L2 does exist. This might be due, in part, to the fact that different components of language have different critical periods (Kuhl, Tsao, & Liu, 2003; Scovel, 1988; Sebastián-Gallés, 2006). With respect to grammatical rules in syntax and morphology, numerous authors maintain that native-like performance is only attained if second language acquisition starts early, the latest at the age of 7 years (Johnson & Newport, 1989, 1991). On the other hand, a recent evaluation of data from 2.3 million immigrants from the 1990 U.S. Census shows that attainment of language skills in the L2 is linearly dependent on the age of immigration and the level of education (Hakuta, Bialystok, & Wiley, 2003), i.e. that a critical period in terms of an abrupt transition does not exist. A linear decline would argue against the concept of separate brain modules for native language acquisition and foreign language learning (Bialystok & Miller, 1999).

In this paper, we focus on the effect of the age of L2 acquisition on the degree of activation during language production in all three languages of trilingual subjects. We hypothesise that in highly proficient multilinguals the age of L2 acquisition (*Simultaneous*, *Covert Simultaneous*, i.e. without awareness of the exposure to a second language, *Sequential*, i.e. acquisition between 1 and 5 years, *Late*, i.e. learned after 9 years of age) has an influence on the cortical representation of the multilingual repertoire. Further, we allude to the question whether a critical time period for native-like representation of late learned languages can be detected.

There exists an extreme diversity of ways in which multilingual repertoires are built and work, from double L1-acquisition, from second (or third) language acquisition in social contexts by children and adult immigrants or from formal language tuition in the class room (Hamers & Blanc, 2000; Romaine, 1995). Under these circumstances a single subject approach would be appropriate. From a socio-cultural and socio-linguistic perspective, multilingualism is defined functionally—in the sense that a multilingual individual is able to adapt her and his language choice to the situation, independent from the competence. In fact, "perfect" competence is often not achieved. Tools for measuring functional multilingualism have been developed, from equilibrated to non-equilibrated forms, particularly by the experts of the Council of Europe (2001). This tool was used in the present study to determine the competency of our respondents in their languages.

In line with this, the language task employed in our study for functional imaging was a free narration task as described by Kim et al. (1997). This language production task does not involve any judgements on correctness. In the everyday use of the languages of a multilingual repertoire in a multilingual environment – as it is the case in the border city of Basel with 25% immigrants under its inhabitants and situated in Switzerland with its four official languages – not the correctness of language processing is of relevance, but language at the narrative and pragmatic level.

High in-between-subject variability was repeatedly found in language studies (Seghier et al., 2004; Xiong et al., 2000). This was also the case in the present study, resulting in blurring of the differences between L1, L2, and L3 in the group-wise analysis. We, thus, apply a single subject approach and carry out a within-subject analysis with a focus on the classical language areas Broca and Wernicke. By estimating the variance in activation in each individual for his/her three languages, we demonstrate that with increasing age of L2 exposure, variability increases.

2. Methods

2.1. Subjects

Forty-four healthy, multilingual subjects (average age: 28 years; range: 18–37 years; female/male ratio: 22/22), who were proficient in and used regularly at least three languages (Table 1), were recruited on a voluntary basis. To render our findings independent of the effect of particular languages, we included subjects with various combinations of languages. After being instructed about the experiment and about the fMRI scanning process, they gave their written, informed consent. The study was approved by the Ethics Committee of the University Hospital of Basel (Switzerland). All subjects included in this study were right-handed as verified by the outcome of the Edinburgh Handedness Inventory (Oldfield, 1971).

2.2. Linguistic data

All participants had successfully passed the requirements for academic education and spoke at least three languages on a level of medium to high proficiency (Table 1). The proficiency in the different languages was scaled by self-assessment, using the common European framework of reference of language proficiency (CERR, Council of Europe, 2001; North, 2000). The CERR provides a standard for comparing and self-assessing proficiency levels across very different languages and the different languages of a speaker. The scale ranges from A1 (break-through) to C2 (mastery) and refers to the five language skills: listening, reading, writing, monologic, and interactive speaking. The existence of a high correlation between self-assessment and rating based on external assessment of foreign language proficiency has been proved (Oscarsson, 1997), securing hence the validity and reliability of the self-assessment instrument.

Language biographies of all participants were gathered in in-depth interviews. This approach provides, among other aspects, detailed data on the age of acquisition of the various languages, the contexts of language exposure, language learning, and language usage (e.g. Franceschini, 2002; Franceschini & Zappatore, 2002; Zappatore, 2006). The analysis of each individual's language biography, both in content and form level (Lucius-Hoene & Depperman, 2002; Schütze, 1987), together with a contrastive analysis of the language biographies, led to the definition of the multilinguals' age and contexts of L2 acquisition and to their classification into four groups: (1) *Simultaneous* bilinguals, i.e. growing up in a bilingual family; (2) *Covert Simultaneous* bilinguals, i.e. growing up in a monolingual family whose language differed from that in the surrounding; (3) *Sequential* bilinguals (1–5 years); and (4) *Late* multilinguals. In this nomenclature, the term "bilingual" notifies those multilinguals who had acquired the L2 during early childhood. All bilinguals are "early multilinguals".

2.3. Experimental task

The experimental task consisted in a language production (silent free narration task) and a baseline condition in an externally triggered periodic block design adapted from Kim et al. (1997) and modified by Wattendorf et al. (2001). Baseline condition as well as silent narration task lasted 30 s each and alternated nine times per language. The three languages were tested in separate runs, i.e. one run in L1 with 9 activation blocks and, correspondingly, one run in L2 and one run in L3. The

Table 1
Language distribution and proficiency level in L1, L2, and L3 in all 44 multilinguals and categorisation into groups depending on the age of L2 acquisition.

Subject	Age of L2 acquisition	L1	L2	L3	Sex
1	Simultaneous	IT: C2	GE[a]: C2	EN: C2	W
2	Simultaneous	EN: C2	GE: C2	IT: B2	M
3	Simultaneous	HU: C2	GE: C2	EN: B1	W
4	Simultaneous	GE: C2	IT: C2	EN: C2	M
5	Simultaneous	FR: B2+	GE: C2	EN: C2	W
6	Simultaneous	SP: B2	CA: B1	GE: C2	M
7	Simultaneous	FI: C2	EN: C1	GE: C2	W
8	Simultaneous	SP: C2	CA: C2	GE: C2	M
9	Simultaneous	HU: C1	GE: C2	EN: B1	W
10	Simultaneous	GE: C2	EN: B2	FR: A2	W
11	Simultaneous	FR: C2	GE: C1	EN: B2+	M
12	Simultaneous	PO: B2	FR: C1	JP: A1	W
13	Simultaneous	GE: C2	IT: C1	EN: C1+	W
14	Simultaneous	GE: C2	IN: B1+	EN: C1	M
15[b]	Simultaneous	CA	SP	EN	W
16	Simultaneous	IT: C1	GE: B2+	FR: B1+	W
17	Covert simultaneous	SK: C2	GE: C2	EN: C1	M
18	Covert simultaneous	IT: C1	GE: C2	SP: B1+	M
19	Covert simultaneous	SLO: C2	GE: C2	EN: C1	W
20	Covert simultaneous	FR: C2	GE: C2	EN: B2	M
21	Covert simultaneous	BU: C2	RU: C1	FR: C1	W
22	Covert simultaneous	IT: C2	GE: C2	EN: B2	M
23	Covert simultaneous	GR: B1 +	GE: C2	SP: C1	M
24	Covert simultaneous	TU: C1	GE: C2	EN: B2+	W
25	1–5 years of age	GE: C2	FR: C2	EN: B1+	W
26	1–5 years of age	GE: C2	EN: C2	HE: B2+	W
27	1–5 years of age	SP: C1	IT: B2	GE: C2	M
28	1–5 years of age	GE: C2	EN: C1	FR: C2	M
29	1–5 years of age	FR: B2	GE: C1	EN: C2	M
30	1–5 years of age	GE: C2	EN: C1	FR: B1	M
31	1–5 years of age	SP: C2	GE: C2	EN: B1+	W
32	1–5 years of age	GE: B2+	FR: B2+	EN: B1+	M
33	Late	IT: C2	GE: B2	EN: B2	W
34	Late	FR: C2	GE: B2+	EN: B1+	M
35	Late	GE: C2	EN: C1	FR: C1	M
36	Late	GE: C2	EN: C2	FR: B2+	W
37	Late	FR: C2	EN: B2+	GE: C2	M
38[b]	Late	GE	FR	EN	W
39	Late	GE: C2	FR: B2	EN: B2	M
40	Late	GE: C2	FR: B2+	RU: B2+	W
41	Late	GE: C2	FR: C2	EN: C2	W
42	Late	GE: C2	EN: C2	IT: B2	W
43	Late	IT: C2	GE: B2+	FR: B2	M
44	Late	GE: C2	FR: B2	EN: B2	M

Our sample of multilinguals uses a variety of different languages with English, (Swiss) German, and French being represented most frequently. The great majority of the participants was highly proficient in more than two languages, and had reached at least medium proficiency level in their third language. As defined by the Common European Reference Framework for languages (CERR, Council of Europe, 2001; North, 2000), the levels of competence progress from A1 to C2. A1 and A2 refer to competence levels of the basic user, B1 and B2 to the independent user, and C1 and C2 to the proficient user. A2+, B2+, and C1+ are intermediate stages. BU: Bulgarian, CA: Catalan, EN: English, FI: Finish, FR: French, GE: (Swiss) German, GR: Greek, HE: Hebrew, HU: Hungarian, IN: Indonesian, IT: Italian, JP: Japanese, PO: Portuguese, RU: Russian, SK: Serbo-Croatian, SLO: Slovenian, SP: Spanish, TU: Turkish.

[a] GE refers to both varieties, Standard German and Swiss German, given the diglossic situation in the German speaking part of Switzerland.

[b] Drop outs.

sequence, in which L1, L2, and L3 were tested, was randomized over the whole cohort. During the silent narration task, subjects were asked to tell an imagined interlocutor what they had done the day before in the morning (stimuli presented visually with the help of a projector: rising sun), at midday (stimuli presented: sun in the zenith), and in the evening (stimuli presented: setting sun). The baseline condition (stimuli presented: small cross) was an attention task: the participants were required to join together thumb and forefinger of the dominant (right) hand when they perceived the scanning sound which occurred in intervals of 6 s. This task did not evoke activation in motor and premotor areas. Its purpose was to uphold and maintain the attention of the examinee without causing linguistic activity in the brain (Binder et al., 1999).

After the scanning session, subjects were required to retell their narration in the three languages for 2–3 min each. These tape records served as control for the content of the narration and for the level of fluency in the languages tested.

2.4. Image acquisition

Data acquisition was performed on a 1.5-T Magnetom VISION (Siemens, Erlangen, Germany) whole body MRI system. To restrict head movements and to limit motion artefacts, a standard head coil with adapted inset was used. For functional imaging, we applied an echo planar imaging sequence with a repetition time of 6 s, a flip angle of 90° and an echo time of 60 ms. The matrix size was 64×64 (FOV 200 mm × 200 mm) and 48 contiguous axial slices parallel to the AC–PC plane (3 mm slice thickness without gap) covered the entire brain resulting in a resolution of 3 mm × 3 mm × 3 mm. For all subjects, functional images were created for all three languages. In each language, 96 measurements were collected. The 96 measurements were composed of 6 prescans, the silent narration task and the control condition. A sagittal T1-weighted anatomical high-resolution data set was acquired subsequently to the functional images with an MP-RAGE sequence. The resolution of the anatomical images was 1 mm × 1 mm × 1 mm.

2.5. Image analysis

The analysis of the anatomical and functional data was performed using BrainVoyager QX (Brain Innovation, Maastricht, The Netherlands). Pre-processing the functional time series according to the standard parameters in BrainVoyager as described in detail elsewhere (Goebel, Esposito, & Formisano, 2006) included 3D motion correction, spatial filtering (Gaussian spatial filtering full width half maximum FWHM of 4 mm), and temporal smoothing with three cycles/point with a high-pass filter. The anatomical volume was realigned to the first functional volume. The realigned images were transformed into Talairach standard space (Tailarach & Tournoux, 1988).

At the first level, we analysed each of the 44 subjects separately in the framework of a fixed effect general linear model (GLM). This created individual main effects for all three languages of all 44 subjects. Each model was adjusted at the same statistical threshold of $p < 0.01$ (Bonferroni corrected) on the voxel level. At the second level, concerning the group analysis, we performed four separate GLM analyses for the four study groups, calculating the group average main effects for the different languages L1, L2, and L3. Given the sample size of the groups, we chose fixed effects GLMs ($p < 0.05$, Bonferroni corrected). The spatial extent threshold was 250 mm^3.

2.6. Analysis of activation size for L1, L2, and L3

Using the implemented Talairach standard brain atlas in BrainVoyager, we determined the size of significant activation clusters for each language in contrast to the baseline condition of each subject in Brodmann areas 22 (Wernicke's area) and 44 and 45 (subsumed as Broca's area) in the left hemisphere. Activated clusters that were not part of BA 22/44/45 were not included in this analysis. We determined the volume of suprathreshold activation for each subject in each language, i.e. 44 (subjects) × 3 (languages) × 2 ROIs (Wernicke's area and Broca's area). Next, we calculated the individual variance in activation size between L1, L2, and L3 *within-subjects* for each subject independently for Broca's and Wernicke's area as follows:

$$s^2 = \frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)};$$

where n = number of languages and x = number of active voxels.

Consequently, we obtained for each area of interest a single individual parameter that reflects the *within-subject* variation in brain activation between the different languages; we denominate this parameter *individual variance*. We compared this individual variance between groups separately for each area using the non-parametric Kruskal–Wallis one-way analysis of variance for multiple samples. Post hoc, pair-wise comparison was done using Mann–Whitney *U*-test.

3. Results

3.1. Language biographies allow categorisation of multilinguals depending on context and age of L2 acquisition

The individual and contrastive analysis of the language biographies showed that the subjects differed with respect to age and contexts of second language acquisition, but also in the quantity and quality of the exposure to that second language. Accordingly, they were classified into four distinctive groups.

- *Simultaneous* bilinguals: 16 subjects (10 female and 6 male) grew up in a bilingual environment. Since birth they had contact with persons in their close environment who regularly interacted with the child in two languages.
- *Covert Simultaneous* bilinguals: 8 subjects (3 female and 5 male) were born into a monolingual family, whose language differed

from the one spoken in the surrounding context. While having only little direct interactive contact and on an irregular base with this second extra-familiar language, they were nonetheless exposed to it since birth, leading to a passive competence that was later on activated by an increase in input and direct interaction (De Houwer, 2005; Quay, 2001).

- *Sequential* bilinguals (age of L2 acquisition: 1–5 years): 8 subjects (3 female and 5 male) were born into a monolingual family speaking the language of their surrounding environment. Because of the emigration of their family to a country in which a different language was spoken, they acquired their second language between the age of one and five years.
- *Late* multilinguals: Twelve subjects (6 female and 6 male) were born into a monolingual family speaking the language of their surrounding environment. These subjects learned their first foreign language at school, i.e. at the age of nine years or older.

All subjects had acquired a third language at the age of nine years or later at school and, thus, were multilinguals. The age of L3 acquisition was comparable over our whole population of subjects, i.e. in all four groups. Bilinguals acquired the L2 early in their childhood and can be subsumed under the term “early multilinguals” contrasting them with the “late multilinguals” who started with their acquisition of L2 only late in their childhood.

First, second, and third language were determined according to their chronological order of acquisition, with the exception of the group of *Simultaneous* bilinguals, in which the dominant language in early childhood was defined as the L1 and the less dominant language as L2. However, language dominance could shift over the years, leading in single cases to a higher proficiency in L2 than in L1 (see Table 1).

According to the self-assessment, the majority of subjects had reached a high level of proficiency in their first language(s) and

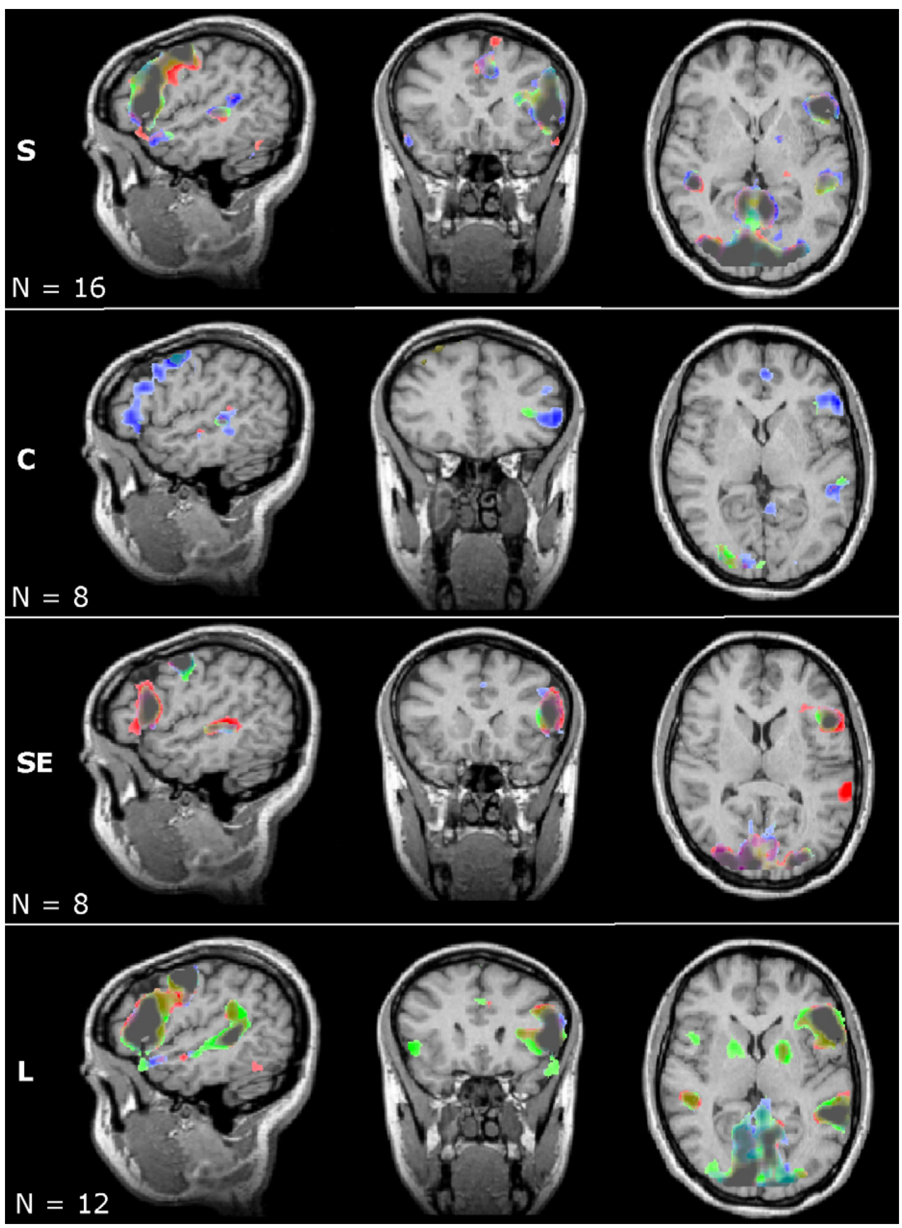

Fig. 1. Group-specific effects during language production in L1 (blue), L2 (green), and L3 (red). Dark grey areas are due to the colouring function and mean a complete overlap in activation elicited by the three languages. Pictures in the sagittal (1st column), coronal (2nd column), and horizontal plane (3rd column) were taken at the activation focus in Broca's area. In Talairach coordinates, this is for the *Simultaneous* group (S): −50/18/3, for the *Covert Simultaneous* group (C): −50/29/5, for the *Sequential* group (SE): −50/18/11, and for the *Late* group (L): −50/22/6.

medium to high proficiency in their second and third language (Table 1). The proficiency level in all three languages is comparable among the four groups, with the group of *Late* multilinguals scoring slightly below the other three groups in their L2. There were no significant differences in language proficiency between the age groups.

3.2. Regional activation pattern shows no major differences between age groups and languages

All four age groups showed activation in Broca's area and in superior temporal sulcus encompassing Wernicke's area. In addition, activation was found in left prefrontal (BA 9 and 10) and premotor cortex (BA 6). Furthermore, visual areas (BA 17 and 18) were showing bilateral activation. On the medial plane of the brain, supplementary motor cortex (SMA) and anterior parts of the cingulated gyrus (BA 24, 32) exhibited activation (not shown).

Concerning differences between languages and between groups at the descriptive level (Fig. 1), the following can be noted: *Simultaneous* bilinguals show overlap in the activation for all three languages and bilateral activation in Wernicke's area. In contrast, the group of *Covert Simultaneous* bilinguals exhibit lateralised activation which is stronger in their L1 than in L2 and L3. The *Sequential* bilinguals' activation is of comparable degree in all three languages but more focused than in the simultaneous group and left sided. The *Late* group presented slightly stronger activation for their late learned L2 and L3 with a tendency for bilateral activation in Broca's and Wernicke's area. In addition, this group exhibited bilateral activity in the basal ganglia.

Taken together, only minor variation in activation was found in these areas both between L1, L2, and L3 as well as between age groups: in fact a substantial overlap in degree and extension of activation was evident in this group analysis.

3.3. Age of L2 acquisition correlates with individual variance of activation in Broca's and Wernicke's area

The individual subject analysis and the within-subject analysis of his/her three languages revealed a high variability in the degree of activation. In particular, not all subjects exhibited activation in all regions mentioned, and in all of their languages, also not in Broca's and Wernicke's areas. In the three groups of "early multilinguals", several subjects showed no activation at all at the threshold selected while all *Late* multilinguals exhibited activation in at least one of their languages. This was in all cases the late learned L2 or L3. Differences in mean number of activated voxels in Broca's area (Fig. 2) or Wernicke's area (not shown) were not significant, neither between L1, L2, and L3 in the group of *Late* multilinguals nor compared to the *Simultaneous* bilinguals or to the three groups of "early multilinguals".

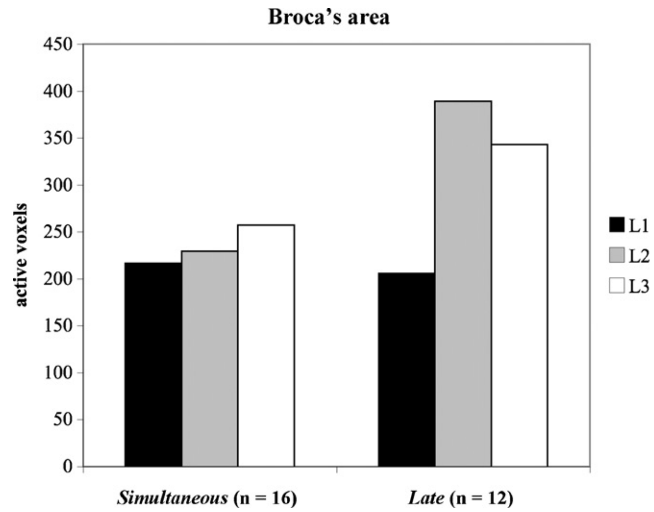

Fig. 2. A comparison of the mean number of activated voxels in the group of *Simultaneous* bilinguals with the group of *Late* multilinguals independently for L1, L2, and L3 is shown here in Broca's area exemplarily. *Simultaneous* bilinguals activate comparable numbers of voxels in all three languages, also the late learned L3. *Late* multilinguals display in L1 a similar degree of activation as the *Simultaneous* ones, but show in the late acquired L2 and L3 higher activation. These differences are not significant, neither between groups nor between languages.

The variation in the number of activated voxels elicited by the 3 languages in Broca's and Wernicke's area, however, is related to the age of L2 acquisition. For Broca's area, this is shown graphically in Fig. 3. In the three groups of "early multilinguals", eleven subjects did not display any activation in Broca's area in any of the three languages, while others show activation in one or more of their languages. In contrast, all *Late* multilinguals exhibit activation in at least one of their late languages. Nonetheless, the highest numbers of activated voxels is found in one *Simultaneous* bilingual and in one *Late* multilingual (i.e. subjects 16 and 44). Thus, the range of activated voxels found in each individual does not relate to the mean value of voxels activated in his/her three languages but depends on

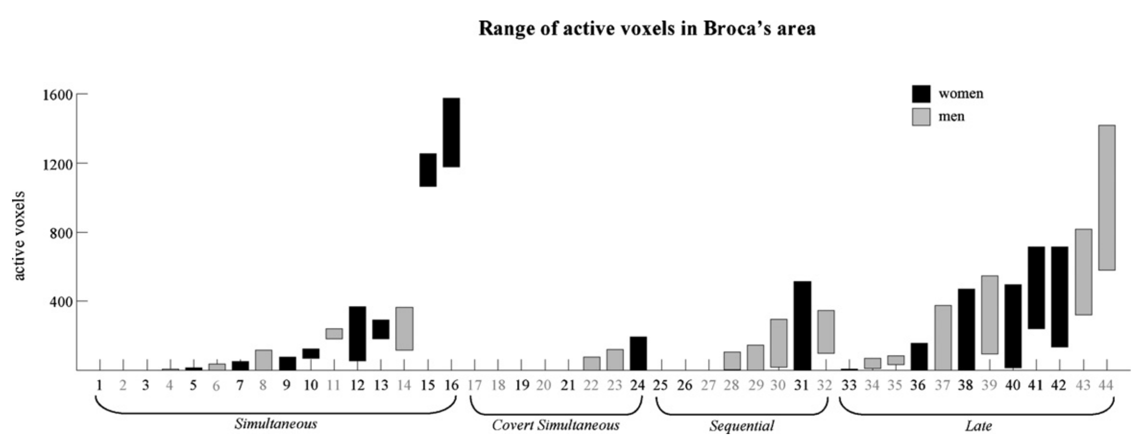

Fig. 3. Range of active voxels elicited by L1, L2, and L3 in Broca's area in each individual subject. Data are arranged in increasing order of the mean of activation for the four groups of subjects. Males are indicated by the grey bars and light numbers, females by the black bars and bold numbers. No obvious correlation can be found between the degree of activation and the age of L2 acquisition: In the *Simultaneous* and in the *Late* group, in particular, some test persons display low, other very high activation. The variance, however, is associated with the age of L2 acquisition: In subjects belonging to the *Simultaneous* group as well as in the *Covert Simultaneous* ones, the range between the lowest and the highest activation of the three languages is rather small; i.e. the bars are short. The voxel counts in L1, L2, and L3 of individuals from the *Sequential* group and even more so in *Late* multilingual subjects differ to a higher degree: the bars are longer.

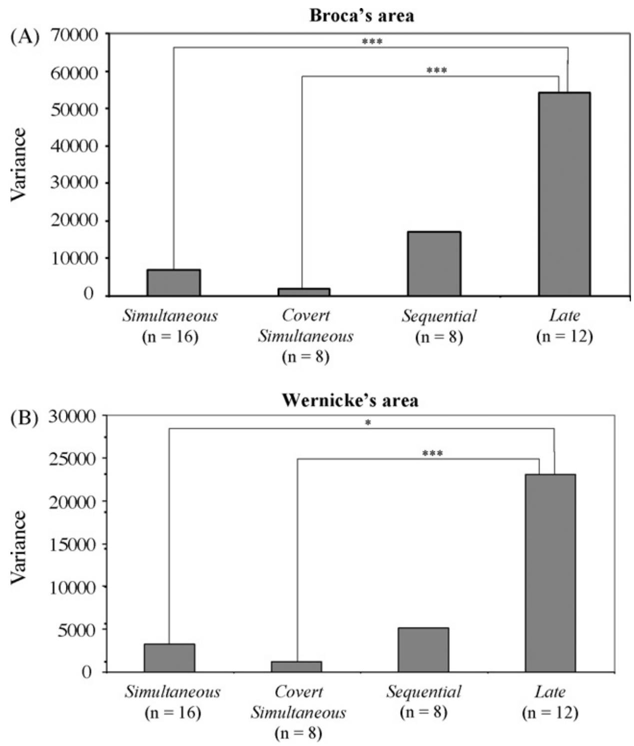

Fig. 4. Variance in the extent of activation elicited by the L1, L2, and L3 in Broca's (A) and in Wernicke's area (B) given as mean value of the single groups. While *Simultaneous* and *Covert Simultaneous* bilingual show low variability, the *Sequential* group, and in particular the group of *Late* multilinguals show very high variability. Significant differences are indicated by $^{*}p < 0.05$ or $^{***}p < 0.005$.

the age of L2 exposure. In other words, variation tends to be lower in the group of *Simultaneous* bilinguals than in *Late* multilinguals, although it is well possible that the absolute amount of active voxels is the same or higher in single *Simultaneous* subjects. *Covert Simultaneous* subjects exhibit low individual activation and low variation therein, and *Sequential* bilinguals lie in between the *Simultaneous* and the *Late* multilinguals. The individual variation in proficiency did not correlate with the variability in activation (compare Table 1 and Fig. 3). Also, sex/gender was of no influence on this parameter.

Fig. 3 shows, in addition, that the differences in brain activation among individuals are much higher than the variability of activation for the three languages in one person, i.e. intra-group variation is higher than the differences elicited by the production of early or late languages in the single individual.

To avoid interference of the high in-between-subject variability, calculation was performed using as measure of variability – instead of absolute voxel counts – the variance in voxel counts between L1, L2, and L3 of single individuals. In *Simultaneous* bilinguals, the mean individual variance in Broca's area is $s^2 = 7015$ (range: 0–46,657). It is lower in *Covert Simultaneous* bilinguals with 1952 (range: 0–9806), but higher in the *Sequential* bilinguals with 17,241 (range: 0–87,894). The differences among these three groups of bilinguals are not statistically significant (Fig. 4A). In contrast, *Late* multilinguals exhibit much higher individual variance: the mean variability is 54,273 (range: 5.3–186,840), and this is significantly different compared to the *Simultaneous* ($p < 0.0050$) and *Covert Simultaneous* ($p < 0.0039$) bilinguals, but not compared to the *Sequential* bilinguals (Fig. 4A). When omitting the individuals without any activation in their three languages from the calculation, differences between the group of *Simultaneous* and *Late* multilinguals remain significant ($p < 0.021$).

In Wernicke's area, individual variance is lower, in general. Again, as in Broca's area, *Simultaneous* bilinguals show low variability with a mean of $s^2 = 3221$ (range: 0–27,724), and *Covert Simultaneous* bilinguals even lower with 1263 (range: 0–9733). The variability in *Late* multilinguals amounts to 23,037 (range: 0.3–79,954). Two bilingual groups show a significant difference to the high variation in the *Late* group with $p < 0.039$ for the *Simultaneous* and $p < 0.0039$ for the *Covert Simultaneous* group. The *Sequential* bilinguals exhibit a moderate variance with a mean of 5121 (range: 0–32,601) which is neither significant versus the *Simultaneous* and *Covert Simultaneous* bilinguals nor versus the *Late* multilinguals (Fig. 4B).

3.4. Typological differences between acquired languages have no impact on the variability in activation

To control for a possible effect of the type of languages within the individual and in between groups, the number of active voxels in Broca's and Wernicke's area was compared between subjects speaking the same language(s). Variance did not differ between subjects using the same languages and those using different languages (data not shown). Further, it was searched for differences in activation between "early multilinguals" using closely related L1 and L2 (e.g. Spanish/Catalan; German/English) and "early multilinguals" speaking distantly related languages (e.g. Hungarian/German, Turkish/German, see Table 1). There was no different pattern between these groups, neither with respect to the number of voxels activated, nor the variance in activation in Broca's and Wernicke's area (data not shown).

4. Discussion

The data presented show that the individual variance in the extent of local cerebral activation during language production is modulated by the age of L2 acquisition (and not by the relatedness of the languages). With growing age of L2 acquisition, the individual variation of local cerebral activation during the production of different languages of a multilingual repertoire is increased in the two main language areas, Broca and Wernicke. Further, our data show that early covert exposure to a L2 results in a similar effect on variance as overt bilingual upbringing is doing.

Before discussing the implications of our results, there are methodological and technical issues in the set up of our study, which could draw criticism: the language proficiency of our subjects and, in line with this, the test condition in the fMRI session.

4.1. Language proficiency

Most forms of (second or third) language acquisition do not lead to a "perfect" competence. There are good reasons why educational language policy makers begin to question the demand that students have to acquire native-like competences in modern languages at school (Lüdi, 1998). Therefore, and consequent to the wide range of languages spoken by our subjects, the level of proficiency in the three languages of our individuals was evaluated by a standardised self-assessment. The self-assessment grid of the CERR has been standardised and evaluated in a number of different settings. Objections due to validity of self-assessment can be refused: research revealed an overall high correlation between self-assessment results and ratings based on a variety of external criteria (i.e. Oscarsson, 1984, 1997; Ross, 1998).

The major focus of our research is the everyday use of the languages of a multilingual repertoire in a multilingual environment. From the viewpoint of functional multilingualism, not the correct use of a single component of language processing or metalinguistic knowledge of correctness is of relevance, but language at the narrative and pragmatic level as it is used in everyday life. Therefore, the test condition employed consisted of a periodic block design alternating between a silent narration task and a control condition as first applied by Kim et al. (1997) and further developed by us (Wattendorf et al., 2001). In the silent narration task, test persons reported about the activities they had performed the day before at a given time of the day. It is an advantage of this task design that it is close to the reality of spoken language.

Although compatible with and mirroring the situation in multilingual urban environment, the used test design has two drawbacks: First, the cooperation of the individual subjects is not controlled, since behavioural data were not be recorded during scanning procedure. Second, we do not know which events the subjects narrated and whether they were accompanied by strong emotions. The subjects, however, were required to record their narration in the three languages after the scanning session, offering a degree of control.

4.2. Regional activation pattern elicited by early and late learned languages

Up to date, most imaging studies showed regional brain activation in a consistent pattern independent of the tested language (i.e. Klein et al., 2006; Perani et al., 2003). Our present study supports this finding: a similar pattern of activation was recognisable in all three languages spoken by a single test person. Consequently, the results suggest that there is considerable overlap in the cortical substrate which supports internal speech in different languages.

Brain areas showing activation in this study were BA 44, 45, 22, 6, 9, 10, 24, and 32, especially in the left, but partially in the right hemisphere as well. They comply with the areas reported in several other comparable studies. In quadrilinguals (Briellmann et al., 2004) and in trilinguals (Vingerhoets et al., 2003) word generation results in overlapping activation in Broca's area and superior temporal gyrus. The two simultaneous quadrilinguals in Briellmann's study exhibit a similar degree of activation, i.e. a low variance in activation, whereas in sequentials activity is lowest in L1 and highest in L4.

Late multilinguals tended to show more activity in L2 and L3 than in their L1. These data confirm the findings of previous studies: Vingerhoets et al. (2003) examining high proficient late multilinguals showed that their test persons had a higher amount of activation in L2 and L3 than in L1. Wartenburger et al. (2003) examining low and high proficient bilinguals, reported that during grammatical processing their late bilinguals – independent of their level of proficiency – displayed more extensive activation in L2 in Broca's region and subcortical structures. The tendency to enhanced activation in *Late* multilinguals may indicate an increase in the workload which is required to process late learned languages, possibly due to a lower degree of training compared to bilinguals: In subjects who learned their first two languages early in their childhood, processing of all languages – including the later learned L3 – requires a comparable workload. This suggests a condition of constant training in the use of different languages.

4.3. High variability in the individual degree of activation

As in other fMRI studies (i.e. Feredoes, Tononi, & Postle, 2007; Seghier et al., 2004; Xiong et al., 2000), the extent of activation and the detailed subregional localisation in single brain areas displayed a high in-between-subject variability. It ranged from no activation at all to a massive activation in the ROIs.

In the three groups of "early multilinguals", the degree of activation in Broca's area tended to be low. In particular, the number of individuals showing no significant activation in all three languages was high (see Fig. 3). The low degree of activity in some bilinguals might be an indicator that they are well trained in using different languages. Training results in specific changes in task-related brain activity with decreased activity after training in the majority of the activated regions (Erickson et al., 2007). The authors suggest that training reduces differences between conditions (e.g., between two tasks) and that brain activity associated with performing these tasks converges over time and practice. This effect is obviously also present in subjects growing up in an environment where the language differs from the one spoken in the family: *Covert Simultaneous* subjects who were unaware of the exposure to a second language show the same results as the *Simultaneous* subjects. In fact, linguistic studies have shown that "passive" exposure to other languages during childhood can lead to an unfocussed form of language learning and to a form of competence that can be reactivated at later stages if necessary (Ellis, 1995; Franceschini, 1996, 1999, 2003).

Due to the high inter-subject variability – mostly higher than the intra-subject differences of L1, L2, and L3, a comparison of the absolute voxel counts for L1, L2, and L3 across groups is not feasible: the differences within the single subjects are at risk to disappear in this approach. We, therefore, determined the variance between the three languages in every single individual and performed the group analysis only at the level of the calculated variance of each subject. Thereby we did not lose the information of individual differences within the single test person.

4.4. In major language areas variance of activation correlates with age of L2 exposure

In Broca's area and Wernicke's area, both the *Simultaneous* and the *Covert Simultaneous* bilinguals exhibit low variability in the degree of activation in the three languages. It is larger in the *Sequential* bilinguals and even more so in the *Late* multilinguals. We propose that the low degree of variability or, in other words, the homogenous activation in "early multilinguals" – independently of the language used – indicates that early exposure to two languages results in the formation of a language processing system that is able to handle all languages acquired, including late learned languages. *Late* multilinguals, in contrast, show much more variability; the different languages cause an inhomogeneous activation. Apparently, monolingual upbringing results in a language network which is not able to accommodate late learned languages to the same degree as it is the case in "early multilinguals".

4.5. Not a critical time period but a gradual decline for native-like representation of late learned languages

Linguistic abilities seem to be sensitive to the age of exposure to a second language. The understanding of these age effects is complicated by the fact that the different components of language have different critical periods. In particular, adults rarely attain a perfect phonological performance although they have the potential for perfect lexical and syntactic acquisition of a second language (Scovel, 1988). The studies of Kuhl et al. (2003) and Sebastián-Gallés (2006) demonstrated that while very young infants are able to perceive all human-language contrasts, between 6 and 12 months they show a decline in perception of non-native sounds and simultaneously an improvement in the perception of native sounds.

The results of our study indicate that variance in representation of a multilingual repertoire increases gradually with the age of L2 acquisition. Looking at the group of *Sequential* bilinguals, the variances of the single subjects – and not the mean of the number of activated voxels in the whole group – tend to be higher than in the groups of *Simultaneous* and *Covert Simultaneous* bilinguals. The data suggests a gradual change from the uniform representation of several languages in "early multilinguals" to the more inhomogeneous representation in "late multilinguals". Our results agree with the findings of Bialystok and Hakuta (1994) as well as of Hakuta et al. (2003). They reported a linear relationship between the age of second language acquisition and performance in language tasks.

5. Conclusion

Our findings indicate that the age of L2 acquisition causes differences in the cortical representation of a multilingual repertoire. With increasing age of exposure to a second language, access to a common network for language processing is gradually decreasing, resulting in a more variable activation.

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