Second Language Research

http://slr.sagepub.com

Measuring second language proficiency with EEG synchronization: how functional cortical networks and hemispheric involvement differ as a function of proficiency level in second language speakers

Susanne Reiterer, Ernesto Pereda and Joydeep Bhattacharya

Second Language Research 2009; 25; 77
DOI: 10.1177/0267658308098997

Published by:
SAGE
http://www.sagepublications.com

Second Language Research 25,1 (2009); pp. 77–106

Measuring second language proficiency with EEG synchronization: how functional cortical networks and hemispheric involvement differ as a function of proficiency level in second language speakers

Susanne Reiterer *Universities of Tübingen and Stuttgart,*
Ernesto Pereda *University of La Laguna, Tenerife* and
Joydeep Bhattacharya *Goldsmiths College, University of London and Austrian Academy of Sciences*

Received April 2007; revised October 2007; accepted January 2008

This article examines the question of whether university-based high-level foreign language and linguistic training can influence brain activation and whether different L2 proficiency groups have different brain activation in terms of lateralization and hemispheric involvement. The traditional and prevailing theory of hemispheric involvement in bilingual language processing states that bilingual and second language processing is always at least in some form connected to the right hemisphere (RH), when compared to monolingual first language processing, the classical left-hemispheric language-processing domain. A widely held specification of this traditional theory claims that especially bilinguals or second language learners in their initial phases and/or bilinguals with poor fluency and less experience rely more on RH areas when processing their L2. We investigated this neurolinguistic hypothesis with differently proficient Austrian learners of English as a second language. Two groups of L2 speakers (all Austrian German native speakers), differing in their L2 (English) language performance, were recorded on electroencephalography (EEG) during the processing of spoken English language. A short comprehension interview followed each task. The 'high proficiency group' consisted of English language

Address for correspondence: Susanne Reiterer, Department of Neuro-Radiology, University of Tübingen, Hoppe Seyler Strasse 3, 72076 Tübingen, Germany; email: Susanne.Reiterer@med.uni-tuebingen.de

10.1177/0267658308098997

students who were about to complete their master's degree for English language and linguistics, while the 'low proficiency group' was composed of non-language students who had only school level performance and less training in English. The age of onset of L2 learning was kept constant: 9 years for both groups. To look for cooperative network activity in the brain, EEG coherence and synchronization measures were analysed for a high EEG frequency range (gamma band). Results showed the most significant group differences in synchronization patterns within the lower gamma frequency range, with more RH involvement (extensive right-hemisphere networks) for the low proficiency group, especially when processing their L2. The results can be interpreted in favour of RH theories of second language processing since, once again, we found evidence of more RH involvement in (late) second language learners with less experience and less training in the L2. The study shows that second language training (and resulting proficiency) and/or differences in ability or state of linguistic alertness can be made visible by brain imaging using newly developed EEG-synchronization techniques as a measure.

Keywords: EEG coherence, EEG synchronization, gamma band, cortical networks, bilinguals, second language acquisition, proficiency level, training, exposure, lateralization, right hemisphere, left hemisphere

I Introduction

Our study followed a twofold aim: we searched for a right-sided bias in hemispheric activation within a special group of second language speakers (low proficiency level) and wanted to know whether this special activation assumes the form of a more expanded network and can be made visible with a newly developed method of signal analysis – phase synchronization estimation applied to the electroencephalography (EEG) gamma band – only recently used in brain imaging research (see, for example, Pereda *et al.*, 2005).

1 Gamma band in language studies

A lot of gamma-band synchronization studies in other domains than language have already been conducted (Bhattacharya *et al.*, 2003; Fell *et al.*, 2003; Bhattacharya and Petsche, 2005a; 2005b) and found that the gamma range, or generally high frequency EEG ranges, reflect high cognitive phenomena requiring sophisticated integrative thinking processes. In the domain of first language processing, the gamma range has already advanced our knowledge about network activity during semantic and syntactic processing and shown that it is a fruitful endeavour to scrutinize this frequency range for the sake of detecting sophisticated language processes (Simos *et al.*, 2002; Micheloyannis *et al.*, 2003; Ford *et al.*, 2005; Hagoort, 2005; Ihara and Kakigi, 2006). Gamma-band analyses in second language processing studies to date do not exist. From the results of previous analyses of our study on EEG coherence (Reiterer *et al.*, 2005a; 2005b) analysing other frequency ranges than gamma (delta, theta, alpha and beta), we learned that EEG coherence is also a valuable tool when it comes to investigating differences between more or less proficient second language speakers. We detected significant differences in network activity between our high and low proficiency groups, especially within the alpha frequency range (lower alpha; see Reiterer *et al.*, 2005b). The coherence differences seen in the alpha band did not, however, occur between the languages (between L1 and L2), but between the two groups regardless of the language of the task. This means that the low proficiency group generally displayed higher coherence and wider networks than the high proficiency group during all language conditions. We could also observe that this cooperative activity reflected in the alpha range involved more extensively the RH (in each language condition, L1, L2) in the low proficiency group, whereas the high proficiency group consistently showed a more focalized coherence pattern almost exclusively over the left hemisphere (LH), and here especially within the temporo-parietal areas. We thus already observed a tendency towards an involvement of RH networks when analysing other frequency ranges; however, the results were not language-driven (language specific to either L1 or L2), but group driven (more coherence in general, involving to a large extent the RH for the lower proficiency group). In the present work we wanted to analyse the higher frequency components of our EEG broadband recordings (gamma) to look for language specific effects, because different frequency ranges are assumed to reflect different aspects of cognition.

2 Second language or bilingual processing and the right hemisphere

According to a prevailing and classical hypothesis – formulated by Obler (1981) and Galloway and Krashen (1980) – the initial stages of adult second language acquisition recapitulate children's right-to-left hemispheric shift in relative hemispheric dominance when acquiring a mother tongue. This goes back to Lenneberg's (1967) famous lateralization theory in which he proposes a critical age or 'sensitive periods' for language acquisition. This 'shift hypothesis' or 'equipotentiality theory' assumes that, initially, both hemispheres are equally able to sustain language functions, with lateralization towards the left hemisphere occurring gradually in the course of development. This was inspired by findings that even despite hemispherectomy of the entire left hemisphere, children can develop normal language functions (Vargha-Khadem *et al.*, 1994); however, the older they are at the time of the left-hemispheric lesion, the more problems they will experience in regaining their language skills. Theories in line with hemispheric shifts for language functions or assuming critical periods have been very successful until now, but one has to emphasize that they are not the only theories. A powerful stream of similar hypotheses put forth the viewpoint that the LH is simply better equipped by evolution from the ontogenetic beginning (birth or conception) onwards for language processing; for example, because it develops faster in ontogenesis (Corballis, 1989; 1992), or because it is better equipped for the processing of fast changing acoustic stimuli (Johnsrude *et al.*, 1997). This theoretical viewpoint (termed, for example, 'irreversible determinism' by Woods and Carey, 1979) differs from the theory outlined above only to the extent that it argues for a pre-determined specialization for the LH, not for a shift after a certain period of time of 'equipotentiality'. These two basic viewpoints are sometimes hard to discriminate, and many newer hypotheses or viewpoints (within the neuroscience of bilingualism and SLA) have merged them and show features of both.[1]

In line with more deterministic arguments, Paradis (1994) states, for example, that during their first years of language acquisition monolingual children have to rely on right-hemisphere-based pragmatic processing

---

[1] In fact, the confrontation of the concept of 'regional specialization' (or modularity of mind/brain) vs. the concept of 'equipotentiality' of function in the brain is such a basic one in the neurosciences that it remains in itself a major, disputed issue (Calvin, 1998; Rakic, 2006).

(a domain of the right hemisphere in contrast to fast phonetic or grammatical processing) in order to derive an interpretation for utterances in that language whose automatic linguistic competence has not yet been fully internalized. However, within the field of bilingual processing, shift hypotheses (initial equipotentiality) have been more often reported, or were at least stronger in the beginnings of neurolinguistic studies about second language processing. The model by Obler (1981), mentioned above, is sometimes also referred to as the 'stage hypothesis' in second language acquisition research. According to this model, the right hemisphere's relative dominant functioning during the initial encounter of novel stimuli, such as foreign orthography and semantics, would be advantageous (Gordon and Carmon, 1976; Hardyck *et al.*, 1980). For example, the right hemisphere would have a pre-eminence over the left hemisphere in the processing of foreign tonal patterns and intonation as well as emotional tone (Galloway and Scarcella, 1982). Obler's model implies increased involvement of the left hemisphere during later stages of the learning process, when grammatical sophistication is gained. This may occur at a time when a basic vocabulary of novel words must be arranged in sentence sequences according to foreign grammatical rules. Werner (Werner, 1957; Werner and Kaplan, 1963), with his concept of microgenesis, argued that learning in adults proceeds from perceptually bound or syncretic modes of information processing to more discrete and more strategically cognitive approaches during relatively short periods of time. Werner – like Obler (1981) and Galloway and Krashen (1980) – argued that developmentally this shift takes time, but that in the adult this perception-to-cognition shift occurs more rapidly. Even though it is not a hemispheric theory *per se*, it suggests that learning styles and strategies may change during initial exposure to information which may be different from later, more grammatical strategies. If Obler's model is correct, then one would expect to see greater right-hemisphere activation during the early stages of adult second language acquisition, e.g. in the first years of learning (if instruction is not very intense). This predominance ought to decline during later stages with increased grammatical knowledge. Also, left-hemisphere activation for the same time and skill progression would either increase or remain the same. This is the case since students in a foreign language class are engaging left-hemisphere processes during language learning activities. Finally, a corollary of Obler's model is a relationship between increased hours of experience in second language acquisition and greater left-hemisphere involvement. Conversely, one would expect right-hemisphere dominance to be associated with limited experience and proficiency level in second language learning. Equally important, Obler's hypothesis is also confirmed by the finding that past experience with foreign languages was associated with left-hemisphere activation, or that right-hemisphere activation is associated with less exposure to second language learning. Although this 'RH hypothesis' of either initial or less experienced second language speakers is still debated controversially and has been heavily criticized, mainly on the grounds of methodological problems (Paradis, 2003), a number of recent studies continue to substantiate it (e.g. Dehaene *et al.*, 1997; Calabrese *et al.*, 2001; Chee *et al.*, 2001; Evans *et al.*, 2002; Ding *et al.*, 2003).

3 Rationale of the study

We hypothesized that lower proficiency L2 speakers would display more RH network activity, especially during their L2 processing, in comparison to higher proficiency L2 speakers, who should, according to the traditional view, rely more extensively on LH networks due to their higher levels of automatic language command. Furthermore, we wanted to explore for the first time the usefulness of EEG synchronization measures, especially in the gamma band, for the investigation of subtle differences in strategies of differently proficient second language speakers.

II Materials and methods

1 Participants

We compared two groups of differentially proficient second language speakers (L2 = English), which differed in their proficiency levels due to extensive training. The participants in the 'high proficiency group' (HP) were university language students studying English language and linguistics for a master's degree. They were all at an advanced level or in the final year of their studies (5–6 years completed). Their level of English proficiency was uniformly 'very good', as rated by a certified English language teacher according to oral fluency test interviews.

Most of the participants in the high proficiency group additionally studied a second foreign language (i.e., an L3) like French, Italian or Spanish, or general linguistics. The average amount of informal exposure to the second language was 10 months (this is based on a questionnaire in which we asked participants for the average amount of time they had spent abroad in an English-speaking country). The participants in the 'low proficiency group' (LP) were university students of various disciplines other than language. They displayed medium second language skills for English, sufficient to pass their school leaving exams at the age 18, but not developed any further. They were able to lead a conversation in English that required basic language skills, but their speech output was full of grammatical errors (characterized by bad pronunciation with a typical foreign accent), and lexical access was slowed down and resulted in longer speech pauses, so that the final performance can be described as non-fluent speech. The mean amount of informal exposure (i.e. the time spent abroad in an English-speaking country) was 5 weeks. With regard to the variety of English (i.e. the country where they had most of their informal language exposure), the two groups were homogeneous. There was no group difference or bias regarding the location (British, American or other English-speaking country) where the participants had spent some time abroad.

We controlled the following variables. Age of onset of L2 learning was kept constant. The average age of onset of L2 was 9 years (s.d. = 1 year) and was matched between the two groups. Gender and handedness: Both groups consisted of each 19 right-handed female students with native language German (language variety: Austrian German). It is important to control for the gender variable, because claims have been made (e.g. Sommer *et al.*, 2004; Clements *et al.*, 2006) that females and males have differential brain lateralization, in particular for lateralization of language functions. It is even more important to control the variable of handedness, because the general empirically accumulated assumption states that approximately 90–95% of right-handed people have their major language-related areas in the left hemisphere, whereas only up to 70% of left-handers show this usual pattern. Left-handers tend to display alternative distribution patterns of brain areas dedicated to language (e.g. including more RH or bilateral distribution; see also Jansen *et al.*, 2007). Age, education and socialization: Mean age was 24 years (s.d. was 2.3 years in the HP group and 2.7 years in the LP group respectively) in both groups, and all participants had similar social (middle class), educational (university students) and cultural (living in Vienna) background. They markedly differed from each other mainly in the amount of second language experience and training they had been exposed to. The difference in countable formal education in English language was approximately 6 years. Summarizing, the differences lay in their linguistic experience and knowledge, hence, in their proficiency level in English as their L2.

2 Stimulus material

We employed a listening-comprehension / discourse-processing paradigm using blocks of coherent radio news (spoken auditory speech input) as stimuli. Three blocks of 2.0–3.2 min sequences of spoken speech in L2 English (balanced for the two main variants of English: British and American English) and L1 German were auditorily presented over earphones in randomized order, equalling a total time of approximately 30 mins of pure stimulus presentation time. The cerebral organization of language at the word and sentence level has been investigated extensively with PET, fMRI and event-related potential studies, but much less research has to date been carried out on the processing of coherent language at the discourse level, where language occurs in its natural context (i.e. where phonetic, syntactic, semantic and pragmatic aspects of language are integrated). The whole recording session took approximately 3 hours in total for each participant, including electrode placement, explanation of the procedure, personal questionnaires, a familiarization task and interruptions for answering detailed comprehension questions performed by short oral interviews with the experimenter after each listening task in the recording room. In these short interviews, after each task, six behavioural reaction parameters were explored with a guided behavioural questionnaire, comprising (1) actual text comprehension, (2) subjective text comprehension, (3) self-reported attention, (4) cognitive work-load, (5) sympathy for the speaker voice and (6) interest in the subject matter of the radio contribution.

3 Data recording

a Recording data: EEG signals were recorded during L1 and L2 processing in a quiet, dimly-lit sound-proof experimental room equipped with a comfortable armchair. Nineteen gold-disc electrodes, carefully attached to the scalp with adhesive electrode cream, were positioned according to the international 10/20 System (Jasper, 1958), with one additional electrode on the front as grounding and two separate electrodes – at the right and left earlobe – as the reference electrodes. The recordings were referenced against the algebraic mean of the two earlobe electrodes; this strategy has been shown (Essl and Rappelsberger, 1998) to minimize the distorting influence of the reference signal. Eye movements were controlled for by a Piezo-electric device attached to the eyelid. Using a conventional Nihon–Kohden 21 channel recorder, the EEG was amplified, displayed and recorded at a sampling rate of 128 Hz for further processing. The electrode resistance at each electrode was checked and did not exceed 5kΩ . Artefacts were eliminated by careful visual inspection.

b The 'reference problem' of EEG data recording: Two important methodological issues that must be commented on in regard to the phase synchronization analysis of the EEG are the possible effects of reference contamination and volume conduction, something that is common to all studies of interdependence between scalp EEG records (Nunez and Srinivasan, 2006). Recent theoretical advances (Nolte *et al.,* 2004; Guevara *et al.*, 2005), have suggested that these two factors may give rise to spurious phase synchrony values or the estimated functional connectivity patterns when applied to raw EEG signals. A possible solution to these problems is to use first Laplacian splines (Nunez and Srinivasan, 2006) on the raw data followed by the estimation of phase synchrony. Laplacian, which acts as a spatial band-pass filter of scalp potential, removes most of the distortions caused by the common reference signal and volume conduction, and emphasizes locally synchronized sources. But Laplacian method requires a high density of electrodes (> 64), whereas we have only 19 electrodes, thus application of Laplacian was not possible. However, the lower number of electrodes helped in restricting the volume conduction since the average electrode spacing for our montage is approximately 70 mm, which is considerably larger than the average spatial resolution of EEG which is 5 mm (Nunez, 1995). Further, we have used an extracephalic reference (linked earlobes) scheme that has been traditionally considered silent enough to minimize these influences; nevertheless, the above effects cannot be completely ruled out from our results. At present we are carrying out theoretical research along these lines with the aim of being able to assess quantitatively the effect of the reference on the EEG phase synchrony results.

4 Data analysis

a Introduction to the method of EEG coherence and synchronization: The discovery of the phenomenon of synchronous oscillations (Gray *et al.*, 1989; Singer, 1993; 1994; 1999; Singer and Gray, 1995) in the cerebral cortex and their measurement (by means of coherence and synchronization analyses) already has a long-standing tradition (mainly in the field of clinical electrophysiological studies). Coherence was first applied to EEG signals more than 40 years ago (e.g. Walter, 1968). Since then, many clinical and behavioural studies have been conducted using electroencephalogram (EEG) and magnetoencephalogram (MEG) synchronization analyses (for review, introduction and methodological aspects about these methods, see Basar, 2005; Pereda *et al.*, 2005). However, this method never became as popular as, for example, measuring ERPs (event related potentials); until recently, as much scientific attention was paid to brain networks and especially time-locked cooperative activity (as reflected, for example, in synchronous oscillations). In recent times these methods have become no longer unique to the field of electrophysiology, but have also been adopted within the field of analysing magnetic-resonance-based brain imaging signals. For example, in fMRI (functional magnetic resonance imaging) the term used is ‘connectivity analysis’ (Marrelec *et al.*, 2006); for an SLA study using fMRI connectivity, see also Dodel *et al.*, 2005.

The significance of the experimental data now published on synchronous oscillations is very substantial, but remains controversial. Theoretical opinions vary, ranging from the view that synchrony may be essentially irrelevant to synaptic interactions and object recognition or even to cognitive processing, to the possibility that synchrony is vital to the co-ordination of synaptic modifications in the brain (Phillips and Singer, 1997). Based on basic cat and monkey experiments, the theoretical concept has been enlarged to be applied also to a more general level of higher cognitive processing. For Engel *et al.* (1999a; 1999b) and Singer (1999) cognitive functions like perception, memory, language or consciousness are based on highly parallel and distributed information processing by the brain. As parallel processing on the basis of coordinated cell assemblies seems to be an important mechanism for higher cognitive information processing in the brain, the computation of coherence and synchronization seems an adequate measurement to elucidate the degree of electric coupling between affected cooperating neuronal systems (Weiss and Mueller, 2003). One of the first groups to measure coherence during the administration of cognitive tasks were Busk and Galbraith (1975). They showed that average coherence values increase with task difficulty and decrease when the tasks are easier. Meanwhile, various EEG coherence studies within a range of cognitive domains have been conducted that revealed and confirmed the usefulness and validity of this method; for example, music processing (Bhattacharya and Petsche, 2005a), artistic imagination (Bhattacharya and Petsche, 2005b), mental imagery (von Stein *et al.*, 1993; 1994; 1999), mental translating (Petsche *et al.*, 1993), L1 language processing (for reviews see Bastiaansen and Hagoort, 2006; Weiss and Mueller, 2003) and phase synchronization measures of language processing (Allefeld *et al.*, 2004a; 2004b).

b Computation of coherence and synchronization analyses: According to Thatcher *et al.* (1984), EEG measures only concerted activity of large-scale cell assemblies and is thus well suited to detect global states of integrated cortical function. EEG coherence as a method of analysis has been developed to represent a statistical measure of the functional cooperation between two cortical areas (to the extent that these areas can be registered by the electrode) by looking at the similarity of the EEG signals within a given frequency band (Rappelsberger *et al.*, 2000). Many studies report the successful use of EEG coherence to measure functional connectivity (e.g. Lopes da Silva *et al.*, 1980; Thatcher *et al.*, 1984; Tucker *et al.*, 1986; Rappelsberger *et al.*, 1988; 1993; 1994; Pereda *et al.*, 2005). However, there are two problems associated with coherence (or magnitude squared coherence) analysis:

- coherence is usually appropriate for linear and stationary signals whereas EEG is often non-linear and non-stationary (Palus, 1996); and
- coherence mixes amplitude and phase information (Wolmersdorf *et al.*, 2007), yet there is no explicit method to separate the phase correlation from the coherence function (Lachaux *et al.*, 1997).

In this experiment we used a newly developed measure of time-locked synchronization, a tool of non-linear multivariate time series analysis: mean phase coherence within the lower gamma frequency range. A generally sophisticated question in EEG analysis is that of the underlying functions of the different frequency ranges. In conventional clinically driven EEG analysis, for a long time only frequency ranges up to approximately 30 Hz have been considered meaningful and worthy for research. The lower frequency ranges (delta: 0–3 Hz, theta 4–7 Hz, alpha 8–12 Hz) have been thought to reflect sleep and resting-state phenomena, memory processes and attentional phenomena, whereas the frequency ranges above alpha (the beta-range; 13–30 Hz) have gradually been discovered to reflect phenomena of higher cognition, like language processing. Only very recently has the formerly neglected high frequency range, gamma ($>$ 30 Hz) been reintroduced into research programs, and it is now intensively investigated. This range is believed to contain valuable information about (amongst others) higher cognitive mental states (including language processing), consciousness, mental integration and representation phenomena, gestalt perception and processes that require a large amount of integrative thinking (for further information on frequency ranges and their possible interpretations, see Basar *et al.*, 1997; 1999; Basar, 2005; Vanhatalo *et al.*, 2005).

c Phase synchronization analysis: Phase synchronization between all electrode regions ((19*18)/2=171 different electrode pairs) was calculated in lower gamma frequency range (30–40 Hz) by using the mean phase coherence index, which measures the degree of phase coherence between a pair of electrodes. Each EEG signal was high-pass filtered using a zero-phase filter with 30 Hz cut-off frequency. We calculated the phases of these filtered signals by using the analytic-signal approach based on a Hilbert transform (Rosenblum *et al.*, 1996).

There are many different ways of assessing phase synchronization between a pair of EEG signals (for a review, see Pereda *et al.*, 2005). Here, we used the mean phase coherence index (Hoke *et al.*, 1989; Mormann *et al.*, 2000), defined as:

1) $$|\gamma_{i,j} = \sqrt{\left\langle \cos\varphi(t) \right\rangle^2 + \left\langle \sin\varphi(t) \right\rangle^2}$$

where |•| indicates modulus, <•> indicates time average and

2) $$\varphi(t) = |\,\phi_i(t) - \phi_j(t)\,| \bmod (2\pi)$$

is the cyclic relative phase, i.e., the phase difference between x_i(t) and x_j(t) wrapped to the interval [0, 2pπ. The mean phase coherence index ranges from 0 (two signals with no phase relationship) to 1 (two signals with complete phase synchrony) and has the advantage of being parameter free. For further mathematical details about the method, see Bhattacharya and Petsche, 2005a; 2005b; Pereda *et al.*, 2005.

d Statistical analysis: The existence of statistical differences in the values of the coherence indexes were checked by means of two non-parametric tests: differences between high proficiency and low proficiency groups (between groups, independent samples) were studied by the Mann–Whitney U test, whereas the Wilcoxon signed-rank test for repeated measures (within-group differences, paired samples) was used to compare the L1 and the L2 situation. Differences were considered significant when the *p*-value (corrected for multiple comparisons) was lower than 0.05. We had to make use of non-parametric tests instead of the traditional approach of using the parametric multivariate analysis of variance (MANOVA) test because, in many cases, the values of the indexes within each group did not fulfil the criteria of normal distribution and homogeneity of the variances, and this may severely bias the results of the MANOVA analysis.

III Results

1 Behavioural results

A comprehension questionnaire, which was applied after each task, revealed (see Figure 1) that the low proficiency group understood approximately 50% of the English (L2) texts, whereas the high proficiency group understood nearly perfectly (95%). Surprisingly, there was also a small difference between the groups with regard to the answers to the comprehension questions about the German (L1) texts. Here the low proficiency group scored slightly worse than the high proficiency group. No differences between the two groups were found for the other psychometric variables (self-reported attention, work load, sympathy for the speaker and interest in the subject matter). Unfortunately, no explicit IQ tests were administered, so we cannot report any verbal or non-verbal IQ scores here to account for possible IQ differences between the groups.

2 EEG brain mapping results

In our between-groups comparisons for second language processing (see Figure 2) we found that the low proficiency group shows a widely distributed long-range network of significant increases in phase synchrony involving predominantly right-hemisphere fronto-central (fronto-parietal) brain regions for L2 processing (see Figure 2: upper panel, right column), whereas for L1 the single significant coherence increase is marginally restricted to a left-hemispheric electrode pair (T5–Cz) (see Figure 2: lower panel, right column).

This result was also corroborated by the synchronization cluster analysis method (Allefeld *et al.*, 2004a), which measures the distribution density of coherence (i.e. indicating focal points that present high global phase synchronization or ‘nodal points’), where the nodal point (the most involved electrode of this right-hemispheric cluster) within the low proficiency group for the L2 task was around the right frontal electrode F8 (prefrontal cortex in RH, approximately the area of the Broca analogon in the RH; see Figure 3: right column). For the high proficiency group, no significant increases were observed either for the L1 or for the L2 (compare Figure 2: left columns, upper and lower panels). However, we could still observe a slight preference for higher clustering density at left prefrontal sites in the high proficiency group when participants were processing their mother tongue (see Figure 3: left column).

High and low proficiency bilinguals could be significantly differentiated by gamma-band synchronization measures (mean gamma phase coherence) predominantly when processing L2. Looking at within-group

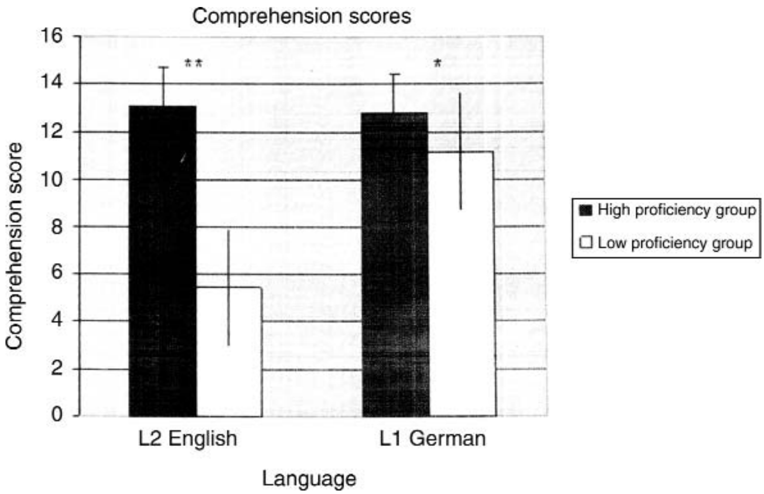

Figure 1 Listening comprehension differences between high proficiency (black columns, $n = 19$) and low proficiency bilinguals (white columns, $n = 19$)

Notes: The mean values of the listening comprehension scores are presented. Maximum score = 14 points. Bars indicate sd. *: significantly lower comprehension score of low proficiency bilinguals in comparison to the high proficiency bilinguals, with $p < 0.05$ (ANOVA and Newman–Keuls test for German); **: $p < 0.01$ (ANOVA and Newman–Keuls test for English)

comparisons for second language processing (see Figure 4), when looking at the task vs. task comparisons between second language and first language processing (L2 vs. L1), the low proficiency group showed stronger network processing (significant increases in mean phase coherence over many electrode-pairs) in L2 than L1 within a right-hemispheric posterior-central (temporo-parietal) network. The high proficiency group showed smaller focal changes for L2 > L1 processing, with marginal increase involving only left fronto-temporal synchrony.

In contrast, for L1 processing the high proficiency group showed a dense coherene increase involving especially prefrontal bilateral areas, with the nodal point clustering around a left prefrontal electrode. Again within the right hemisphere, the low proficiency group shows very few small-range frontal coherence increases. Stronger synchronization for the right temporal area (clustering around the right temporal electrode T4) for L2 in the low proficiency group, and stronger synchronization for prefrontal bilateral areas for L1 in the HP group, were also confirmed by the synchronization cluster analysis (see Figure 5).

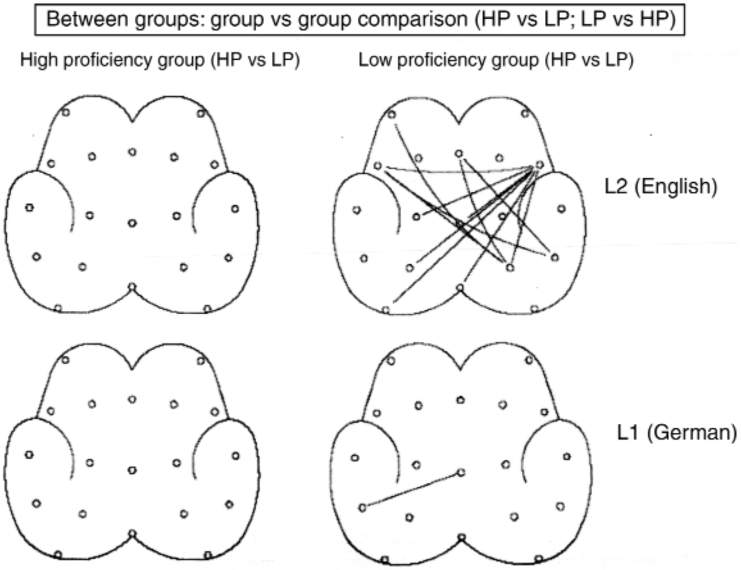

Figure 2 Brain maps depicting mean (gamma) phase coherence during first and second language processing with respect to between-groups comparison (high proficiency / left column; low proficiency / right column)

Notes: Upper panel: L2 (sig. higher synchronization within the RH for low proficiency group); lower panel: L1 (almost no group difference). Significance level at $p < 0.05$, corrected for multiple comparisons, using non-parametric Mann–Whitney U-test.

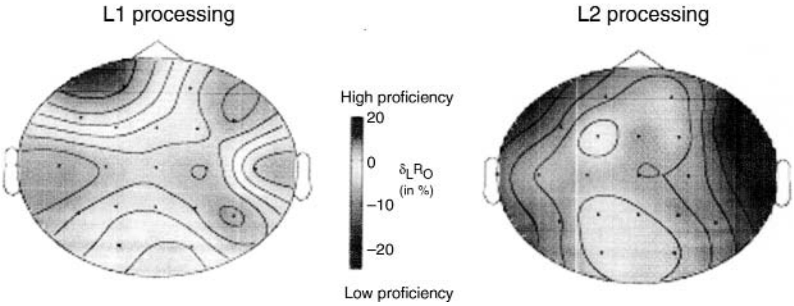

Figure 3 Topography of synchronization density: schematic brain maps

Notes: High proficiency group as ‘high values’or upper line and low proficiency group as ‘low values’ blue or lower line represented in left-brain map for L1 processing and in right-brain map for L2 processing. Maps of the synchronization cluster analysis values (SCA) at the different electrode sites, which reflects ‘density’ clusters at the given electrodes as a function of between-group differences of long-range gamma-phase synchronization during L1 (left-side) and L2 (right-side) processing.

Turning to within-group comparisons for first language processing (lower panel in Figure 4), for the reverse comparison (L1 > L2) the low proficiency group displayed only a few significant right-hemispheric prefrontal coherence increases, whereas the significant gamma phase coherence increases within the high proficiency group for L1 as compared to L2 were slightly higher in quantity and were located bilaterally over the prefrontal lobes, clustering at the left prefrontal electrode (Fp1); this can also be seen in the results based on the cluster analysis (see Figure 5: left column).

Finally, we found an overall inverse (negative) relationship between proficiency level and synchronization density, i.e. the higher the proficiency, the lower the synchronization. High proficiency correlated most strongly (see Figure 6) with lowest synchronization density at the electrode channels in the vicinity of a right-hemispheric network including the temporo-parietal channels: Cz, C4, T4 and P4.

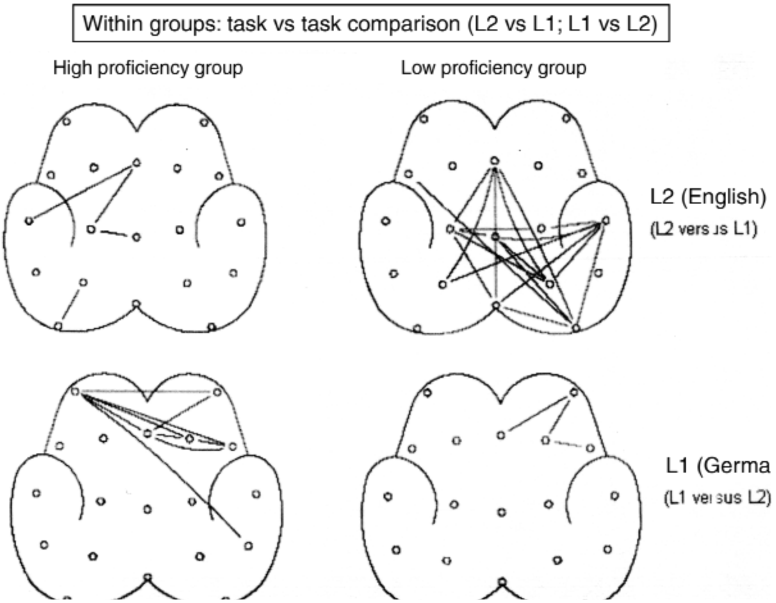

Figure 4 Brain maps depicting mean (gamma) phase coherence during first and second language processing

Notes: Task vs. task comparisons measuring within-group differences (high proficiency / left column; low proficiency / right column) for second language (upper panel) and first language (lower panel) at $p < 0.05$, corrected for multiple comparisons, using Wilcoxon signed-rank test for repeated measures.

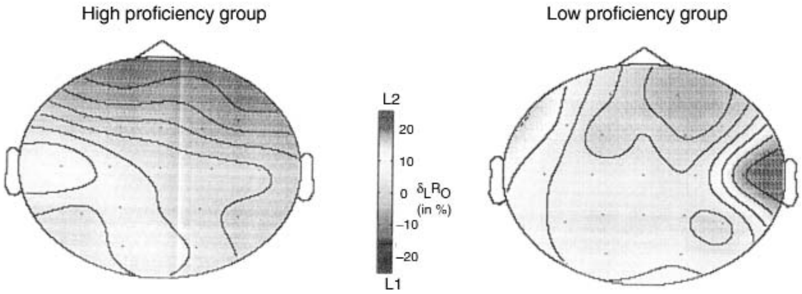

Figure 5 Topography of synchronization density: schematic brain maps

Notes: 'High values' represent L2, 'low values' L1; left column = high proficiency group; right column = low proficiency group. Maps of the synchronization cluster analysis values (SCA) at the different electrode sites, which reflects 'density' clusters at the given electrodes as a function of within-group differences of long-range gamma-phase synchronization during first ('lower values' or lower line) and second ('high values' or upper line) language tasks.

IV Discussion

Based on the results of our EEG synchronization study, we could corroborate our hypotheses and positively answer the questions posed. We found that the right hemisphere was significantly more involved in second language processing in our less proficient, less fluent second language speakers and the form of activation was reflected in long-range synchronization patterns, within the gamma frequency range.

These results also confirmed that the gamma frequency range is a range within which it is possible to detect subtle hemispheric differences of activation patterns within two groups of differently proficient second language speakers. Since this is the first study, to the best of our knowledge, where an EEG (phase) synchronization measure was used to investigate a phenomenon of bilingual language processing, we cannot directly or strictly speaking compare the study to the available literature. Is there really more RH involvement for bilinguals?

The concept that bilinguals should process their second languages more in the right hemisphere, though often reported by various experiments (see, amongst others, Galloway and Krashen, 1980; Vaid and Genesee, 1980; Obler, 1981; Galloway and Scarcella, 1982; Dehaene *et al.*, 1997; Chee *et al.*, 2001; Evans *et al.*, 2002), has also been heavily criticized, mainly on methodological grounds. Paradis (2003)

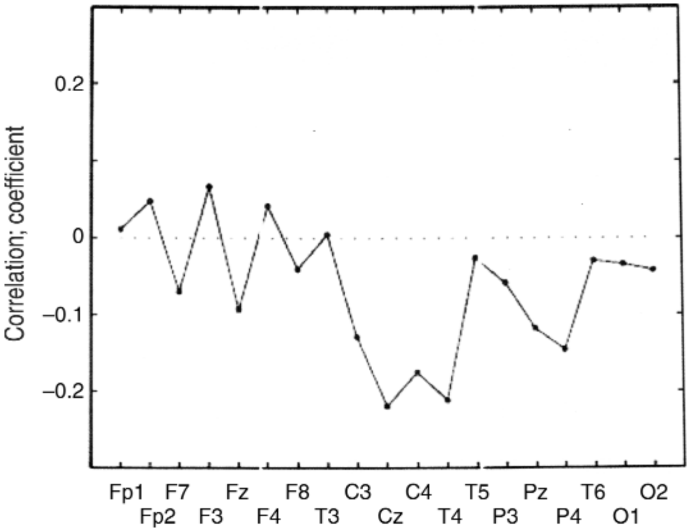

Figure 6 Correlation (inverse correlation) between proficiency level and synchronization density (i.e. higher proficiency / lower synchrony)

Notes: Plot of correlation coefficient (indicated on y-axis) at electrode positions (brain topography, x-axis), showing high proficiency correlated with lower phase synchrony. Stronger effects at Cz, C4 and T4.

doubts the validity of such a theory or assumption; he even calls it a ‘Loch Ness monster’, and criticizes its existence because of the various methodological shortcomings of past experiments. He especially calls into question the classical laterality measures that have been used in this field of research (tachistoscopic and dichotic listening paradigms), noting that everybody uses a different paradigm and that there is no established method for laterality measures. However relevant this critique may be – and however relevant tachistoscopic measurements may underlie certain shortcomings and variability in usage – in the meantime new studies (mainly fMRI) have appeared that report new ‘Loch Ness monsters’. These are not measured using the former laterality measures but have established new methods of assessing laterality. Most fMRI studies are analysed in a uniform way because of certain freely available, constantly developing and hence successful software packages. There have recently been further fMRI studies reporting more RH involvement in bilinguals (Dehaene *et al.*, 1997; Chee *et al.*, 2001; Calabrese *et al.*, 2001; Ding *et al.*, 2003; Pillai *et al.*, 2003). Dehaene *et al.* (1997) investigated early vs. late bilinguals (age of onset after 7), and in age of onset they found a crucial variable influencing brain activations in these different bilinguals. They found more RH involvement for the group of late bilinguals – sometimes exclusive RH involvement in this group and sometimes bilateral involvement – which led them to conclude that for the group of the late bilinguals there is much higher variability and less reproducibility in the brain activation patterns. This ranged from complete RH, via bilateral, to complete LH. On the other hand, the Chee *et al.* (2001) study found that the informative variable for the bilinguals under investigation was level of proficiency. More RH activation during L2 processing was observed in the least proficient bilinguals. Calabrese *et al.* (2001) also found additional right-hemisphere activations (RH prefrontal) for the processing of L2 in their group of bilinguals. Ding *et al.* (2003) investigated Chinese–English bilinguals with fMRI and found that, despite the typological difference between English and Chinese, they observed more RH activation for the L2 English during reading (orthographic search) and semantic tasks (categorization). In another fMRI study (Pillai *et al.*, 2003) on Spanish–English bilinguals using semantic and phonological tasks, the researchers found more RH activation for the L2 processing, especially for the phonological tasks.

Using EEG and ERPs rather than fMRI, another recent study (Proverbio *et al.*, 2002) suggested that polyglottism shapes the brain. They did not claim directly that more RH activation would be typical for bilingual processing, but found that in monolinguals semantic processing preferred the RH, and syntactic processing involved the LH, whereas in bilinguals this pattern is inversed. The conclusion here is that, neurally speaking, bilinguals are different. Again adopting a recent methodology of EEG, our own EEG coherence results (Reiterer *et al.*, 2005a) also showed more RH involvement in low proficiency bilinguals. Thus, it seems that a RH bias for bilingual processing is reported not only by employing 'older' or more indirect methods (like the tachistoscope or the dichotic listening technique); however, the 'Loch Ness monster' phenomenon also seems to persist also when newer, more sophisticated and more direct methods of brain imaging are adopted. Thus, the observed phenomenon is recurring, but the question whether or not there is more RH involvement in bilinguals is difficult to answer in a straightforward way, despite of evidence in favour of it. The major obstacle is the difficulty of identifying the ‘real’ explanatory variable, i.e. the key variable (or variables) that bring about this often observed RH shift in diverse bilinguals. The question thus remains whether it is the time window in which the additional languages are learned (age of onset and the conventional distinction between early and late bilinguals), the proficiency level (with the distinction between high and low proficiency bilinguals) or another variable (e.g. number of languages already acquired, motivation, learning strategy, teaching method, language aptitude, language or social attitudes, or even general IQ) that is the key or crucial factor to be singled out. To date some researchers have suggested that it might be age of onset (e.g. Lenneberg, 1967; Dehaene *et al.*, 1997), and some that it might be proficiency level (Calabrese *et al.*, 2001; Chee *et al.*, 2001; Reiterer *et al.*, 2005a; 2005b); others argue that it is neither proficiency level nor age of onset, but the mere fact that someone is bilingual or polyglot and knows more languages (e.g. Obler, 1981; Proverbio *et al.*, 2002); finally, some try to reconcile proficiency level with age of onset and claim that both matter (e.g. Evans *et al.*, 2002; Mechelli *et al.*, 2004; Hull and Vaid, 2006). In fact, the option that both of these most investigated factors matter is an interesting suggestion (other factors might also be in play, but they have been investigated much less or have not been investigated at all with currently available brain imaging techniques). In a recent meta-analysis of the literature (23 laterality studies) performed on that topic, Vaid and colleagues (Hull and Vaid, 2006) came to a conclusion that at first glance seems contrary to older and more conventional assumptions (e.g. Obler, 1981). They conclude that the essence of the observations shows that early bilinguals (contrary to the classical view) display more RH or bilateral brain activation for L2 processing, and late bilinguals display more LH activation, just like monolinguals do. According to their survey the strongest effect seems to be that proficiency also matters, but only in a specific way. High proficiency in early bilinguals causes a bias towards the RH, whereas high proficiency in late bilinguals causes a bias to the LH.

The results of our present and previous work are compatible with this rather sophisticated view, since we observed – along the investigated frequency ranges (mostly in the alpha and gamma range, Reiterer *et al.*, 2005a; 2005b) – a higher concentration of coherence connections or clusters within the LH for the higher proficiency group (which were at the same time all late onset learners). Since we only investigated late bilinguals (after age 9) with differences in proficiency level, we cannot draw any conclusions about differences that could have been induced by age of onset. However, our results are in line with theories and studies (e.g. Obler, 1981; Galloway and Scarcella, 1982; Evans *et al.*, 2002; Chee *et al.*, 2001; Hull and Vaid, 2006) that found RH activations for less fluent (either due to less exposure, experience or formal training) second language speakers. The question of why the RH should be more involved in less fluent bilinguals is still unanswered. A plausible possibility would be that it is involved for recruitment of additional processing substrate (as a means of compensation). This possibility would also be corroborated by our earlier results (Reiterer *et al.*, 2005a; 2005b; in preparation) and by the fact that we found a negative correlation between coherence density and L2 performance, especially in RH electrode places. Other possible explanations would be that the RH houses more holistic learning strategies, or because – and this is the final conclusion of the Hull and Vaid (2006) study – it is, by nature, simply better equipped for bilingual processing needs (because of its slower development).

However, the fact that proficiency level and age of onset are both important is not surprising, considering the fact that they are related (Birdsong, 2006; Wattendorf and Festmann, 2008). Higher proficiency very often goes hand in hand with earlier age of onset (although this is not necessarily so). The search for the crucial factor that could explain bilingual brain representation is generally a large and fervidly investigated battle field (regardless of the question whether there is more or less RH involvement or not). Within the whole field of bilingual brain representation, only some major factors are discussed, mainly featuring age of onset and proficiency level. However, a word of caution is needed about the term ‘proficiency level’ itself. Conceptually speaking, proficiency level is a misleading term. The explanatory power of the term could in part be explained by the fact that proficiency level is not a singular or ‘pure’ factor, but a complex one that functions as an umbrella term and subsumes many of the other factors that have been mentioned above (for example, training, aptitude, exposure time and learning strategy). Proficiency level can not be regarded as a biological, psychological, social nor linguistic factor because it is the sum of all. It is the measure or the outcome of the phenomenon of language learning itself, the acquisitional process measured at any given point in time. In contrast, age of onset would be a simple biological factor, which can be easily operationalized. Even though the term proficiency level has widespread usefulness, strictly speaking it is a fuzzy term for investigating the phenomenon of bilingualism, because it is a sum factor reflecting the phenomenon itself, not a variable that contributes to it. This and other terminological issues (like the terms ‘bilingualism’, ‘second language acquisition’ and ‘second language learning’) give rise to confusion, possibly because of lack of interdisciplinary integration between the fields of brain imaging and neuroscience, on the one hand, and second language acquisition, applied linguistics and theoretical linguistics on the other. This is a fact that calls for more joint efforts of neuroscientists and language researchers to build new links for paving the common ground for future projects in this area of research.

Although many studies so far have reported RH involvement in bilinguals, it is still not known exactly which factor contributes to its existence, why this should be so, and whether or not it might not really be an illusion. In the search for factors that contribute to bilingual brain representation and that make bilinguals different from monolinguals – and in search of shifts in hemispheric dominance or shifts in general network activity within the whole brain during the L2 acquisitional process – more studies are needed that are inspired by interdisciplinarity, that are carried out with new brain imaging techniques using standardized and comparable paradigms and methods of analysis, along with more detailed descriptions (profiles) of the bilinguals or multilinguals that have been investigated. For example, it is possible that distinctions such as ‘early vs. late’ or ‘fluent vs. non-fluent’ easily lead to misunderstandings because they are insufficient (for a recent review on brain imaging studies of bilinguals or multilinguals, see also De Bot, 2008).

V Conclusions

In conclusion we can say that our hypotheses were supported: on the one hand there is more RH involvement for lower proficiency second language speakers (especially during L2 tasks) and, on the other hand EEG coherence and synchronization analyses, especially within the gamma frequency range, are valuable methods of inquiry about bilingual brain representation and second language processing. However, there is still a lot more work to be undertaken in this field of research before the final word is spoken. As brain imaging techniques are getting more sophisticated, study designs and subject search criteria should also become more sophisticated. This will help to clarify what the crucial factors are that make a bilingual's brain differently organized.

Acknowledgements

We would like to sincerely thank Anna Schneider for technical support with the EEG measurements and Professor Peter Rappelsberger for his assistance in making this study possible, for his methodological support and for the use of the EEG equipment of the EEG laboratory at the former institute of Neurophysiology and Brain Research Institute, Medical University of Vienna. Susanne Reiterer is supported by a DFG (German Research Foundation) grant (research grant AC 55/7-1) and Joydeep Bhattacharya by JST (ERATO Implicit Brain Function project).

VI References

Allefeld, C. and **Kurths, J.** 2004a: An approach to multivariate phase synchronization analysis and its application to event-related potentials. *International Journal of Bifurcation and Chaos* 14, 417–26.

Allefeld, C., Frisch, S. and **Schlesewsky, M.** 2004b: Detection of early cognitive processing by event-related phase synchronization analysis. *NeuroReport* 16, 13–16.

Basar, E. 2005: Memory as the 'whole brain work': a large-scale model based on 'oscillations in super-synergy'. *International Journal of Psychophysiology* 58, 199–226.

Basar, E., Basar-Eroglu, C., Karakas, S. and **Schürmann, M.** 1999: Are cognitive processes manifested in event-related gamma, alpha, theta and delta oscillations in the EEG? *Neuroscience Letters* 259, 165–68.

Basar, E., Hari, R., Lopes da Silva, F. and **Schürmann, M.** 1997: Brain alpha activity: new aspects and functional correlates. *International Journal of Psychophysiology* (special issue) 26, 1–482.

Bastiaansen, M. and **Hagoort, P.** 2006: Oscillatory neuronal dynamics during language comprehension. *Progress in Brain Research* 159, 179–96.

Bhattacharya, J. and **Petsche, H.** 2005a: Phase synchrony analysis of EEG during music perception reveals changes in functional connectivity due to musical expertise. *Signal Processing* 85, 2161–77.

—— 2005b: Drawing on mind's canvas: differences in cortical integration patterns between artists and non-artists. *Human Brain Mapping* 26, 1–14.

Bhattacharya, J., Pereda, E. and **Petsche, H.** 2003: Effective detection of coupling in short and noisy bivariate data. *IEEE Transactions on Systems, Man and Cybernetics* B 33, 85–95.

Birdsong, D. 2006: Age and second language acquisition and processing: a selective overview. *Language Learning* 56, 9–49.

Busk, J. and **Galbraith, G.** 1975: EEG correlates of visual-motor practice in man. *Electroencephalography in clinical Neurophysiology* 38, 415–22.

Calabrese, P., Neufeld, H., Falk, A., Markowitsch H.J., Muller, C., Heuser, L., Gehlen, W. and **Durwen, H.** 2001: Word generation in bilinguals: fMRI study with implications for language and memory processes. *Fortschritte in Neurologie und Psychiatrie* 69, 42–49.

Calvin, W.H. 1998: *The cerebral code: thinking a thought in the mosaics of the mind*. Cambridge, MA: The MIT Press.

Chee, M.W., Hon, N., Lee, H.L. and **Soon, C.S.** 2001: Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. *NeuroImage* 13, 1155–63.

Clements, A., Rimrodt, S., Abel, J., Blankner, J., Mostofsky, S., Pekar, J., Denckla, M. and **Cutting, L.** 2006: Sex differences in cerebral laterality of language and visuospatial processing. *Brain and Language* 98, 150–58.

Corballis, M.C. 1989: Laterality and human evolution. *Psychological Reviews* 96, 492–505.

—— 1992: On the evolution of language and generativity. *Cognition* 44, 197–226.

De Bot, K. 2008: The imaging of what in the multilingual mind? Review article. *Second Language Research* 24, 111–33.

Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., van de Moortele, P.F., Lehericy, S. and **Le Bihan, D.** 1997: Anatomical variability in the cortical representation of first and second language. *NeuroReport* 8, 3809–15.

Ding, G., Perry, C., Peng, D., Ma, L., Li, D., Xu, S., Luo, Q., Xu, D. and **Yang, J.** 2003: Neural mechanisms underlying semantic and orthographic processing in Chinese–English bilinguals. *NeuroReport* 14, 1557–62.

Dodel, S., Golestani, N., Pallier, C., Elkouby, V., Le Bihan, D. and **Poline, J.B.** 2005: Condition-dependent functional connectivity: syntax networks in bilinguals. *Philosophical Transactions of the Royal Society of London: Biological Sciences* 360(1457), 921–35.

Engel, A., Fries, P., König, P., Brecht, M. and **Singer, W.** 1999a: Does time help to understand consciousness? *Consciousness and Cognition* 8, 260–68.

—— 1999b: Temporal binding, binocular rivalry, and consciousness. *Consciousness and Cognition* 8, 128–51.

Essl, M. and **Rappelsberger, P.** 1998: EEG coherence and reference signals: experimental results and mathematical explanations. *Medical and Biological Engineering and Computing* 36, 399–406.

Evans, J., Workman, L., Mayer, P. and **Crowley, K.** 2002: Differential bilingual laterality: mythical monster found in Wales. *Brain and Language* 83, 291–9.

Fell, J., Fernandez, G., Klaver, P., Elger, C.E. and **Fries, P.** 2003: Is synchronized neuronal gamma activity relevant for selective attention? *Brain Research Reviews* 42, 265–72.

Ford, J.M., Gray, M., Faustman, W.O., Heinks, T.H. and **Mathalon, D.H.** 2005: Reduced gamma-band coherence to distorted feedback during speech when what you say is not what you hear. *International Journal of Psychophysiology* 57, 143–50.

Galloway, L. and **Krashen, S.** 1980: Cerebral organization in bilingualism and second language. In Scarcella, R., Krashen, S., editors, *Research in second language acquisition*. Rowley, MA: Newbury House, 74–80.

Galloway, L. and **Scarcella, R.** 1982: Cerebral organization in adult second language acquisition: is the right hemisphere more involved? *Brain and Language* 16, 56–60.

Gordon, H.W. and **Carmon, A.** 1976: Transfer of dominance in speed of verbal response to visually presented stimuli from right to left hemisphere. *Perceptual and Motor Skills* 42, 1091–1100.

Gray, C., König, P., Engel, A. and **Singer, W.** 1989: Oscillatory responses in cat visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties. *Nature* 338, 334–37.

Guevara, R., Velazquez, J.L., Nenadovic, V., Wennberg, R., Senjanovic, G. and **Dominguez, L.G.** 2005: Phase synchronization measurements using electroencephalographic recordings: what can we really say about neuronal synchrony? *Neuroinformatics* 3, 301–14.

Hagoort, P. 2005: On Broca, brain, and binding: a new framework. Review. *Trends in Cognitive Science* 9, 416–23.

Hardyck, C., Cotton, B. and **Tzeng, O.J.L.** 1980: Role of cerebral hemispheric processing in the visual half-field stimulus-response compatibility effect. *Journal of Experimental Psychology: Human Perception and Performance* 6, 13–23.

Hoke, M., Lehnertz, K., Pantev, C. and **Lütkenhöner, B.** 1989: Spatiotemporal aspects of synergetic processes in the auditory cortex as revealed by magnetoencephalogram. In Basar, E., Bullock, T., editors, *Dynamics of cognitive and sensory processing in the brain*. Berlin: Springer, 84–105.

Hull, R. and **Vaid, J.** 2006: Laterality and language experience. *Laterality* 11, 436–64.

Ihara, A. and **Kakigi, R.** 2006: Oscillatory activity in the occipitotemporal area related to the visual perception of letters of a first/second language and pseudoletters. *NeuroImage* 29, 789–96.

Jansen, A., Lohmann, H., Scharfe, S., Sehlmeyer, C., Deppe, M. and **Knecht, S.** 2007: The association between scalp hair whorl direction, handedness and hemispheric language dominance: is there a common genetic basis of lateralization? *NeuroImage* 35, 853–61.

Jasper, H.H. 1958: The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology* 10, 371–75.

Johnsrude, I., Zatorre, R., Milner, B. and **Evans, A.** 1997: Left-hemisphere specialization for the processing of acoustic transients. *NeuroReport* 8, 1761–65.

Lachaux, J.P., Rodriguez, E., Martinerie, J. and **Varela, F.J.** 1997: Measuring phase synchrony in brain signals. *Human Brain Mapping* 8, 194–208.

Lenneberg, E. 1967: Biological foundations of language. New York: Wiley.

Lopes da Silva, F.H., Vos, J.E., Mooibroeck, J. and **Van Rotterdam, A.** 1980: Relative contributions of intracortical and thalamo-cortical processes in the generation of alpha rhythms, revealed by partial coherence analysis. *Electroencephalography and Clinical Neurophysiology* 50, 449–56.

Marrelec, G., Bellec, P. and **Benali, H.** 2006: Exploring large-scale brain networks in functional MRI. *Journal of Physiology: Paris* 100, 171–81.

Mechelli, A., Crinion, J., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. and **Price, C.** 2004: Neurolinguistics: structural plasticity in the bilingual brain.*Nature* 431(7010), 757.

Micheloyannis, S., Vourkas, M., Bizas, M., Simos, P. and **Stam, C.J.** 2003: Changes in linear and nonlinear EEG measures as a function of task complexity: evidence for local and distant signal synchronization. *Brain Topography* 15, 239–347.

Mormann, F., Lehnertz, K., David, P. and **Elger, C.E.** 2000: Mean phase coherence as a measure for phase synchronization and its application to the EEG of epilepsy patients. *Physica D* 144, 358–69.

Nolte, G., Bai, O., Wheaton, L., Mari, Z., Vorbach, S. and **Hallet, M.** 2004: Identifying true brain interaction from EEG data using the imaginary part of coherency. *Clinical Neurophysiology* 115, 2292–2307.

Nunez, P. and **Srinivasan, R.** 2006: A theoretical basis for standing and travelling brain waves measured with human EEG with implications for an integrated consciousness. *Clinical Neurophysiology* 117, 2424–35.

Nunez, P. 1995: *Neocortical dynamics and EEG rhythms*. Oxford: Oxford University Press.

Obler, L. 1981: Right hemisphere participation in second language acquisition. In Diller, K., editor, *Individual differences and universals in language learning aptitude*. Rowley, MA: Newbury House, 53–64.

Palus, M. 1996: Nonlinearity in normal human EEG: cycles, temporal asymmetry, nonstationarity, and randomness, not chaos. *Biological Cybernetis* 75, 389–96.

Paradis, M. 1994: Neurolinguistic aspects of implicit and explicit memory: implications for 163 bilingualism and SLA. In Ellis, N.C., editor, *Implicit and explicit learning of languages*. San Diego, CA: Academic Press, 393–420.

—— 2003: The bilingual Loch Ness monster raises its non-asymmetric head again; or, why bother with such cumbersome notions as validity and reliability? Comments on Evans *et al.*, 2000. *Brain and Language* 87, 441–48.

Pereda, E., Quian Quiroga, R. and **Bhattacharya, J.** 2005: Nonlinear multivariate analysis of neurophysiological signals. *Progress in Neurobiology* 77(1–2), 1–37.

Petsche, H., Etlinger, S. and **Filz, O.** 1993: Brain electrical mechanisms of bilingual speech management: an initial investigation. *Electroencephalography and Clinical Neurophysiology* 86, 385–94.

Phillips, W.A. and **Singer, W.** 1997: In search of common foundations for cortical computation. *Behavioral and Brain Sciences* 20, 657–722.

Pillai, J., Araque, J.M., Allison, J.D., Sethuraman, S., Loring, D., Thiruvaiyaru, D., Ison, C., Balan, A. and **Lavina, T.** 2003: Functional MRI study of semantic and phonological language processing in bilingual subjects: preliminary findings. *NeuroImage* 19, 565–76.

Proverbio, A.M., Cok, B. and **Zani, A.** 2002: Electrophysiological measures of language processing in bilinguals. *Journal of Cognitive Neuroscience* 14, 994–1017.

Rakic, P. 2006: A century of progress in corticoneurogenesis: from silver to impregnation to genetic engineering. *Cerebral Cortex* 16, i3–i17.

Rappelsberger, P. and **Petsche, H.** 1988: Probability mapping: power and coherence analyses of cognitive processes. *Brain Topography* 1, 46–54.

Rappelsberger, P., Lacroix, D. and **Petsche, H.** 1993: Amplitude and coherence mapping: its application in psycho- and patho-physiological studies. In Rother, M. and Zwiener, U., editors, *Quantitative EEG-analysis-clinical utility and new methods*. Jena: Universitätsverlag, 179–286.

Rappelsberger, P., Pfurtscheller, G. and **Filz, O.** 1994: Calculation of event-related coherence: a new method to study short-lasting coupling between brain areas. *Brain Topography* 7, 121–27.

Rappelsberger, P., Weiss, S. and **Schack, B.** 2000: Coherence and phase relations between EEG traces recorded from different locations. In Miller, E., editor, *Time and the brain: conceptual advances in brain research*. Neward, NJ: Harwood Academic, 297–330.

Reiterer, S., Hemmelmann, C., Rappelsberger, P. and **Berger, M.L.** 2005a: Characteristic functional networks in high- vs. low-proficiency second language speakers detected also during native language processing: an explorative EEG coherence study in 6 frequency bands. *Cognitive Brain Research* 25, 566–78.

—— 2005b: Decreased EEG coherence between prefrontal electrodes: a correlate of high language proficiency? *Experimental Brain Research* 163, 109–13.

Rosenblum, M.G., Pikovski, A.S. and **Kurths, J.** 1996: Phase synchronization of chaotic oscillators. *Physical Review Letters* 76, 1804–07.

Simos, P.G., Papanikolaou, E., Sakkalis, E. and **Micheloyannis, S.** 2002: Modulation of gamma-band spectral power by cognitive task complexity. *Brain Topography* 14, 191–96.

Singer, W. 1993: Synchronization of cortical activity and its putative role in information processing and learning. *Annual review of Physiology* 55, 349–74.

—— 1994: Coherence as an organizing principle of cortical functions. *International Review of Neurobiology* 37, 153–83. Discussion, 203–207.

—— 1999: Neuronal synchrony: a versatile code for the definition of relations? *Neuron* 24, 49–65.

Singer, W. and **Gray, C.M.** 1995: Visual feature integration and the temporal correlation hypothesis. *Annual Review of Neuroscience* 18, 555–86.

Sommer, I., Aleman, A., Bouma, A. and **Kahn, R.** 2004: Do women really have more bilateral language representation than men? A meta-analysis of functional imaging studies. *Brain* 127, 1845–52.

Thatcher, R.W., Krause, P.J. and **Hrybyk, M.** 1984: Cortico-cortical associations and EEG coherence: a two compartment model. *Electroencephalography and Clinical Neurophysiology* 64, 123–43.

Tucker, D.M., Roth, D. and **Bait, T.B.** 1986: Functional connections among cortical regions: Topography of EEG coherence. *Electroencephalography and Clinical Neurophysiology* 63, 242–50.

Vaid, J. and **Genesee, F.** 1980: Neuropsychological approaches to bilingualism: a critical review. *Canadian Journal of Psychology* 34, 417–45.

Vanhatalo, S., Voipio, J. and **Kaila, K.** 2005: Full-band EEG (FbEEG): an emerging standard in electroencephalography. *Clinical Neurophysiology* 116, 1–8.

Vargha-Khadem, F., Isaacs, E. and **Muter, V.** 1994: A review of cognitive outcome after unilateral lesions sustained during childhood. *Journal of Child Neurology* 9, supplement, 2S67–2S73.

von Stein, A., Rappelsberger, P., Filz, O. and **Petsche, H.** 1993: EEG-Korrelate bildlicher Vorstellung: Eine Amplituden- und Kohärenzuntersuchung [EEG correlates of mental imagery: an amplitude and coherence study]. *Zeitschrift EEG-EMG* 24, 217–24.

von Stein, A., Petsche, H., Rappelsberger, P. and **Weiss, S.** 1994: Cognitive function of frequencies outside the 40 Hz range: several frequency ranges play specific roles in different steps of language processing. *Brain Topography* 7, 334.

von Stein, A., Rappelsberger, P. Sarnthein, J. and **Petsche, H.** 1999: Synchronization between temporal and parietal cortex during multimodal object processing in man. *Cerebral Cortex* 9, 1047–3211.

Walter, D.O. 1968: Coherence as a measure of relationship between EEG records. *Electroencephalography and Clinical Neurophysiology* 24, 282.

Wattendorf, E. and **Festmann, J.** 2008: Images of the multilingual brain: the effect of age of second language acquisition. *Annual Review of Applied Linguistics* 28, 3–24.

Weiss, S. and **Mueller, H.** 2003: The contribution of EEG coherence to the investigation of language. *Brain and Language* 85, 325–43.

Werner, H. 1957: The concept of development from a comparative and organismic point of view. In Harris, D., editor, *The concept of development*. Minneapolis, MN: University of Minnesota Press, 125–47.

Werner, H. and **Kaplan, B.** 1963: *Symbol formation: an organismic developmental approach to language and the expression of thought*. New York: John Wiley.

Wolmersdorf, T., Schoffelen, J.M., Oostenveld, R., Singer, W., Desimone, R., Engel, A.K. and **Fries, P.** 2007: Modulations of neuronal interactions through neuronal synchronization. *Science* 316, 1609–12.

Woods, B.T. and **Carey, S.** 1979: Language deficits after apparent clinical recovery from childhood aphasia. *Annals of Neurology* 6, 405–409.