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Research Report

Characteristic functional networks in high- versus low-proficiency second language speakers detected also during native language processing: An explorative EEG coherence study in 6 frequency bands

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Abstract

An EEG coherence study was performed with a twofold objective: first, to scrutinize the theoretical concept of "cortical efficiency" in connection with second language (L2) acquisition and, second, to detect cooperations between cortical areas in specific frequency bands indicative for highly proficient L2 processing. Two groups differing only in their level of L2 proficiency were contrasted during presentation of natural language videos in English (L2) and German (native language, L1), with explorative coherence analysis in 6 frequency bands (0.5 – 31.5 Hz). The coherence brain maps revealed more pronounced and widespread increases in coherences in the α1-band (8 – 10 Hz) in low-proficiency than in the high-proficiency L2 speakers. Surprisingly, this difference was obtained also during L1 processing and corroborated for both languages by multivariate permutation tests. These tests revealed additional differences between the low- and the high-proficiency group also for coherences within the β1- (13 – 18 Hz) and the β2-band (18.5 – 31.5 Hz), again during L2 and L1 processing. Since the same group differences were observed during L1 and L2 processing, our high-proficiency group might have profited from a more generic advantage in language or text processing strategy. This strategic advantage was most evident at α1 frequencies, possibly related to a specific way of processing internal mental states (top-down processing).

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Cortical efficiency; Second language learning; Bilingualism; Language training; Proficiency; EEG coherence; Cortical network

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1. Introduction

The well established concept of "cortical efficiency" [13,20,21,23 – 25,39] implies that higher ability in a cognitive task is associated with more efficient neural processing. Whereas intuitively, we would expect higher performance to correlate with more activity, for the cerebral cortex the contrary seems to be the case: higher performance in several tasks, including verbal [50], numeric, figural, and spatial reasoning [38,73] goes in line with reduced consumption of energy in several cortical areas. This phenomenon has also been studied with EEG techniques in different frequency bands. The amount of α background power (7.5 – 12.5 Hz) decreases during cognitive activity compared with a resting state (event-related desynchronization, ERD); this decrease has been observed to correlate with higher performance in subjects with higher

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IQ scores [20,21] or with higher performance after training, indicating a more efficient processing strategy for a cognitive task [48]. Most of these studies come from the psychological literature, focusing mainly on the domain of intelligence but drawing relatively little attention to the investigation of task performance in second language learners or bilinguals. Here, we try to extend the "cortical efficiency" paradigm to an EEG coherence study on second language (L2) processing/bilingualism.

The acquisition of an L2 is equivalent to the training of a cognitive–behavioral skill, and some individuals respond to this training more efficiently than others. If an L2 is acquired before a certain age, even native speaker proficiency is achieved easily (early bilingualism). If training starts later in life, the proficiency level achieved depends on the amount of training, exposure, and on some kind of "predisposition" of the individual. Whereas, in general, L2 processing involves the same language-specific cortical areas (with left hemisphere preference) as native language (L1) processing (see review by Perani and Abutalebi [52]), neuroimaging studies have repeatedly shown that lower L2 proficiency is correlated with more widespread cortical activity [8,33,55,80], tacitly in line with the "cortical efficiency" concept, but not explicitly investigating it. We therefore were prompted to apply this concept as main research hypothesis to late bilinguals/second language learners, comparing, with EEG recording techniques, the recruitment of cortical areas during L2 processing in 2 groups of individuals differing profoundly in L2 proficiency (although both had started to learn L2 at the same age). In contrast to other investigative tools (like fMRI and PET), the EEG can be recorded in a natural environment with inputs very close to casual language use. As a control, we recorded the EEG during processing of L1, a task in which both groups should exhibit the same (native speaker) proficiency. According to the "cortical efficiency" paradigm, we expected lower levels and focused networks of cortical recruitment in both groups during the L1 tasks, but during the L2 tasks only in the group with high L2 proficiency. Bearing in mind the EEG results with other cognitive tasks [20,21,48], we focused our investigation to the α-band, separating it further into a lower (8–10 Hz, α1) and a higher frequency range (10–12 Hz, α2). For explorative comparison, other frequencies were recorded as well (from 0.5 Hz up to 32 Hz). The main results from the lower α-band have been published in short form elsewhere [64]. To our knowledge, this is the first EEG coherence study investigating second language proficiency.

2. Materials and methods

2.1. Subjects

We contrasted two groups of differentially proficient second language speakers (L2 = English). Based on the field of university study (languages versus other domains), a detailed introspective questionnaire and fluency test interviews, the subjects were divided into a group of high and low second language attainment. The students in the "high-proficiency group" were all university language students studying English language and linguistics for a master's degree. Their level of English proficiency was uniformly "very good", as rated by a certified English language teacher. They exhibited an exceptionally high interest in English, self-reported a high motivation to learn foreign languages, called themselves language-talented, used English also in private settings, and had reached their almost native-speaker-like level of L2 proficiency by inclination and their own decision, and not, as in most studies on bilingual subjects, as a consequence of accidental circumstances, as, e.g., birth in a foreign country. Most of them additionally studied a second foreign language (i.e., an L3) like French, Italian, or Spanish, or general linguistics. The average amount of time they had spent abroad in an English speaking country was 10 months.

The students in the "low-proficiency group", university students of various disciplines as medicine, psychology, biology, business, or mathematics (no languages), started to acquire English as their L2 at the same age as the language students (at 9 years, SD 1 year), but never developed their L2 skills any further beyond high school level and regarded themselves as being not specifically talented for languages. The mean amount of time spent abroad in an English speaking country was 5 weeks. In none of the groups, the time spent abroad concerned predominantly a British or an American language background, i.e., in that respect both groups were heterogeneous.

The EEG was recorded from all together 46 female students, but the data of 8 subjects (5 from the high-proficiency group) had to be excluded from the analysis, due to artifacts as, for example, paroxysmal activity. We finally included 19 right-handed students in each group, mean age 24 years in both groups (SD 2.3/2.7 years). L1 in both groups was Austrian German, and both started learning their L2 (English) at the age of 8–10 years. Both female groups were of similar social, educational, and cultural background studying in Vienna. They markedly differed from each other only in their attitude towards language learning, their linguistic experience and knowledge, and hence, their proficiency level in English as their L2.

2.2. Stimulus material

In doing language research, it is important to clarify what we mean by "language": A word? A simple sentence? Or, a complex and enriched, context-dependent discourse? Here, we presented language stimuli as multi-modal speech, with speakers visibly articulating and gesticulating, to simulate a natural communicative situation of every-day life and to investigate the mental processing of language as it occurs in context. The cerebral organization of language at the word and sentence level has been investigated extensively with

PET, fMRI, and event-related potential studies, but voices have been raised that more research should be carried out on the processing of coherent language at the discourse level, where phonetic, syntactic, semantic, and pragmatic aspects of language are integrated, i.e., language as emergent phenomenon [79]. Some brain imaging studies with the focus on L2 proficiency already aspired to full context language input (short story processing), using PET and fMRI [11,53,54].

To be able to control for and investigate different accent effects and different modalities of presentation, we used an enriched paradigm. Since our subjects had been variably exposed either to British or to American English, we balanced our stimulus material to avoid bias towards one of these accents and to provide equal opportunities for the understanding of the texts. Nine different video sequences of TV or radio news (using only male speakers) in British English, American English, and Austrian German were presented within a block design, in randomized order, and in 3 conditions: either as normal TV/video (visual + acoustic); in purely acoustic form (radio reports); or in purely visual form (TV/video with inaudible speakers). By using three different control conditions (blue screen, black point, gray noisy screen) being inserted randomly, we additionally controlled for baseline effects. The three baselines led all to relatively similar coherence patterns in the task versus baseline comparisons. On comparing the baseline tasks between the groups, the Wilcoxon test returned a few significant differences between the 2 groups. However, these changes were only marginal and not reminiscent of the changes seen during the language tasks (Fig. 1).

The gray noisy screen was chosen as most appropriate baseline for the analysis. The duration of the tasks ranged between 2.0 and 3.2 min and the control-items' duration was 1.5 min. The whole recording session took approximately 3 h in total for each student, including interruptions for answering comprehension questions. After each task, 6 psychological reaction parameters were explored with a behavioral questionnaire, comprising (1) actual text comprehension (7 specific questions referring to the actual content, or 4 more general questions after the purely visual tasks—the questions were asked in the language of the task), (2) subjective text comprehension, (3) self-reported attention, (4) cognitive work-load, (5) sympathy for the speaker, and (6) interest in the subject matter.

2.3. EEG recording

We recorded the EEG during L1 and L2 processing in a quiet audio–visual natural discourse setting, conditions easy to realize with EEG recording, whereas the use of fMRI scanners, even if extensive sound shielding is used, is always associated with disturbing background noise and uncomfortable body position.

19 gold-disc electrodes were carefully attached to the scalp with adhesive electrode cream, positioned according to the international 10/20 System [28], 1 additional electrode on the front as grounding; 2 separate electrodes, at the right and left ear-lobe, as the reference electrodes. The recordings were referenced against the calculated mean of the 2 independent ear electrodes (not linked ears); this strategy has been shown [14] 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 and filtered (time constant: 0.3 s; low pass filter at 35 Hz), displayed, and recorded at a sampling rate of 128/s on paper and in digital form for further processing. The electrode resistance at each electrode was checked and did not exceed 10 kΩ. Artifacts were eliminated by careful visual inspection, after EEG datasets had been depersonalized (blinded). Each recording session began with alternating eyes open and eyes closed conditions of several minutes' duration. During control conditions with eyes open, the subjects were instructed to relax, to keep their head in a fixed position when looking onto the screen, and to try to stay cognitively in a resting or idling state. The subjects were requested to keep their eyes always open

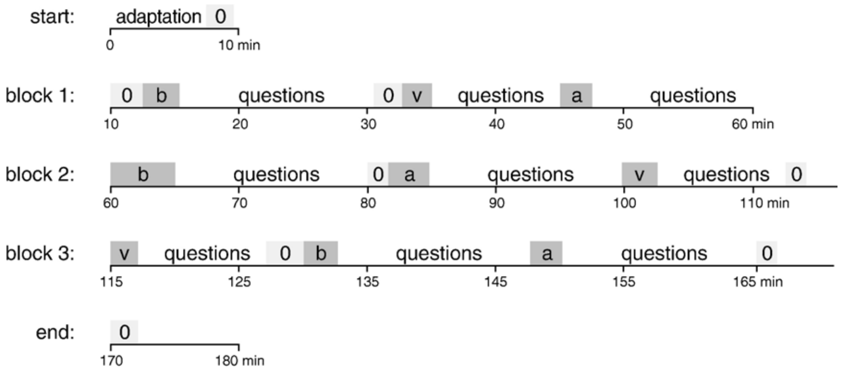

Fig. 1. Timing of the experimental design (at an example). The 3 tasks of each language variety (British English, American English, or Austrian German) were linked together in one block, and the 3 blocks (3 tasks each block/3 blocks) were presented in a randomized order. After each language task (b = bimodal; a = acoustic; v = visual presentation), recording was interrupted for questions to explore comprehension of the language tasks and the attention, work-load, interest in the topic, and attitude towards the speaker. 0 = baseline task.

during the tasks (verified by the piezo eye movement registration device and a video camera).

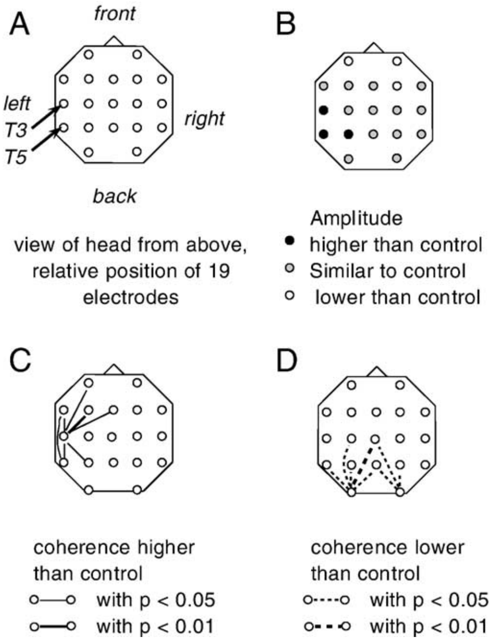

Fig. 2. Explanation of the symbols used in Figs. 4–8. The small circles indicate schematically the positions of the 19 electrodes on the surface of the head. T3 and T5 label specific left temporal positions (referred to in the text). A significant change of amplitude in relation to the default condition ($P < 0.05$) is indicated by the shade of the circles (B). Solid lines connecting single electrode positions: significant increase in coherence as compared to baseline activity (C). Broken lines (D): decrease in coherence as compared to the baseline condition (i.e., more cooperative activity under baseline conditions than in the task).

2.4. Coherence analysis

According to Thatcher et al. [67], the EEG reflects concerted activity of large scale cell assemblies and thus should be well suited to detect global states of integrated cortical function and to elucidate the degree of “electric coupling” between “cooperating” neuronal systems. Based on the concept that similarity of signals reflects similarity of function, EEG coherence analysis has been developed as a statistical measure for the functional cooperation between two cortical areas (to the extent that these areas can be registered separately by scalp electrodes [63]). Many studies report the successful use of EEG coherence to measure functional connectivity [41,61,67,69]. To differentiate the various frequency ranges, the EEG signal as a function of time is transformed into a function of frequency (“spectrum”) by Fourier Transformation (FFT). Broadband EEG was recorded and divided into the following frequency ranges: Delta (δ): 0.5–3.5 Hz; Theta (θ): 4.0–7.5 Hz; Alpha 1 (α1): 8.0–10.0 Hz; Alpha 2 (α2): 10.5–12.5 Hz; Beta 1 (β1): 13.0–18.0 Hz; Beta 2 (β2): 18.5–31.5 Hz. Within a given frequency range, the degree of similarity between the recordings from 2 electrodes is expressed by a coherence value (a kind of correlation coefficient). While *correlation* is a measure for the linear dependence of entities on each other, the term *coherence* has been introduced as a measure for linear frequency-dependent entities. For each frequency band, coherence values were computed. A coherence value can range from “0” (no linear relation between the two signals) to “1” (perfect linear synchronization between the two signals at the frequency under consideration). For graphical presentation, coherence is assigned a statistical weight and represented as a line on a schematic brain map, connecting the 2 electrodes concerned (for details, see Fig. 2). For further mathematical descriptions and technical aspects of coherence analysis, see [4,5,61–63,76].

2.5. Signal and data analysis

Artifact-free 2-s epochs were Fourier-transformed and averaged. The epoch length determined the resolution in the frequency domain. The power spectra C_{xx} and cross-power spectra C_{xy} were computed over all these averaged epochs with a resulting frequency resolution of 0.5 Hz. Averaged cross-power spectra were calculated between all available electrodes, resulting in a maximum of 171 combinations. Data acquisition occurred almost without losses for most frequency bands; however, for β frequencies, some electrodes had to be ignored because of muscle artifacts. In 13 of 19 high- and in 10 of 19 low-proficiency subjects, a mean number of 44 and 34 electrode pairs, respectively, had to be ignored (out of 171). Amplitude (square root of power) and squared coherence per frequency band were computed, leading to 19 power spectra and 171 cross-power spectra for each recording condition (i.e., language tasks and control). Data reduction of the spectra to gain the broadband spectral values was performed for six frequency bands (see Section 2.4) by averaging the neighboring 0.5-Hz frequency bands. As a last step, coherence was computed. It is defined as the squared normalized cross-power spectrum and may be written as the following equation (with K^2 meaning “squared coherence”; C_{XY} (*f*) meaning “smoothed cross-power spectrum” and C_{XX} (*f*) and C_{YY} (*f*) meaning “smoothed auto-spectra of two EEG signals, respectively”):

$$K^2_{\mathrm{XY}}(f) = \frac{|C_{\mathrm{XY}}(f)|^2}{C_{\mathrm{XX}}(f) \cdot C_{\mathrm{YY}}(f)}$$

Statistically significant changes in amplitude and coherence values in comparison to the baseline condition are compiled (see Figs. 4–8—Wilcoxon test of paired samples; symbols are explained in Fig. 2). For evaluating a difference between the English students and the non-English students, we have to consider several variables, simultaneously. In order to find a global effect over all coherence values a so-called global or multivariate test has to be used. Therefore, we used a multivariate permutation test (1000 permutations) with two different two-sided test statistics $t_{\mathrm{sum}} = |\Sigma t_i|$ and $t_{\mathrm{max}} = \max |t_i|$, respectively, where t_i is the student t test (see, e.g., [7,27,29]). t_{sum} is sensitive to departures of all coherence values in the same direction and t_{max} in only a few coherence values.

Note, due to muscle artifacts, some records could not be used for coherence calculation (especially in β1- and β2-band). In such cases, we replaced the missing values with the corresponding group mean.

3. Results

3.1. Behavioral results

A comprehension questionnaire applied after each task revealed (as expected) that the low-proficiency L2 students understood approximately 50% (see Fig. 3) of the English (L2) contributions, whereas the high-proficiency group understood the texts nearly perfectly (95%). Surprisingly, when it came to reproducing the German (mother tongue) texts, the low-proficiency group also scored slightly worse than the high-proficiency group (Fig. 3). No differences between the 2 groups resulted for the other psychometric variables: self-reported attention, work-load, sympathy for the speaker, and interest in the subject matter.

3.2. δ-band (0.5–3.5 Hz)

At these lowest frequencies investigated, no significant group differences could be measured. Coherence during the tasks was often lower than during the baseline condition in both groups, involving especially occipital electrodes (dotted lines in Fig. 4A). We additionally compared the baseline. Amplitude increases were widespread in low-proficiency as well as in high-proficiency students. During the more difficult tasks (L2 processing), coherence increases seemed to be more pronounced in low-proficiency than in high-proficiency second language learners. Multivariate permutation tests, however, were unable to identify any significant group differences ($P > 0.05$ at all tasks, Table 1).

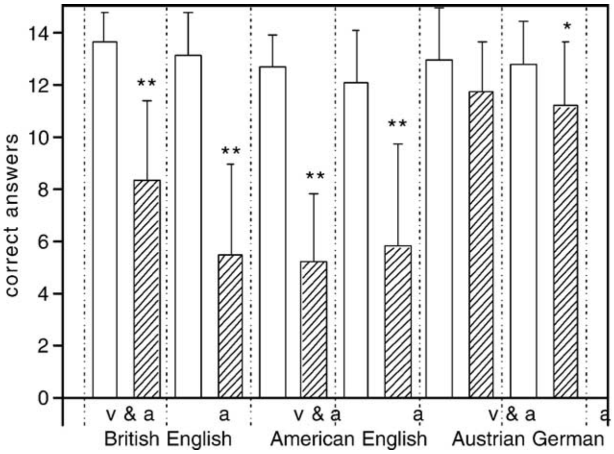

Fig. 3. Text comprehension in high-proficiency (open columns, $n = 19$) and low-proficiency students (shaded columns, $n = 19$). Mean values of the text comprehension scores (maximum score: 14 points for 7 correct answers), bars indicate SD; a, acoustic presentation only; v and a, visual and acoustic presentation; *, **, significantly lower comprehension score of non-English students in comparison to the English students, with $P < 0.05$ (ANOVA and Newman–Keuls test for Austrian German only), $P < 0.01$ (ANOVA and Newman–Keuls test for British and American English), respectively.

3.3. θ-band (4.0–7.5 Hz)

Lower coherence during the tasks than during the baseline, involving frontal and occipital electrodes, was frequently observed for the high-proficiency group (Figs. 4B and C), pointing to a possible group difference. This impression, however, was not substantiated the global permutation test ($P > 0.1$ for all tasks). Coherence increases more often involved electrodes on the left than on the right hemisphere, including left temporal electrodes, but without systematic relation to the experimental design (no relation to language, no relation to group, observed even during the purely visual task, Fig. 4C). Amplitude increases were only seen during the tasks involving acoustic presentation.

3.4. α1-band (8–10 Hz)

The most systematic group differences concerned the synchronized EEG activity in this frequency range, whereas differences concerning amplitudes, again, were unremarkable. In acoustic and in bimodal tasks (i.e., in all audible speech tasks; Figs. 5A and B), increases in coherence had a left temporal focus, independent of the language of the task (L1 or L2). In the low-proficiency group (*left columns*), many additional areas were involved, regardless whether the task involved L1 or L2. The visual impression of a group difference was corroborated by global permutation tests for all 3 British English tasks, by the t_{max} test for the first American English task, but (by the t_{sum} test) also for the first L1 task (Table 1). Coherence decrease involving prefrontal electrodes bilaterally (Fig. 5) was only observed in the high-proficiency group. The obvious impression that reductions in coherence (dotted lines) at prefrontal electrodes were more pronounced in the high- than the low-proficiency group, was corroborated by testing for group differences with a multivariate permutation test (published elsewhere see [64]) for all 3 British English tasks (including the purely visual task), and for all tasks with bimodal presentation (visual and acoustic, including the L1 task).

3.5. α2-band (10.5–12.5 Hz)

In the low-proficiency L2 speakers (Fig. 6), coherence increases were more prominent in the LH than in the RH at all tasks. However, in the high-proficiency L2 speakers (*right columns*), increases in coherence were located more centrally. This difference between high- and low-proficiency

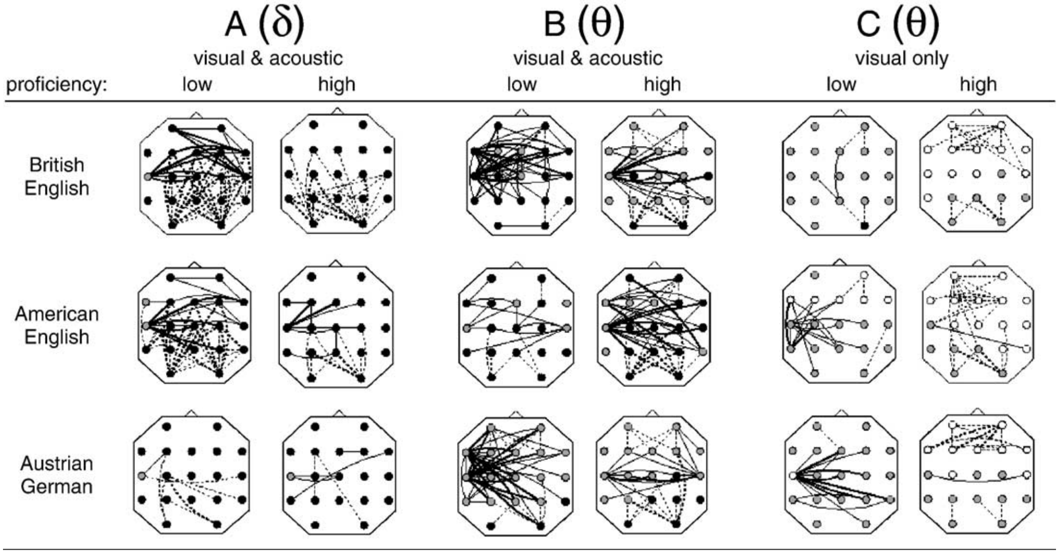

Fig. 4. Significant coherence changes in high-proficiency versus low-proficiency bilinguals relative to the default condition (silence, noisy screen) in the δ frequency band (0.5–3.5 Hz) during processing of visual and acoustic signals (A), and in the θ-band (4.0–7.5 Hz), during processing of visual and acoustic signals (B), and of visual signals only (C). The text was either in British English (1st row), American English (2nd row), or in Austrian German (3rd row). Symbols used in the coherence maps are explained in Fig. 2.

speakers was even apparent with purely visual presentation of speaking humans (Fig. 6C). There were no consistent changes in amplitude. The group difference apparent from visual inspection of the coherence maps was corroborated at least for one of the tasks (British English, combined visual and acoustic presentation by a $t_{\max}$ global permutation test; Table 1).

3.6. β1-band (13–18 Hz)

During bimodal and acoustic language presentation (Figs. 7A and B), the low-proficiency group exhibited left temporal increases in coherence, whereas in the high-proficiency group, increases in far reaching coherences dominated. Increases in amplitude were widespread, without relation to task or group. The $t_{\max}$ global permutation test pointed to several significant group differences (Table 1): the visual impression that low-proficiency differed from high-proficiency students during both bimodal L2 tasks (Fig. 7A) was corroborated, but also for all purely visual tasks (Fig. 7C). One of these purely visual tasks (American English, Fig. 7C) even yielded a significant group difference with the multivariate permutation test t_{sum} (Table 1), based on coherences between all available electrodes.

3.7. β2-band (18.5–32 Hz)

With combined acoustic and visual presentation (Fig. 8A), a dense network of coherence increases became apparent for both groups. Under purely acoustic conditions, the number of coherence increases was smaller. In high-proficiency, but not in low-proficiency students, an inaudible person speaking induced coherence increases almost as dense as in the bimodal situation (Fig. 8C). This was true, whether the (inaudible) language of input was L1 or L2. A $t_{\max}$ global permutation test corroborated the impression of group differences for both

Table 1

Significance (*$P < 0.05$; **$P < 0.01$) for group differences in coherences (6 frequency bands), between high and low-proficiency L2 speakers during 9 language tasks; multivariate permutation tests based on t_{sum} (sensitive to deviations of all coherence values in the same direction) or on $t_{\max}$ (sensitive to deviations in only a few coherence values)

		Two-sided test statistics $t_{\text{sum}} = \lvert\Sigma t_i\rvert$						Two-sided test statistics $t_{\max} = \max \lvert t_i\rvert$					
		δ	θ	α1	α2	β1	β2	δ	θ	α1	α2	β1	β2
British English	Visual and acoustic	0.355	0.128	0.023*	0.065	0.129	0.828	0.119	0.823	0.017*	0.005**	0.001**	0.001**
	Acoustic only	0.937	0.532	0.014*	0.418	0.375	0.859	0.737	0.677	0.022*	0.662	0.051	0.291
	Visual only	0.762	0.906	0.015*	0.834	0.746	0.390	0.989	0.989	0.038*	0.192	0.006**	0.025*
American English	Visual and acoustic	0.532	0.738	0.082	0.236	0.717	0.690	0.319	0.698	0.034*	0.284	0.002**	0.009**
	Acoustic only	0.774	0.886	0.127	0.764	0.321	0.900	0.988	0.978	0.433	0.809	0.164	0.115
	Visual only	0.617	0.435	0.158	0.759	0.026*	0.836	0.353	0.485	0.280	0.113	0.002**	0.005**
Austrian German	Visual and acoustic	0.948	0.644	0.040*	0.955	0.467	0.935	0.777	0.875	0.116	0.434	0.883	0.026*
	Acoustic only	0.079	0.395	0.055	0.740	0.295	0.024*	0.230	0.297	0.178	0.186	0.072	0.001**
	Visual only	0.573	0.489	0.620	0.567	0.754	0.991	0.715	0.622	0.728	0.229	0.027*	0.144

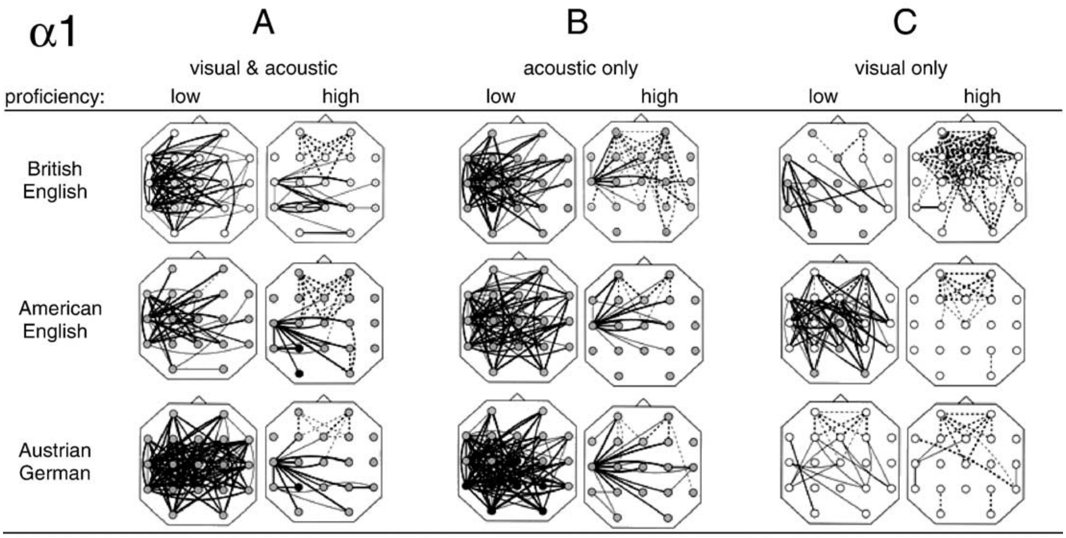

Fig. 5. Frequency band α1 (8.0–10.0 Hz), significant coherence changes (analogous to Fig. 3).

purely visual L2 tasks. Surprisingly, the permutation test returned significant group differences also for all bimodal tasks and for the purely acoustic L1 task (Table 1). This last task (Fig. 8B, last row) even yielded a significant group difference with the multivariate permutation test t_{sum} based on coherences between all available electrodes.

3.8. Influence of modes of presentation (accents, modalities)

Whereas at none of the studied frequencies, the accent, or rather, the language variety of the presented material (American versus British English) was of any discernable influence on the coherence maps, the specific modality of the presentation (visual and acoustic (video mode), acoustic only (radio mode), visual only (mute video) was of significance. Especially the visual only mode triggered patterns different from the other modes, more difficult to interpret with regard to language phenomena. However, even the bimodal and the acoustic only modes exhibited some subtle distinctions. In the α1 frequency band, there was a slight bias towards involvement of frontal electrodes in the "acoustic only" tasks, and towards occipital electrodes in the bimodal tasks ("video mode", visual and acoustic), but only in the high-proficiency group (Fig. 5). In both groups, coherences in the β2-band were much denser during bimodal than during acoustic only presentation (Fig. 8).

4. Discussion

4.1. Overview of the results obtained with 6 frequency bands

We obtained the most striking differences between high- and low-proficiency L2 speakers in the α1 frequency band

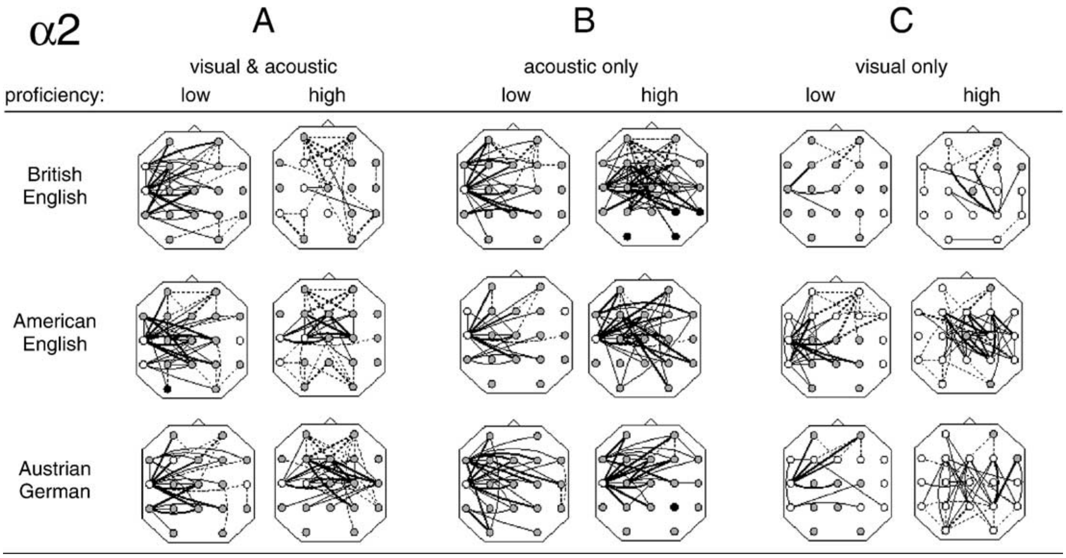

Fig. 6. Frequency band α2 (10.5–12.5 Hz), significant coherence changes (analogous to Fig. 3).

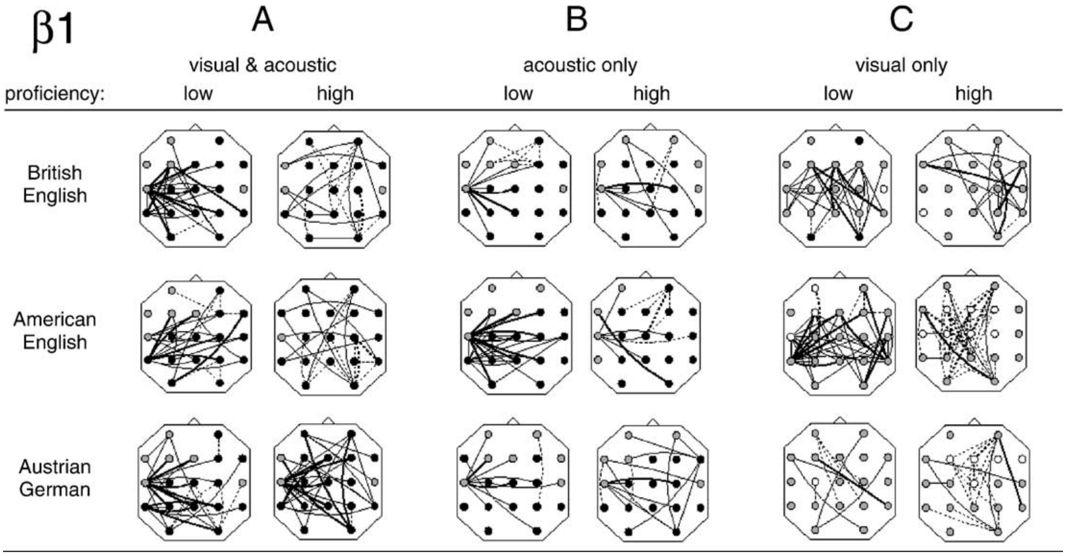

Fig. 7. Frequency band β1 (13.0–18.0 Hz), significant coherence changes (analogous to Fig. 3).

(8.0–10.0 Hz). A trivial reason could have been a decline in attention and interest of the subjects having difficulties to follow a text in a foreign language, favoring the transition into an indifferent, dazing condition with an increased risk for eye closures, inevitably followed by increased α activity. Such an explanation can be excluded for several reasons: (1) practically no increase in α amplitudes was observed during L2 processing (almost no black circles in Figs. 5 and 6). An increase in α power could have been taken as an indication for reduced alertness [34], but the group differences observed by us concerned α coherence, not α amplitudes. This would suggest that there was no difference in general state of alertness between the groups, but that the cooperative networks engaged were different. (2) α1 coherence increases were also seen during the L1 tasks, which should have been equally distracting for the two groups. (3) The duration of the tasks was short (2.0–3.2 min), and each presentation was followed by a demanding control interview, in which (4) the low-proficiency L2 speakers rated their level of attention and interest in the presentations not lower than the high-proficiency speakers did. (5) α coherence increases were not more pronounced for the purely visual tasks, which in the absence of any audible language input could have been more "boring". (6) A video camera system allowed careful observation of the subjects during the tasks, and (7) eyes were directly supervised by a piezo device. Therefore, we interpret our observation as increased α1 coherence during an attentive alert state, invested in the active processing of sensory information.

EEG activity in the α-range (8–12 Hz), often regarded as an "idling rhythm" of the brain, is diminished if attention is

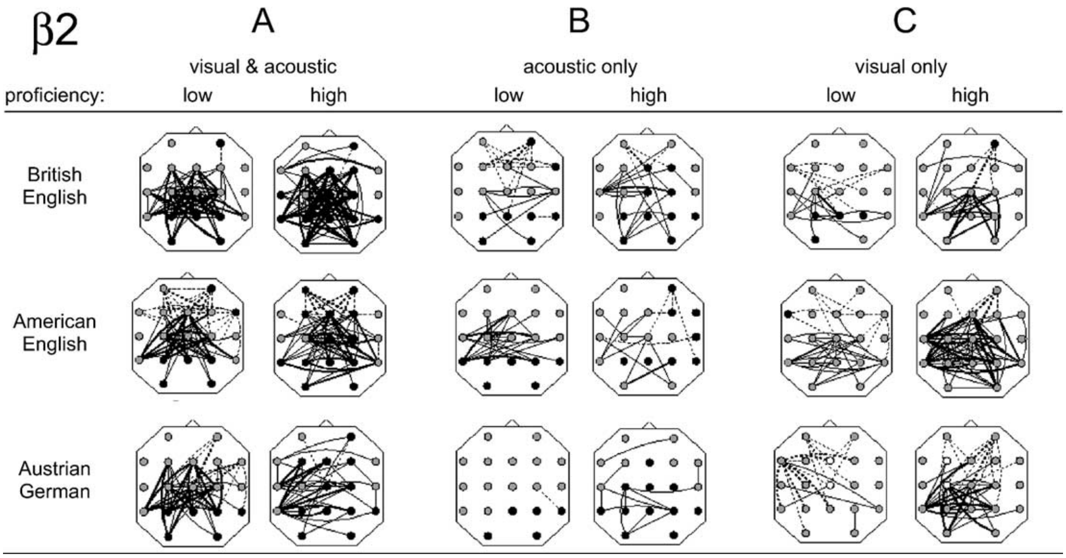

Fig. 8. Frequency band β2 (18.5–31.5 Hz), significant coherence changes (analogous to Fig. 3).

focused to sensory stimuli (for review, see [34]). In visual areas, increased α amplitudes have been correlated with decreased overall metabolism [16]. Cortical cooperation in this frequency range, however, may not reflect an inactive brain state, but internal mental activity (top-down processing, [74]). In the high ability L2 speakers of our study, α1 (8–10 Hz) coherence increases were much more limited than in the low ability L2 speakers, emanating exclusively from left temporal electrodes (involving temporo-parietal language areas). If this group difference would have been seen only in the L2 tasks, we could interpret it as indicative for increased attention of the high-proficiency students directed to the tasks ("alpha blocking"), whereas the low-proficiency students exhibited less attention towards tasks they didn't really understand. However, the same group difference was seen with the L1 tasks and, therefore, cannot simply be explained by different levels of attention. Reduced coherence in the α1-band between cortical areas of our high-proficiency L2 speakers is reminiscent of the studies of the Neubauer group [20,21,48], who observed a decrease in α ERD in several brain regions of subjects with superior performance in cognitive tasks (including verbal tasks). These latter authors proposed this phenomenon as a correlate of intelligence. Although a difference in intelligence of our two groups cannot be excluded, there is no obvious reason for such a difference (both groups consisted of individuals studying for an academic degree).

Cortical cooperations in the α2-band have been interpreted similarly as in the α1-band, with emphasis on semantic memory processes [35,37,65]. In this higher α-band (10.5–12.5 Hz), the low-proficiency group yielded coherence increases involving predominately left temporal electrodes (suggesting involvement of fronto-temporal language areas), but not so the high-proficiency group, where increase in coherence predominantly involved the central electrodes. Again: If this difference would have been seen only during L2 processing, we could have speculated on linguistic "extra duties" of our low-proficiency students; but it was seen also during L1 processing.

The coherence maps obtained in the frequency ranges below and above α provided different results, with each band exhibiting its own pattern. Proposals for cognitive correlates of EEG activity in the δ-band during wakefulness are scarce; one has been attention directed to internal processes during mental tasks [26]. A tendency in low-proficiency, but not in high-proficiency students, to δ coherence increases during L2, but not during L1 processing, could be interpreted as increased mental effort invested by the less skilled students to compensate for their lower level of L2 proficiency. EEG activity in the θ-band has been related to processes at the interface of memory and language, reflecting dynamic interactions between the hippocampus and the neocortex [3,36], and recently also to grammatical processing [31]. In our experiment, θ coherence during the task often was lower than during the rest condition, especially in the high-proficiency group. Although it is tempting to speculate on a relation to cortico-hippocampal cooperation and memory processes, it remains unclear why this should happen even during the purely visual tasks (Fig. 4C). In summary, the exploratory results obtained in the lower frequency bands δ and θ did not allow for any convincing conclusions in the search for correlates for language proficiency.

Frequencies in the β-bands have been related to higher cognitive functions and to problem solving via symbolic systems, independent of the sensory modality involved, often in relation to language-specific neuronal activities or in relation to visual activities [22,58,75,77]. Since in our recordings the EEG spectra have been averaged over 2 min, they reflected the "cognitive state" of the subjects rather than the correlate of a short lasting specific linguistic accomplishment. This might explain why we found more significant results within the α than the β range in our study. At β1 frequencies, left temporal clustering of coherence increases in the low-proficiency group was reminiscent of the results obtained at α2 frequencies, again without clear difference between L1 and L2 processing. A totally different pattern emerged at β2 frequencies, but the coherence maps did not reveal any obvious differences between high and low ability speakers during the "real" language tasks (i.e., those tasks with acoustic language presentation). During purely visual presentation of the test material, however (i.e., material without explicit communicative meaning, since no sign language was used, see Fig. 8C), increase in β2 coherence appeared more pronounced in high-proficiency than in low-proficiency speakers. EEG activities at β2 frequencies during language processing have been related to imagery [32,75], and in our study the high-proficiency speakers might have been more prompted and eager to make sense of lip movements and gestures. In both β-bands, the $t_{\max}$ permutation test returned more significant group differences (Table 1) than would have been expected after inspection of the coherence maps. This observation is in line with the experience that group differences during cognitive tasks in that frequency band often rely on selected electrode pairs [75] and not on clusters of electrodes as in the α-band. Further studies with new groups would be required to clarify if particular pairs of electrodes were involved reliably in this effect.

4.2. Subcortical involvement?

Exclusively in the high ability group, we observed decreases in α1 coherence at prefrontal electrodes during the language tasks in comparison to the rest condition. A decreased metabolic rate in the left prefrontal cortex during a language task, subsequently to experience and practice, has already been observed in PET studies with monolinguals [68]. Methodologically, more similar to our results, Petsche et al. [57] have observed a "decrease in coherence" during silent simultaneous interpreting, a cognitive task to some degree comparable to ours, in the same frequency band as we (α1). The authors have tentatively interpreted this task-related prefrontal decrease in coherence as a hint towards more cooperation of the prefrontal cortex with subcortical brain regions during the task of interpreting than during the baseline condition [57,58]. Subcortical regions (basal ganglia) in bilingual processing have also been reported to play a crucial role in language switching and language selection, as evidenced by a case of subcortical polyglot aphasia [1].

Highly mechanized activities like walking or speaking (or text processing) happen without our conscious awareness of all details involved. PET studies provide evidence that the cerebellum (together with the motor cortex) participates in imagined, mental movement, and silent speech [56]. In an fMRI study investigating lexical–semantic working memory, Crosson [9] found increased activation in the thalamus and the caudate nucleus during differentiation of semantically related words from each other. Language processing is tightly related to speech production [17,45,78] and several observations point to the involvement of the basal ganglia in the latter (e.g., [10]). The frontal/basal ganglia circuitry forms also the core of one of the recent neurolinguistic explanatory theories of language processing (procedural/declarative model) [70,71]. Although language is predominately regarded as a cognitive skill, it relies heavily on the concerted fine-tuning of motor activity (tongue, lips, jaw, larynx, airways, etc.). A recent PET study on cerebral blood flow changes in Parkinson patients subjected to voice training [40] suggests a shift from an abnormally effortful (premotor cortex) to a more automatic (basal ganglia, anterior insula) implementation of speech–motor actions in Parkinson patients after training. A crucial role for subcortical structures in informal L1 acquisition is proposed by Fabbro [15]: "*When an L2 is learned formally and mainly used at school, it apparently tends to be more widely represented in the cerebral cortex than the first language* (*L1*)*, whereas if it is acquired informally, as usually happens with the L1, it is more likely to involve subcortical structures* (*basal ganglia and cerebellum*)". Interestingly, if bilinguals acquire Parkinson's disease, their L1 tends to be affected more severely than their L2 [81], pointing to a more important role of the basal ganglia for the more fluent language. If, during skillful language processing, neuronal activity of the prefrontal cortex would be recruited into cooperation with subcortical regions (for anatomical connections between the prefrontal cortex and subcortical regions see [47]), the result might well be a reduced cooperation of the prefrontal cortex with other cortical regions, in comparison to the baseline condition ("default state"), which is known to involve specifically prefrontal activity [42,60]. In another study, Raichle et al. [59] have found that prefrontal activity decreases with overlearning of a verbal task. Future research using combined recording techniques (EEG and fMRI), allowing direct access to subcortical regions, may shed more light on this issue.

4.3. The L1 paradox

The widespread increase of coherence in the α1 frequency band in the low-proficiency group may have reflected a more effortful way of processing in the absence of skilled L2 routines, in agreement with the "cortical efficiency" paradigm. However, the same increase in α1 coherences was observed also during the L1 tasks. It seems paradoxical that the low-proficiency L2 speakers should have invested also more effort to understand the texts in their mother tongue. Although it cannot be excluded that the EEG coherence patterns reflected in part the motivation of the subjects (with language students being more motivated to participate in a language-related study), the psychometric variables explored after each task did not point into this direction. For example, the high-proficiency subjects did not report a higher interest in the subject matter of the task. Rather, these patterns may reflect more general language processing strategies.

On the one hand, the L1 and the L2 systems are highly inter-related [66], and proficiency in foreign languages can indeed back-propagate to native language proficiency, as has been shown already in purely behavioral experiments [72]. In fact, also in the behavioral part of our study, the high-proficiency subjects, when answering to the questionnaire, produced slightly better results even for the L1 tasks (Fig. 3). A possible explanation for this result might be improved L1 comprehension after years of extensive L2 training. Among linguists, this phenomenon is known as "backward transfer". Findings from linguistic research demonstrated that intensive and successful foreign language learning can have a beneficial effect on the development and use of mother tongue skills [30].

On the other hand, the behavioral difference in L1 was, however, smaller than in L2. It must be concluded that the differences in these brain maps were not so much related to the ease or skill of specific L2 processing alone. More likely, they relate to fundamental differences between the two groups in terms of general language processing, listening comprehension, or cognitive control strategies, with little relation to the degree or familiarity with a particular language, but perhaps in relation to the amount of linguistic training in text processing or listening comprehension skills or the amount of general sensitivity to linguistic structures in all languages (L1 and/or L2). The group of the highly proficient L2 speakers habitually might apply more efficient or more focused linguistic strategies, maybe as a consequence of more sophisticated language training and knowledge. In a recent study by Bialystok et al. [6], bilinguals showed faster reaction times than monolinguals in tasks requiring cognitive control. Faster reaction times were correlated with activity (detected with MEG) in superior and middle temporal, cingulate, and superior and inferior frontal regions, largely in the left hemisphere. Other recent studies refer to the crucial role of phonological working memory (with participation of several parts of the frontal cortex (for review see [12]) in nearly-perfect L2 attainment [8]. The increased ability to process unfamiliar speech sounds in fast L2 learners was correlated with a higher degree of myelination in left parietal regions (as quantified by voxel-based morphometry); more efficient myelination may increase the speed of neuronal processing [19]. Further functional [18] and structural data [2,46] strengthen the supposition of a neurobiological correlate of enhanced language learning ability. Since we recruited our high-proficiency group from a university institute dedicated to L2 processing ("anglistics", i.e., English studies), we may have selected for individuals with enhanced language learning ability. Whether this enhanced ability existed from birth on, due to genetic predisposition [43,44,49], or was acquired later by training, or is a consequence of both factors, must remain an open question to be clarified by future research (for a recent review on the bilingual nature/nurture debate see [51,52].

4.4. Conclusion

In conclusion, we have found, based on patterns of EEG coherence, that well trained, highly proficient, and highly motivated L2 speakers differed profoundly from non-proficient L2 speakers, not only during L2, but also during L1 processing. In the trained L2 speakers, a typical language processing pattern limited to left temporal electrodes became apparent in the α1 frequency band only, whereas in less proficient subjects, α1 coherence was more widespread, and left temporal clustering was observed also for α2 and β1 coherence increases. Since these group differences were also observed during native language processing, our explorative data may point to the EEG coherence correlate of differing language processing strategies in general. The strategy of our high-proficiency group may rightfully be described as more economic, in support of the "cortical efficiency" paradigm. Cortical efficiency might be a key concept for several factors important for language learning, such as, practice, exposure and inclination or motivation to language acquisition in general.

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