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RESEARCH NOTE

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Decreased EEG coherence between prefrontal electrodes: a correlate of high language proficiency?

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Abstract To investigate the influence of proficiency level on the cortical organization of foreign language processing, two groups of German speaking students, differing only in their proficiency in English as a second language, were subjected to EEG coherence analysis during foreign and native language processing (news reports, alpha1 frequency band). In the group with minor experience with English, coherence increase was observed with all electrode combinations, with left hemisphere (LH) predominance. In the high proficiency group, coherence increase was limited to temporal electrodes over LH. In the latter group only, coherence between prefrontal electrodes was significantly lower during the language tasks than during the baseline task (silence, noisy screen). Both results were obtained with foreign as well as native language processing. We suggest that reduced EEG coherence in highly proficient foreign language speakers reflects a more efficient operating strategy not only for their second, but also for their native language.

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Introduction

Polyglot aphasics sometimes recover only one of their languages, for example a foreign (L2) instead of native language (L1) (Aglioti and Fabbro 1993). This provoked the idea of multilinguals storing each of their languages in separate areas of the brain (multi-center model, additional areas for L2) (Paulesu et al 2000). The opposite viewpoint on multilingual processing postulates common eloquent cortical regions and the same manner of processing for all of the languages known by an individual (one-store model) (Klein et al 1999; Chee et al 1999). Between these two extreme positions, more dynamic models of partly overlapping and interacting areas of processing have been proposed; for a recent example see Vingerhoets et al 2003. Recent research has focused on two main factors crucial for the wiring of multiple languages in a single brain: (1) age of acquisition, accentuating maturational processes during a critical developmental period, and (2) level of proficiency of the speaker. PET- (Kim et al 1997) and fMRI-experiments found commonly activated areas for L1 and L2 in early bilinguals (acquisition of L2 before age seven) and distinct, partly overlapping areas in late bilinguals (after age ten), with the latter showing greater variability for the representation of their L2 (Dehaene 1997). However, questioning the exclusive relevance of age of acquisition, Perani et al (1998) found similar brain glucose consumption during L1 and L2 processing in high proficiency speakers, regardless of age of acquisition. With the level of proficiency being recognized as a decisive factor, aspects like manner of acquisition, extent of training and exposure to L2 received increasing attention. To address the contribution of proficiency level, we compared L2 processing in high and low proficiency speakers (L1 Austrian German, L2 English), who all started to acquire L2 at the same age (8–10). Thus, the two groups differed only in the duration and quality of training and exposure, not in the age of acquisition. We investigated the processing of natural discourse in L1 and L2 with EEG coherence in the frequency band alpha1, which has repeatedly been related to language processes (Klimesch 1999; Weiss and Mueller 2003). This technique allows for a natural setting including acoustic presentation, which cannot be so easily realized with PET or fMRI scanners.

Methods

EEG coherence analysis provides a statistical measure of large-scale cooperative activity between cortical areas, and is based on the similarity of EEG signals within a given frequency band (Rappelsberger and Petsche 1988). Large-scale time-locked synchronicity of cell assemblies has been proposed as one of the principal mechanisms used by the brain to encode and decode cognitive and perceptual information (Singer 1999). The EEG, as a signature of concerted activity of large cell assemblies, appears well suited to detecting global states of functional connectivity and integrated cortical activity (Thatcher et al 1986; Rappelsberger and Petsche 1988; Weiss and Mueller 2003). A coherence value of 1 is interpreted as identifying two signals, independent of their amplitudes, whereas a coherence value of 0 corresponds to unrelated patterns of electrical activity.

We investigated two groups, each with 23 students, all female, L1 Austrian German, right-handed, mean age in both groups 24 years (range 20–30), differing only in their L2 (English) proficiency level. *Group 1* ("high proficiency group") had 14 years (mean value) of exposure to L2 (eight years of school English, six years of university-level English instruction for a degree in English Language and Linguistics). *Group 2* ("low proficiency group") had eight years (mean value) of school training in English and studied for university degrees in various subjects except for languages. Acquisition of L2 started in both groups at the age of 8–10. In a personal pre-test interview conducted in English and in a language experience questionnaire, students of group 1 reported high fluency, high motivation to speak English whenever possible, a high extent of informal L2 use (at the cinema, among friends, via the media), and experience in an English-speaking country (mean time abroad: ten months), whereas students of group 2 reported medium to low fluency level in L2 and very little exposure to a natural English-speaking environment (mean time abroad: four weeks).

The EEG was recorded while the students were confronted with sequences (2–3.2 min) of TV (visual and acoustic) and radio (acoustic only) reports in British English, American English, and Austrian German, matched in length, difficulty, content, and mode of presentation and recorded from radio and television channels of comparable reputation (BBC, CNN, ORF). Thus, language was considered as emergent phenomenon being embedded in a natural context, containing all four levels of linguistic description (semantics, syntax and morphology, phonology, pragmatics). The stimuli were presented in random sequence on a TV monitor using earphones. Immediately after each sequence (1) comprehension was assessed by asking seven factual comprehension questions; additional questions explored (2) subjective comprehension, (3) self-reported attention, (4) cognitive work-load, (5) sympathy for the speaker, and (6) interest in the subject matter. The whole procedure lasted 3 h for each subject. All subjects included gave written informed consent to participate according to the guidelines of the local ethics committee, which had approved the study.

Continuous EEG was recorded with the 10/20 System (sampling frequency: 128 Hz, signal bandpass: 0.5–35 Hz, frequency resolution 0.5 Hz, resistance < 10 kΩ, time constant 0.3 s). We did not use "linked ears"; instead the averaged signals were recorded independently from both earlobes as reference, a method that has been shown to minimize reference artefacts (Essl and Rappelsberger 1998). Each recording session began with alternating eyes open and eyes closed conditions. During the task items, subjects were requested to keep their eyes open. A piezo registration device was attached to the eye lids to control for eye movements, and subjects were under permanent video supervision. In a block design, three baseline conditions (random noise, blank screen, black dot) of 1.5 min duration each were inserted randomly, and the average of the three episodes of random noise was chosen as the most consistent baseline condition. Because of various artefactual reasons (eyeblinks, muscle activity, abnormal paroxysmal activity), eight of the 46 subjects had to be excluded from statistical analysis, resulting in a final group size of 19 subjects per group.

As many of the non-overlapping artefact-free EEG epochs of 2 s duration as possible were Fourier transformed (by FFT), and spectral coherence values were calculated for the alpha1 standard EEG frequency band (8–10 Hz); results for the other five frequency bands will also be published. Coherence values were calculated for all 171 possible combinations between the 19 electrodes. Exploratory data analysis resulted in topographical probability maps (Fig. 1) depicting significant changes of coherence values during the task versus baseline (Wilcoxon test of paired samples). For confirmatory statistical testing, we applied a nonparametric multivariate procedure based on the principle of permutation testing to clusters of significant coherence changes of both groups. We used a permutation test performing 1,000 permutations with the test statistic $t_{\mathrm{sum}} = \sum_{j=1}^{k} t_j$, where the values t_j of the t-statistic for the case of two independent samples were calculated separately for each of the k components (Blair et al 1994).

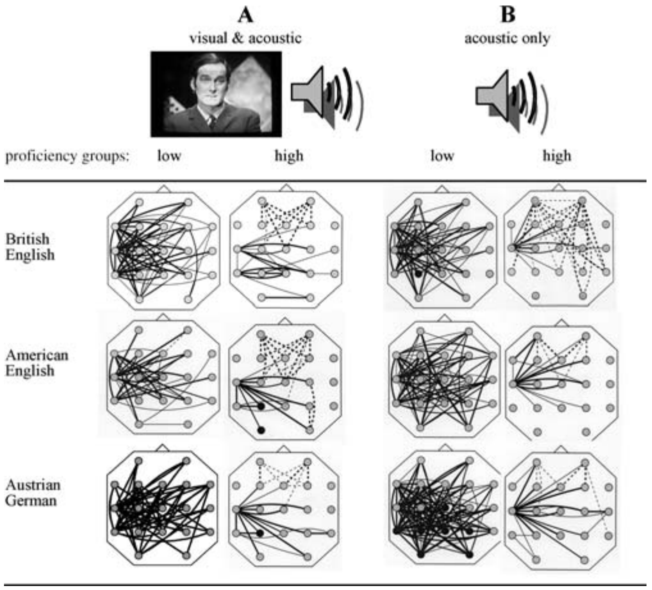


Fig. 1 Topographical probability brain maps of coherence based on non-parametric Wilcoxon tests of paired samples. The 19 electrode positions are indicated by *gray circles*. Continuous lines connect electrodes exhibiting significantly increased coherence in the alpha1 band during the respective task relative to the baseline condition (*thick lines* $P < 0.01$, *thin lines* $P < 0.05$). *Broken lines* symbolize decreases in coherence. High-proficiency and low-proficiency English speakers were confronted with stimulus material (visual and acoustic or acoustic only) in either British English, American English, or Austrian German. The most frequently involved areas were in the left hemisphere (*LH*), with more coherence increases in the low proficiency group

Results and discussion

Cognitive performance

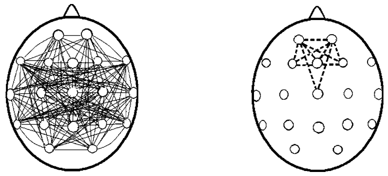
After the recording sessions, high proficiency (HI) and low proficiency students (LO) reported on similar subjective impressions (rating scale from 0 to 5; numbers in parentheses are medians) of required attention (HI: 3–4; LO: 3–5), workload (HI: 2–4; LO: 3–5), sympathy for the speaker (HI: 3–5; LO: 3–4), and interest in the subject (HI: 2–5; LO: 1–5). For 14 out of 24 ratings, the medians of the two groups were identical, and they never differed by more than one rating unit. In subjective comprehension, however, the LO-group students rated themselves lower (1–3) than the HI-group students (4–5). Confronted with seven task-specific comprehension questions, the percentage of correct answers on the English language tasks was (mean values) 86–97% for HI, but only 38–59% for LO students ($P < 0.001$, ANOVA). Even in the two mother tongue German tasks (visual and acoustic or acoustic only), the performance of HI students was slightly better (91%/92%) than that of LO students (84%/80%, $P < 0.05$ for acoustic presentation, ANOVA). Improved L1 proficiency after L2 training has also been observed in a recent fMRI-study on Chinese/English bilinguals (Tan et al 2003).

Topographical probability maps

Visual inspection of the topographical probability maps (Fig. 1) revealed the most systematic differences between the English high-proficiency and low-proficiency speakers for the alpha1 frequency band. A prominent role of this frequency band has been suggested for attention, for inter-individual intelligence differences (Klimesch 1999), and for language processes (modality of input, semantic memory) (Weiss and Mueller 2003). In detail, the group of students with less experience with English (“low proficiency group”) showed more coherence increases than the experienced group (“high proficiency group”) over the entire cortex, with a preference for the left hemisphere (LH, solid lines in Fig. 1). These coherence increases were only rarely accompanied by increases in EEG amplitudes. In contrast, the high proficiency group showed coherence increases only in posterior areas of the LH, in other words, close to those cortical regions responsible for language understanding, whereas prefrontal coherences were typically even lower during language than during baseline tasks (“reduced coherence”, broken lines in Fig. 1). Both characteristic group patterns (widespread LH and interhemispheric coherence increases in low-proficiency speakers, prefrontal coherence decreases in high-proficiency speakers) were observed with all L2 tasks, but surprisingly, also with the L1 tasks (Fig.1, last row). In fact, simply by looking at the coherence probability maps, it would not be possible to tell the difference between the L2 and the L1 tasks.

Confirmation by permutation test with test statistic t_{sum}

Although all changes in coherence indicated by solid and broken lines in Fig.1 were significant, it is difficult to judge the significance of the global impression provoked by these probability maps. Therefore, we subjected two of these “global impressions” to a multivariate test, the permutation test with test statistic t_{sum}. The global impression that coherence increases between all electrodes (cluster A in Fig. 2) were more pronounced in the low-proficiency group than in the high-proficiency group was statistically corroborated for both tasks (visual and acoustic or acoustic only) with British English and with Austrian German, but failed significance for American English. The global impression that coherence decreases between prefrontal electrodes (cluster B in Fig. 2) were more pronounced in the HI group than in the LO group was statistically corroborated for all tasks, with the exception of the acoustic tasks in American English and in German. Thus, in the majority of the tasks, the global impressions from the probability maps were confirmed, although with no distinction between L1 and L2.



cluster :	A: total		B: prefrontal	
proficiency:	low n = 19	high n = 19	low n = 19	high n = 19
British English (L2)				
visual & acoustic	0.036	-0.002*	0.001	-0.065**
acoustic only	0.028	0.001*	0.003	-0.038*
American English (L2)				
visual & acoustic	0.030	0.000	-0.016	-0.063^{+}
acoustic only	0.044	0.008	0.004	-0.032
Austrian German (L1)				
visual & acoustic	0.050	0.007*	-0.002	-0.049*
acoustic only	0.048	0.011*	0.008	-0.022

+, *, **, COH significantly lower in high than in low proficiency group, with p = 0.05, <0.05, <0.01 (global permutation test based on t-statistics)

Fig. 2 Mean coherence differences relative to baseline in two clusters of electrode combinations in the high proficiency group (HIGH) compared to the low proficiency group (LOW) during six different language tasks. Cluster A (all 171 possible electrode combinations): mean coherence increase in the LOW group, not in the HIGH group. Cluster B (11 prefrontal combinations): mean decrease of coherence in the HIGH, not in the LOW group. In both clusters, group HIGH differs significantly from group LOW not only during the L2, but also during the L1 tasks

Improved "cortical efficiency" in the high-proficiency English speakers?

The reduced recruitment of brain regions as a consequence of extensive training of a specific faculty has been repeatedly observed with PET for skills other than language acquisition (Haier et al 1992). With language-specific practice tasks (such as verb generation), reduced brain activity in the prefrontal and especially in the left prefrontal lobe (BA 9, 10, 46) was observed during well practised automatic performance in a series of PET studies (Raichle et al 1994; Petersson et al 1999). FMRI experiments have shown that less proficient bilinguals activated more areas than highly proficient bilinguals during L2 tasks (Chee et al 2001). According to Perani et al 2003, reduced prefrontal activity with a long-term language routine might reflect a decreasing dependence on controlled processing. Reduced coherences between all electrodes in our high proficiency group during the language tasks, therefore, might reflect a more appropriate way of processing the task at hand; but can it also explain coherences below the values observed in the control task (silence, noisy screen), as observed between prefrontal electrodes? These surprisingly robust reductions below baseline require additional explanations.

Coherence reductions at prefrontal electrodes

A range of higher cognitive executive functions (including language functions) have been ascribed to the prefrontal cortex (for review see Duncan and Owen 2000). For example, a language monitoring role, termed "language switch", has been assigned to the dorsolateral part of the prefrontal cortex (Hernandez et al 2000). The prefrontal cortex together with the basal ganglia has been reported to play a crucial role in procedural memory functions necessary for efficient syntactic processing (Ullman et al 1997). Increased recruitment of prefrontal areas in the high proficiency group might be an alternative interpretation of our results and might have gone undetected by our recording technique if (1) coherences occurred at distances too short to be resolved by the 10/20 system, or (2) sub-cortical regions (such as basal ganglia, thalamus) not accessible to EEG recording were involved. In both cases, the intensified cooperation with undetectable regions may have resulted in the observed reduction in coherence between the prefrontal electrodes. Further EEG experiments with higher resolution and/or the application of imaging techniques allowing the investigation of sub-cortical regions (fMRI, MEG) might resolve this issue.

The native language paradox

If the reduced recruitment of cortical areas, with reductions even below baseline at prefrontal electrodes, indeed was the EEG correlate of the more skillful handling of L2, why were the same group differences also observed during L1 processing? Apparently the two groups differed in their listening strategies, regardless of the language of input. Interestingly, the low proficiency group scored slightly lower than the high proficiency group in text comprehension, even of native language texts, while reporting a similar extent of attention, cognitive workload, speaker-sympathy, and interest. Either extensive linguistic L2 training and exposure (even after the age of 8–10) have more impact on brain plasticity than the "critical period" theories would allow for, or our high proficiency speakers had already developed their more efficient approach to language handling during L1 acquisition, or even before, by being predisposed to easier language handling by heritable factors. Thus, EEG coherence analysis could not distinguish between L1 and L2 processing in high- or in low-proficiency speakers. Our results, therefore, are more in agreement with a one-store than with a multi-center model of bilingual language processing. The specific extent and level of complexity of this "one- store" depends on the proficiency of the speaker, and not on the number of acquired languages.

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