ELSEVIER

International Journal of Psychophysiology 26 (1997) 77–97

INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY

The possible meaning of the upper and lower alpha frequency ranges for cognitive and creative tasks

H. Petsche*, S. Kaplan, A. von Stein, O. Filz

Institute of Neurophysiology, University of Vienna, Währingerstr. 17, A 1090 Wien, Austria

Abstract

This study is aimed at verifying the functional independence of two frequency bands within the alpha range. It is based on experiments that examined the role of these two bands with regard to the amount of local electrogenesis (amplitude) and the cooperation of brain areas (coherence) in mental tasks concerning: (1) visual perception and imagery; (2) listening to and composing music; (3) verbal and visual creativity; and (4) aspects of mood. In all experiments EEG were recorded for at least 1 min during each task, separated one from another by at rest periods of at least equal lengths. EEG electrodes were pasted according to the 10/20 system (averaged ear lobes as reference). After FFT power was calculated for all 19 electrodes, coherence was estimated for all possible electrode pairs (i.e. 171). This was done for six frequency ranges between 1.5 and 31.5 Hz, the alpha range having been divided into two (7.5–9 Hz and 9.5–12.5 Hz). The spectral parameters obtained during each task were compared with those of the merged EEG at rest, significant changes ($P \leq 0.01$–$P \leq 0.05$) were entered into schematic maps of the brain. Generally, fewer differences were found for amplitude than for coherence. In all four tasks concerning visual perception the clearest differences were found in single person studies. But also in group studies more or less distinct differences were found between alpha 1 and 2. Also in the series with music the two alpha bands did not behave uniformly, nor were uniform features found in the two series of musically trained and untrained subjects. Distinct discrepancies were also found in a verbal and visual imagery task. With respect to mood, only elevated mood was correlated with a decrease of coherence in alpha 2 and an increase of amplitude in alpha 1. This study though hinting at a different functional significance of these two alpha bands, however, does not allow to draw any conclusions as to their distinct functional meanings. Generally, the long-term coherence changes observed under these different mental tasks support the idea that part of information processing in the brain is reflected by the EEG. Structural peculiarities and microelectrode recordings of the cortex support this conclusion. © 1997 Elsevier Science B.V.

Keywords: Functional independance; Local electrogenesis; Cooperation of brain area's

* Corresponding author.

PII S0167-8760(97)00757-5

1. Introduction

It has often been claimed that the subdivision of the EEG into different frequency bands, which goes back to Hans Berger and has its origin in the clinical EEG, is justified also from a functional point of view. However, its alleged uniformity has often been questioned, particularly with regard to the alpha band. Although the problem of its individuality was studied by several authors by means of factor analysis (Herrmann et al., 1980) no unanimous answer to this question has been found so far. Based on structure–analytic reflections several authors recommended a subdivision of the alpha into at least two bands. Since, moreover, several psychological studies also support the idea of a functionally different meaning of higher and lower-frequency alphas (Klimesch et al., 1993), we wanted to know whether differences within the alpha range might also show up in cognition studies with ERP in the on-going EEG. For this purpose two spectral parameters, amplitude and coherence, were used as indices. Klimesch (1996) found that the upper alpha band reflects the retrieving of semantic long-term memory information by determining an 'individual alpha peak frequency' for each subject separately. Our study, based on broad frequency bands, therefore, had a priori lower chance to help solving this problem, all the less as our studies were performed mainly on groups and not on individuals. In spite of these drawbacks, our amplitude and coherence studies on cognitive processes brought further evidence that splitting the alpha may allow more insight into the possible functional meaning of the alpha rhythms.

With this aim in mind the ongoing EEG was studied in several sets of experiments. One of them concerned the visual world with contemplating and memorizing pictures, mentally creating images and silently reading, another the world of sounds while listening to and composing music. The third set of experiments concerned eventual correlations between the skill in performing mental tasks and the amount of coherence changes. We called the two frequency bands to be studied alpha 1 and 2; they were arbitrarily defined between 7.5 and 9, and between 9.5 and 12.5 Hz, respectively.

2. Method

The method used in this study has been developed by us several years ago (Rappelsberger and Petsche, 1988). It compares the values of amplitude and coherence during a mental process with those during the averaged EEG at rest. Since this method is based on EEG epochs of at least 1 min duration, the results represent average values of the changes of these parameters by a mental process. The EEG is recorded from the usual 19 electrodes of the 10/20 system with respect to averaged recordings from both ears (TC 0.3, HF filter 35 Hz) and is digitized at 128/s. All artifact-free 2-s periods of each record are Fourier transformed (FFT) to compute grand averaged power (19) and cross-power spectra (171) in order to estimate coherence values for all possible pairs of electrodes. The coherences are Z-transformed towards an $N_{0,1}$ distribution. The spectral parameters are computed off-line for six frequency bands between 1.5 and 31.5 Hz. In order to obtain a survey over the entire scalp and to reduce the number of data, no absolute values but, instead, their significant (Wilcoxon) increases and decreases with respect to the EEG at rest are taken into account and topographically plotted as probability maps. Up to now this method has been successfully applied to more than 500 subjects.

Empirically, this method has proven most useful for various mental tasks, among them listening to music and speech, simultaneous interpreting of languages, reading, doing mental arithmetic, conceptual thinking and others (Petsche et al., 1986, 1987, 1988, 1992, 1993; Lindner et al., 1989; Richter et al., 1993; Von Stein et al., 1993). A drawback of this procedure in its application to the EEG is that the EEG is not a stationary process and the phase relationships between different brain regions are not only linear. Therefore this method is far from being perfect. If, in spite of these restraints we believe it to be valid it is because it has yielded a great number of reasonable and consistent results which proved to be plausible in terms of both neurophysiology and neuroanatomy and helped in understanding several phenomena.

3. Results

3.1. Visual tasks

The first series to be reported concerns visual tasks. The following results are from an experiment on 38 females in which four different visual tasks had to be performed: (1) to contemplate a slide of a painting projected onto the wall; (2) to silently read a text, for distraction; (3) to memorize the painting shown just before; and (4) to mentally create a picture of one's own choice. Each task was performed for 2 min and was repeated with four paintings of different periods of the history of the Fine Arts (the so-called 'bean-festival' by Jordaens, an etching by Rembrandt, an abstract painting by Kandinsky and a portrait by Holbein). The spectral data of the EEG recorded during these tasks were compared with those of the merged EEG at rest recorded before, between and after the tasks, each time again for 2 min. The first aim of this study was to examine the influences of these four tasks on both amplitude and coherence in comparison to their values during the merged EEG at rest. A second aim was to look for possible EEG differences with regard to a pre-education in the Fine Arts (half of the 38 females had successfully passed an artistic training in the Viennese Academy of the Fine Arts and obtained the Master degree). This latter aspect, however, will only be touched on here. First the group is considered as a whole with the main emphasis being put on the alpha band.

The upper part of Fig. 1 presents the summarized findings averaged over the total group of 38 subjects and concerns only the amplitude during the four above mentioned tasks. Local changes of amplitude with respect to the EEG at rest are represented topographically as probability maps on schematic drawings of the head as seen from the top (the squares at the electrode sites indicate probabilities, the largest ones for $P \leq 0.01$, the smallest for $P \leq 0.1$; black squares indicate significant increases of amplitude, white squares decreases). Only the two alpha bands are being discussed here.

The following differences can be recognized: while contemplating the pictures(Fig. 1A), amplitudes turned out to decrease in both alpha bands over almost the entire skull, but to a lesser extent in alpha 1 than in alpha 2; in contrast to this, while memorizing the paintings (Fig. 1B) the extent of decrease in amplitude was less in alpha 2 than alpha 1; this effect was somewhat slighter while mentally creating a picture (Fig. 1C); reading (Fig. 1D), finally, influenced alpha 1 less than alpha 2. Many more differences were found in the beta bands, which, however, are not to be discussed here. The slight differences in the reactions of amplitude hinted at different functions of the upper and the lower alpha band: whenever visual perception was involved, as with contemplating and reading, a larger area of the cortex was concerned and showed more of a decrease in alpha 2 than in alpha 1, in contrast to those conditions which did not require visual perception. The reverse holds true of alpha 1.

Such a subdivision of the alpha into two bands seems to be even more justified if the subjects were divided into two subgroups, according to their artistic training; this is shown in the lower part of Fig. 1 for the same four tasks. The respective left columns refer to the 19 artists (A), the right columns to the group of non-artists (N-A). Group differences were found with all four tasks.

While contemplating the pictures, the extent of the zone of amplitude reduction in the two alpha bands was, in all four tasks, considerably smaller in artists than in non-artists, probably because artistically trained subjects are more accustomed to contemplate paintings and, thus, are not aroused so much as untrained subjects.

While memorizing the pictures, the group differences became even more distinct: almost only alpha 1 was affected by memorizing in the artists, whereas alpha 2 hardly showed any reaction. If one takes into account that the upper alpha band is said to be involved in task-specific and memory processes and subjects talented for the Fine Arts may be supposed to have visual memory capacities superior to those of non-talented and therefore also artistically non-educated subjects, one could surmise that the almost missing amplitude reduction in alpha 2 in artists while memorizing reflects these abilities.

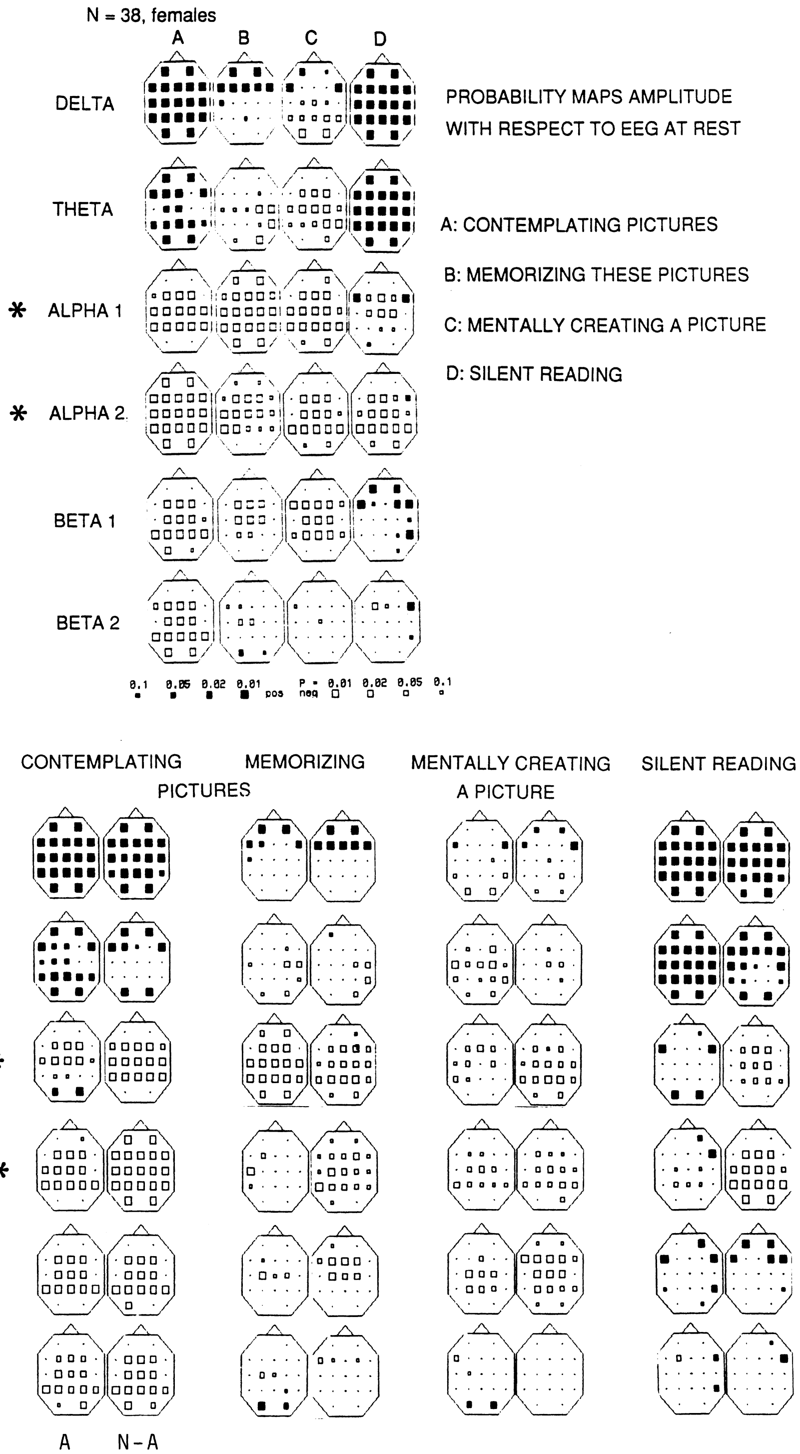


Fig. 1. Probability maps for changes of amplitude with respect to the merged EEG at rest while (A) contemplating pictures, (B) memorizing these pictures, (C) mentally creating a picture and (D) silent reading. Upper part: 38 females, lower part: the same

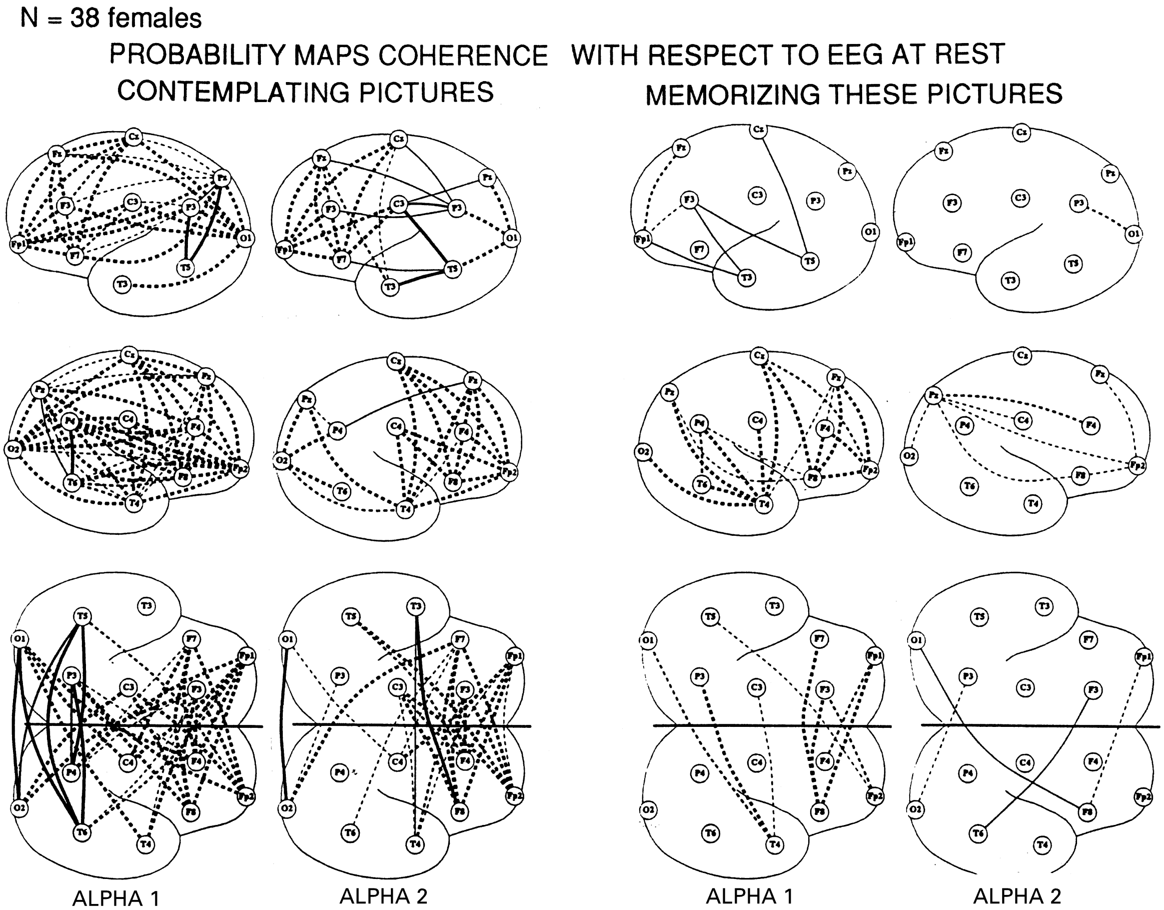
When pictures had to be mentally created both alpha bands were affected in much the same way; but also under this condition, the extent of amplitude reduction was lesser in artists than non-artists.

Silent reading, similar to contemplating, hardly affected artists in amplitude, quite in contrast to non-artists. Also this difference could be due to the higher developed ability of pattern recognition in artists, which is an important component of the reading process.

As a matter of fact, the two alpha bands evidently behave in different ways in these four visual tasks. The differences between artists and non-artists very likely are due to the fact that the former are better trained in the processing, memorizing and mental creating of visual patterns and therefore need not so much 'brain work' for this purpose. That the difference between the two groups is most conspicuous in memorizing and in alpha 2 may be caused by retrieval from memory requiring less effort in artists than non-artists.

Coherence estimates for these four tasks turned out to reveal even more conspicuous differences

subjects but separated into artists (A, $n = 19$) and non-artists (N-A, $n = 19$). Full squares: increases, empty squares: decreases of amplitude with respect to the merged EEG at rest. The sizes of the squares are porportional to the degree of significance ($P \leq 0.01$, 0.01, 0.05 and 0.1). Note the differences of amplitude changes in each of these four visual tasks as well as the differences between artists and non-artists.



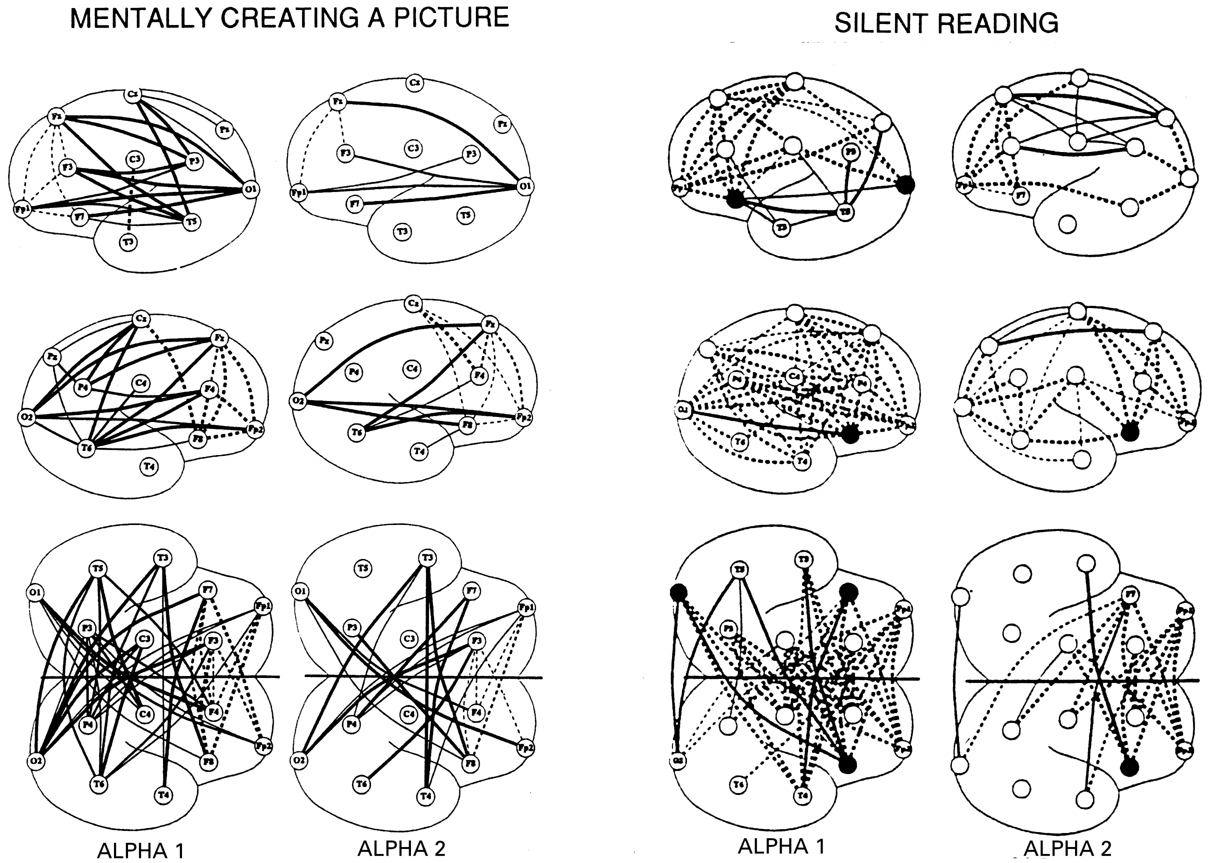


Fig. 2. Significant changes of coherence in alpha 1 and 2 for 38 females while performing the four tasks as described in Fig. 1. The curved lines connecting electrode sites indicate significant increases (drawn-out) and decreases (dashed) of coherence with respect to the merged EEG at rest ($P \leq 0.01$ for the thickest, $P \leq 0.05$ for the thinnest lines). The coherence changes with respect to the EEG at rest are strictly different for the two alpha bands and for all four tasks.

between the two alpha bands as shown in Fig. 2 for the total group of 38 females. These changes, based on the Wilcoxon signed ranks test, are represented as probability maps; to this purpose pairs of electrodes with significant coherence changes were connected by lines, drawn-out for increase and dashed for decrease. The strength of the lines is proportional to P between ≤ 0.01 for the thickest and ≤ 0.05 for the thinnest lines. The maps show the intra- and the interhemispheric coherence changes with respect to the EEG at rest between all of the 171 possible electrode pairings. Each of these maps represents an average of several hours of EEG recording: 6 h each for contemplating, memorizing and reading, 1 h 16 min for mentally creating an image and 3 h 48 min for EEG at rest.

While contemplating the pictures, coherence generally decreased with respect to EEG at rest in each hemisphere, the right one, however, being clearly more involved in alpha 1 than in alpha 2. The moderately large number of coherence decreases in O1 and O2 is noteworthy and is discussed below. In addition, there is more ipsi- and contralateral functional coupling and decoupling between hemispheres in alpha 1 than in alpha 2. Nevertheless, increased symmetric interhemispheric cooperation was found in the posterior parts of the brain mainly in alpha 1. The cooperation between the two frontal areas, on the other hand, was considerably reduced in both alpha bands while contemplating the pictures. This is in agreement with previous findings of a reduction of frontal cooperation when opening the eyes (Petsche et al., 1988).

Memorizing the pictures induced much fewer coherence decreases in the two alpha bands. Alpha 2 was least concerned. Just as with contemplating the pictures, the right hemisphere presented more coherence decreases in alpha 1 than alpha 2.

Up to now, the differences between the two hemispheres can only be interpreted as a hint to the importance of the right hemisphere, and especially the electrode sites T4, F8 and Fp2 for both contemplating and memorizing pictures.

Mentally creating a picture, on the other hand, induced a completely different pattern: an outstanding feature of this task are the numerous long-distance connections with increased coherence, both ipsi- and contralaterally; these increases were more pronounced in alpha 1 than in alpha 2. Interhemispheric cooperation increased mainly in alpha 1 between the posterior parts of the brain. Such an activation of long-distance connections has often been found when creative activities were demanded. Only a few interfrontal decreases were seen, particularly in alpha 1.

Finally, silent reading seemed to produce the greatest differences between the two alpha bands. In the left hemisphere, a gravity center of coherence increase was found in T5 for alpha 1 but not for alpha 2, which, in contrast, was characterized by long-distance increases between occipital and frontal regions in the right hemisphere; apart from that, numerous connections with decreasing coherence were also found. Between the hemispheres, most decreases were found in alpha 1. However, the interhemispheric increases between F7, T3, T5 and O1 on the one hand, and F8, T4 and O2 on the other in alpha 1 seem to be of some importance for the process of silent reading.

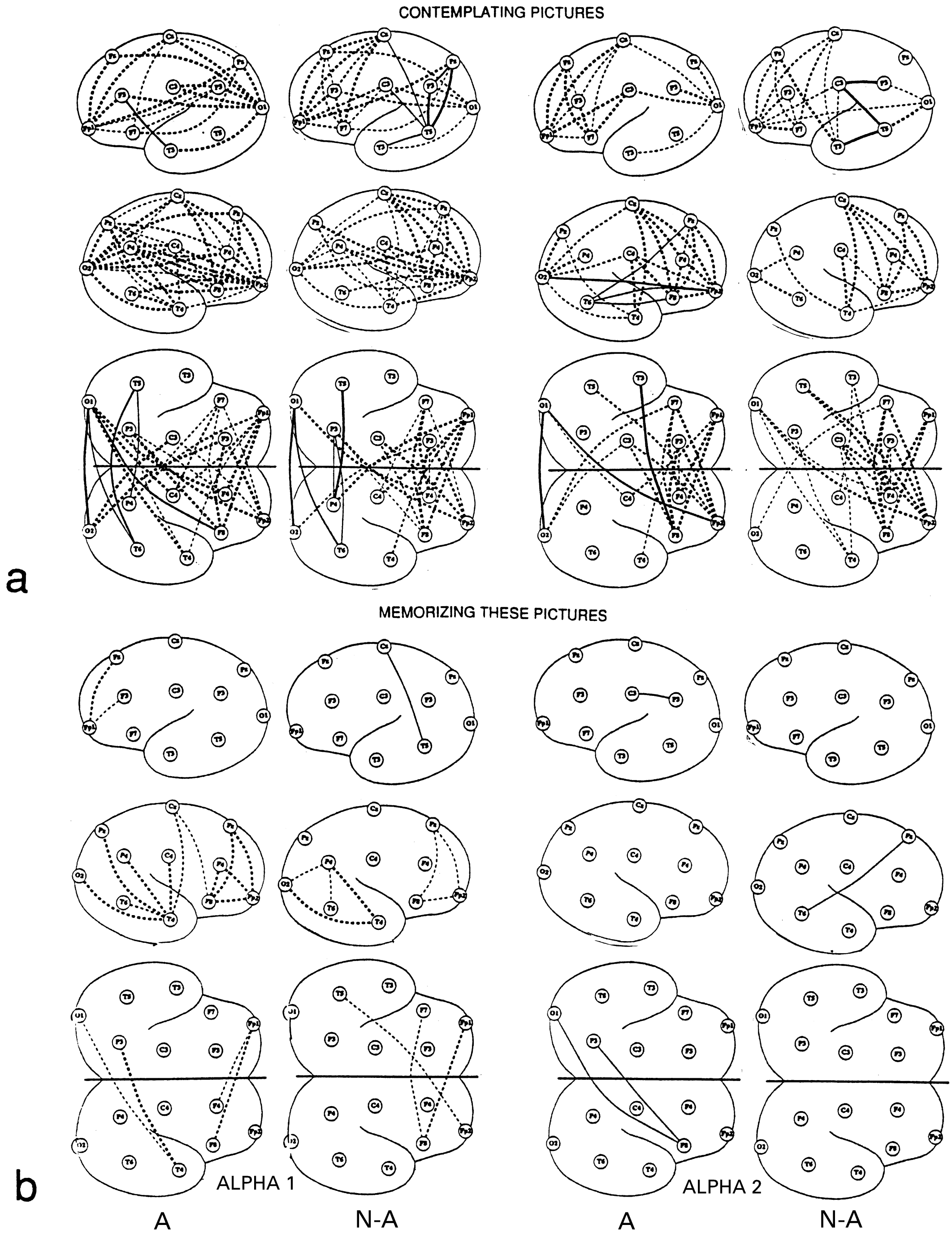
In order to become more familiar with the problem of the possible individuality of these two alpha bands, it may be worth considering their behaviour if the groups of artists and non-artists are looked at separately under the aspect of coherence.

Separated for three of the four visual tasks, the results are shown in Fig. 3 in which four columns of coherence patterns can be recognized: the pair of columns on the left represents the findings in alpha 1, the pair on the right those in alpha 2; the findings for the 19 artists are represented in the first and third column (A), those for non-artists in the second and fourth column (N-A). Differences between these two groups were found in each of the two alpha bands.

While contemplating the pictures (Fig. 3a) the main difference between A and N-A in alpha 1 is in the center of gravity of coherence increases in T5, which was found only in non-artists. Artists, instead, had almost only decreases of coherence. The number of coherence decreases involving O1 and O2 was greater in A than N-A. The former also presented a greater number of contralateral functional decoupling between occipital and frontal than the latter. Also in alpha 2, artists produced more intrahemispherical coherence decreases than non-artists, particularly concerning O1 and O2. In addition, several long-distance coherence increases in the right hemisphere as well as between the hemispheres were seen only in artists.

While memorizing (Fig. 3b), the differences between artists and non-artists were most striking in alpha 1 where the number of decreases in the right hemisphere was much larger in artists. In alpha 2 only artists presented a few increased coherences between left parieto–occipital and right frontal regions.

No differences were found between these two groups while creating a picture, whereas, while silently reading (Fig. 3c) both groups, artists and non-artists, presented considerable differences: in alpha 1, artists, in the left hemisphere, produced a center of gravity of coherence increases in T5 (comparable to that produced by non-artists while contemplating the pictures), whereas non-artists displayed more coherence decreases between occipital, parietal and mid-frontal regions. Another striking difference between A and N-A is the presence of highly significant symmetrical coherence increases between occipital and frontobasal (between O1 and F8, and O2 and F7, respectively) in non-artists. The differences in the interhemispheric relations are difficult to describe. In alpha 2, artists generally produced more intra- and interhemispheric increases than non-artists.



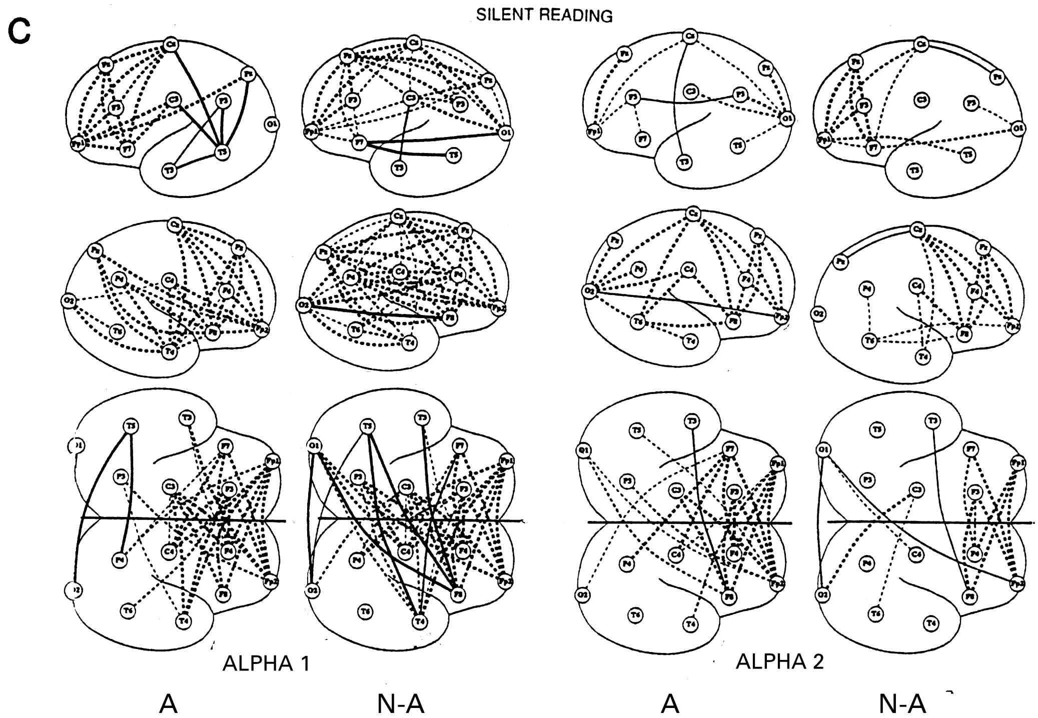


Fig. 3. Same as Fig. 2 but separated for artists (A, $n = 18$) and non-artists (N-A, $n = 18$), for (a) contemplating, (b) memorizing and (c) silent reading.

These coherence increases mainly extended over large distances.

These findings though suggesting that different functions could be contributed to the two alpha bands, however, should not encourage one to jump to premature conclusions speculating on any possible specific functional nature of the alpha bands: all that can be said up to now is that a separation of the alpha range into at least two bands seems justified, but strictly defined functions cannot be attributed to these bands as yet. However, it may be that certain mental events are reflected by these bands only under distinct conditions, as in case of contemplating pictures and silent reading.

It is hard to interpret these findings without speculating about the possible meaning of coherence changes. This point is dealt with in more detail below. All one can say up to now is that in both tasks, contemplating and memorizing pictures, the right posterior half of the brain seems to be more involved in artists than in non-artists and more in alpha 1 than in alpha 2. The manifold findings while reading in this respect cannot be interpreted as yet.

In this context, a further question arises: the presented maps were obtained from fairly broad spectral ranges with rigid boundaries. Do these maps allow one to make any statements about the actually involved frequency range in any task? In other words: are always distinct frequency ranges concerned with coherence changes? It turned out that characteristic patterns of in- and decreases in the sub-alpha ranges often extend over both the delta and the theta-bands; the same occasionally holds true of the beta ranges, whereas only rarely the boundary between alpha 1 and 2 is blurred by a uniform pattern in both ranges. One exception is creative tasks in which (if the group behaviour of coherence changes is studied) the alpha seems to loose its individuality so to speak and to hide behind either the coherence patterns of the theta or the beta range.

In summarizing the inferences from this first study on visual processing, one can only say that the two alpha bands are independent and behave like Proteus in greek mythology who was known for continuously changing his shape. However, it may be that this impression may be caused by the method we have been using, which is based on the silent assumption that the brain produces persistent activities that could be classified by means of spectral analysis. In other words: identities of spectral characteristics would hint at identities of their functions. However, this assumption may turn out to be wrong. The inspection of a few single cases in the following will even add to the idea of a proteus-nature of the alpha.

3.2. Composing

A second set of experiments concerned the world of sounds and comprised seven male composers. The experiments were performed in a similar way as in the series on visual processing, with the difference, that the subjects were confronted, via head-phones, with four pieces of music of different styles (Bach, Beethoven, Schönberg and a Jazz piece), each for 5 min and with eyes closed. In addition, each subject agreed to compose for another 5 min, also with eyes closed, and to write his composition down after the EEG.

In these musical tasks, both alpha bands were considerably involved in all subjects, but they did not behave uniformly. With the exception of one subject, alpha amplitude did not react equally in the two bands, neither while listening to these four pieces nor while composing. The great variety in the behaviour of the amplitude of these two bands led us to assume that the alpha amplitude may be more sensitive to other than cognitive or memory processes, most likely to emotional components (Machleidt et al., 1994). In the following, only composing is to be discussed with respect to coherence.

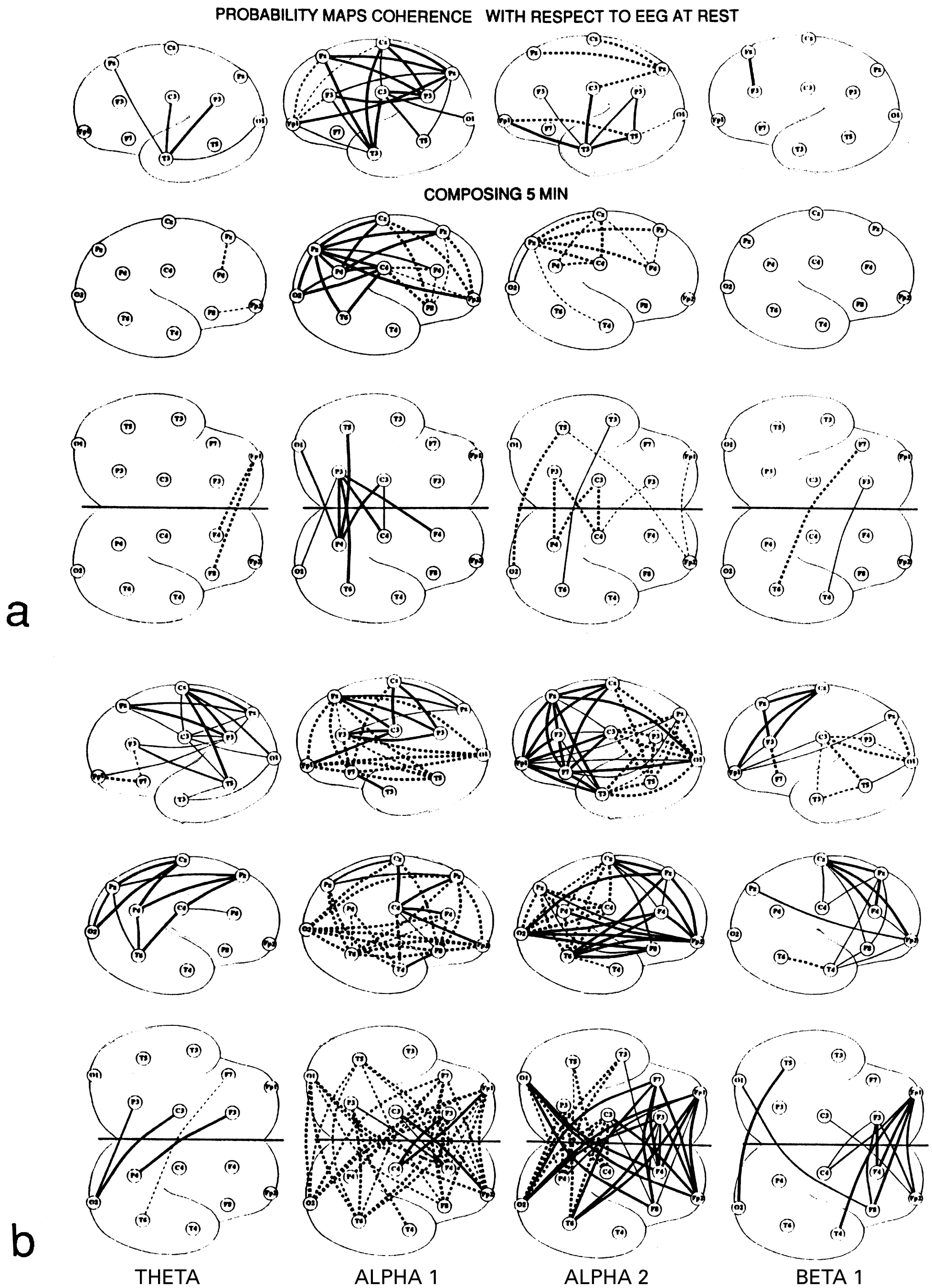
It is selfevident that composing is a highly individualistic creative process which could best be approached by single person studies. This surmise was confirmed by the finding of different coherence patterns in the two alpha bands in six out of the seven composers of this study. These patterns also distinctly differed from those in the neighboured bands, by thus indicating their independence. Manifold changes of coherence were found in these two bands. In order to show the clear boundaries between the two alpha bands and also their sharp boundaries towards the neighboured bands, samples of three composers are demonstrated in which also the adjacent bands, theta and beta 1, are shown.

In this subject (Fig. 4a), most coherence increases accompanying composing were observed in alpha 1, where the coherence pattern clearly differed and was sharply separated from those in theta and also in alpha 2. Both hemispheres were strongly involved; in alpha 1, composing increased the intracortical communication within and between the hemispheres. Alpha 2, on the other hand, was much less concerned and displayed mainly decreases; also this pattern distinctly differed from those in the adjacent bands. In contrast to coherence both bands behaved similarly in amplitude which decreased in the left anterior parts of the skull in this subject (not shown here).

In contrast to this composer, another subject while composing (Fig. 4b) produced coherence increases, both intra- and interhemispherically, mainly in alpha 2, whereas decreases between the frontal areas were the prominent feature in alpha 1. Incidentally, this subject presented a clear distinction between these two bands also in amplitude which was lowered over the whole skull in alpha 1 and was increased in the frontal parts in alpha 2.

Fig. 4c represents the findings of a third composer. In contrast to the other two subjects, this one produced, while composing, only in alpha 2 a pattern of increases which proved to be independent of the events in both adjacent frequency bands. On both sides the topography of coherence changes was totally different from the pattern in beta 1. Alpha 1 was hardly concerned at all.

The composer of Fig. 5 deserves special interest. In order to demonstrate the multifariousness of results in this case the coherence patterns are represented for frequency bands of only 1-Hz width. For this purpose and in order to present as much data as possible in one picture and so to be able to illustrate the great diversity of findings, we chose a presentation we had used several years ago: all electrode positions are entered on the circumference of a circle, those on the left hemisphere on the left side and vice versa. Frontal is on the top. The three midline elctrodes are entered in the uppermost sector. In such a circle all



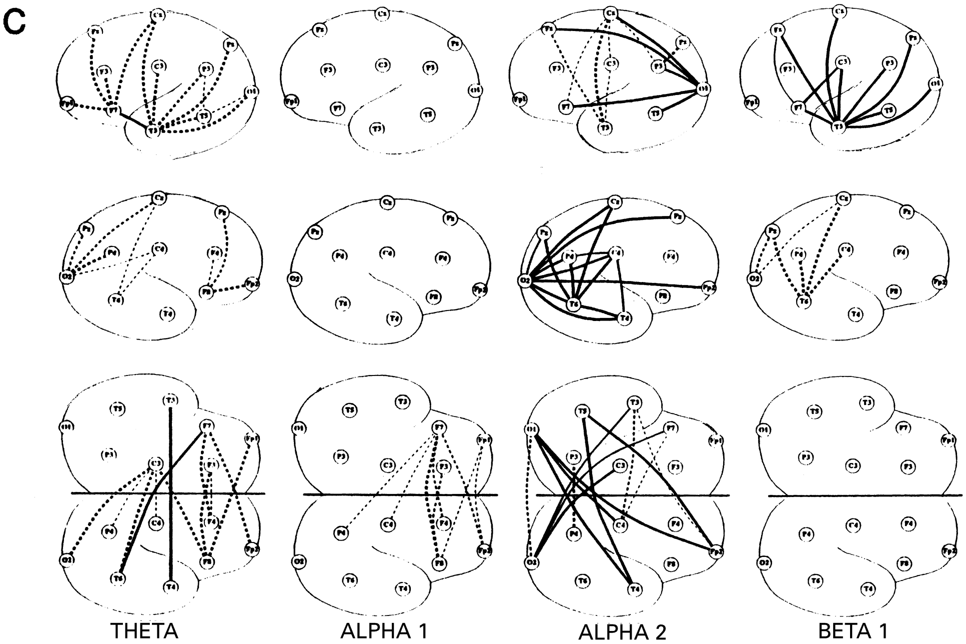


Fig. 4. Significant changes of coherence while composing 5 min, with respect to the averge EEG at rest. Alpha 1 and 2 and the two adjacent bands, theta and beta 1. Maps as represented in Figs. 2 and 3 (a) 27-year-old composer: alpha 1 is mainly concerned. (b) 59-year-old composer: both alpha bands are concerned, but in different ways. (c) 54-year-old composer: almost only alpha 2 is concerned.

electrode pairs between which coherence is significantly changed by a task can be connected by straight lines, drawn out for increase and dashed for decrease, which yields web-like patterns. Each of these webs represents the results of one task for a frequency band of 1-Hz width. The figure shows the findings between 6 and 15 Hz. In addition to composing, this subject was also listening to pieces of music by Bach, Beethoven, Schönberg and to a Jazz piece. Each of these pieces was presented for 5 min.

Fig. 5 shows the results for the 10 frequency bands between 6 and 15 Hz. Among the vast number of data presented by this figure only three facts should be pointed out: first, that composing induced many more coherence changes than mere listening; secondly, that listening to the four pieces produced different patterns of coherence changes and, thirdly, that sharp frequency limits between different coherence patterns can be seen, and this not only within the alpha, but also in lower and higher frequency ranges. However, a detailed discussion of these findings would go beyond the scope of this paper. The purpose of this demonstration is to underline the futility of attempts to divide the EEG into rigid frequency bands and to search for their possible functional meanings.

This high and task-dependent specificity of coherence patterns with respect to frequency bands in individual composers, however, should not lead to the assumption that no common features were found if the EEG changes with respect to the EEG at rest while composing were examined for the total group of these seven composers. In this case the following was found (Fig. 6): the alpha bands, particularly the upper one, exhibited relatively few changes; besides, part of the features of the coherence patterns in either of the two alpha bands proved to be found also in the adjacent bands, theta and beta 1. This means that the two alpha bands as such do not seem to have great relevance for common creative activities underlying the composing of music, in con-

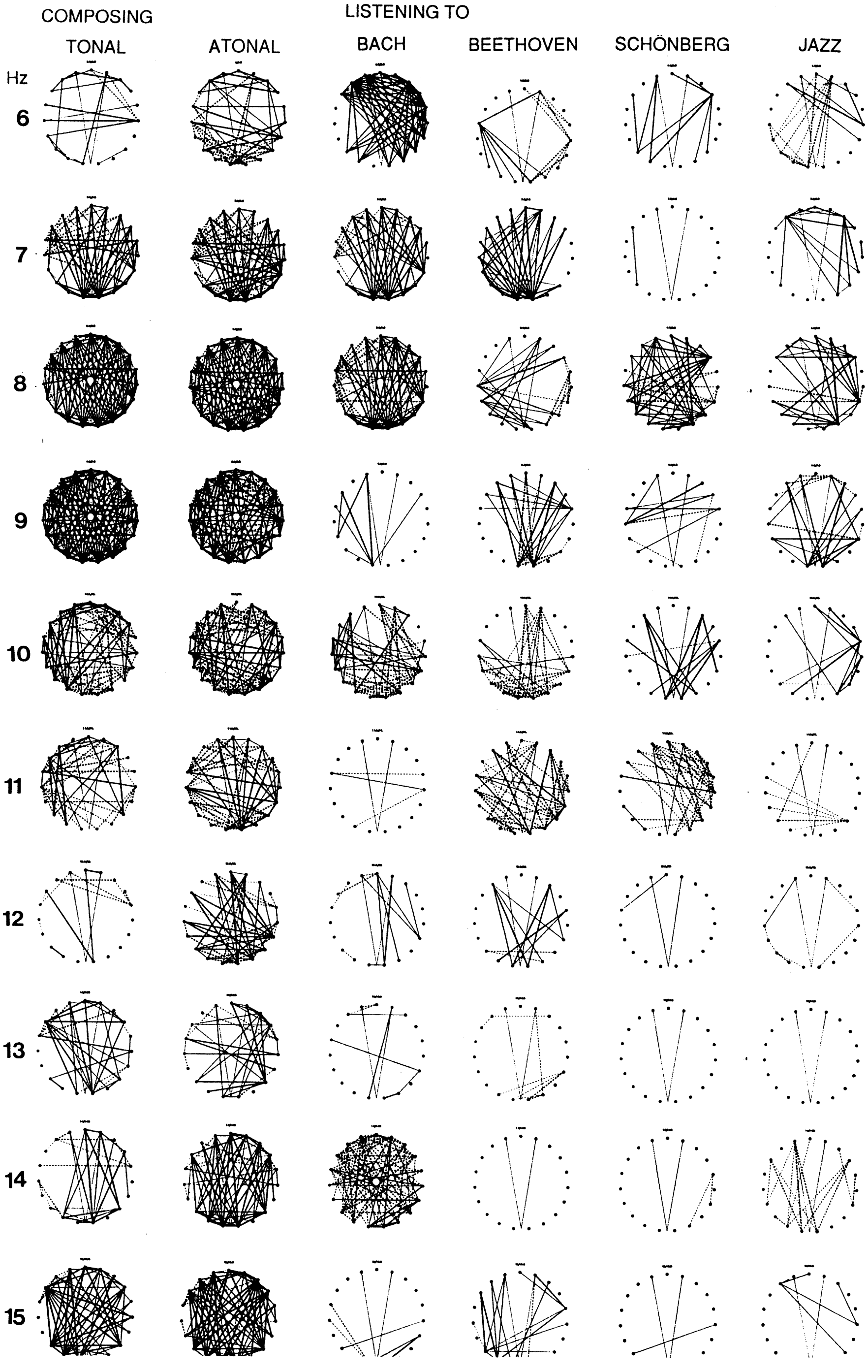


Fig. 5. Fifty-four-year-old composer while composing tonally and atonally and while listening to four, stylistically different pieces, each for 5 min. Coherence changes with respect to the averaged EEG at rest, represented for 10 frequency bands of 1-Hz width between 6 and 15 Hz. The dots at the circumference of each circle represent the electrode positions (details see text); coherence in- and decreases with respect to the merged EEG at rest are entered as straight lines between the respective electrodes, drawn-out for increases and dashed for decreases.

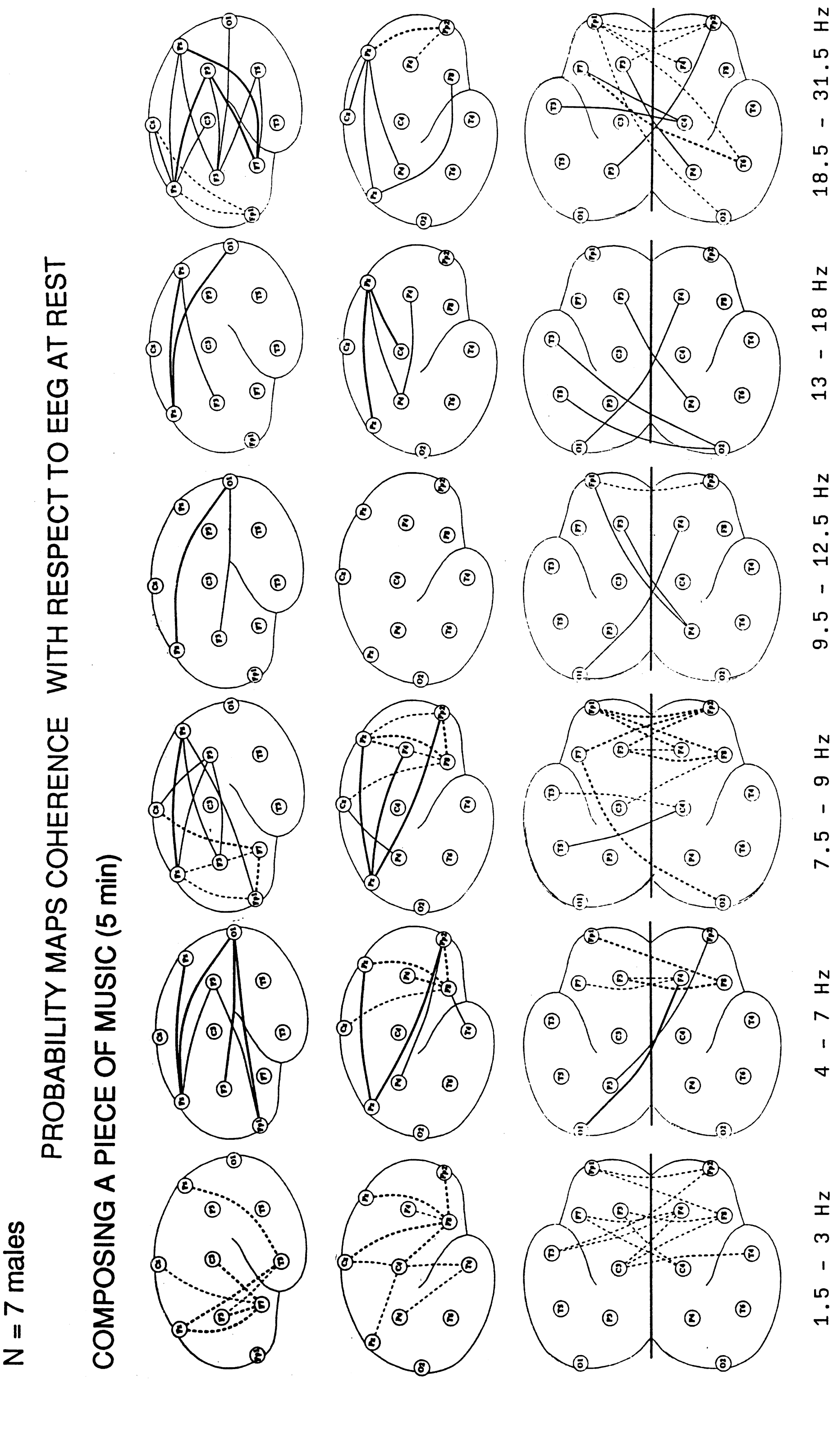


Fig. 6. Seven musicians while composing for 5 min. Coherence changes with respect to the averaged EEG at rest. Group behaviour for the total spectral range.

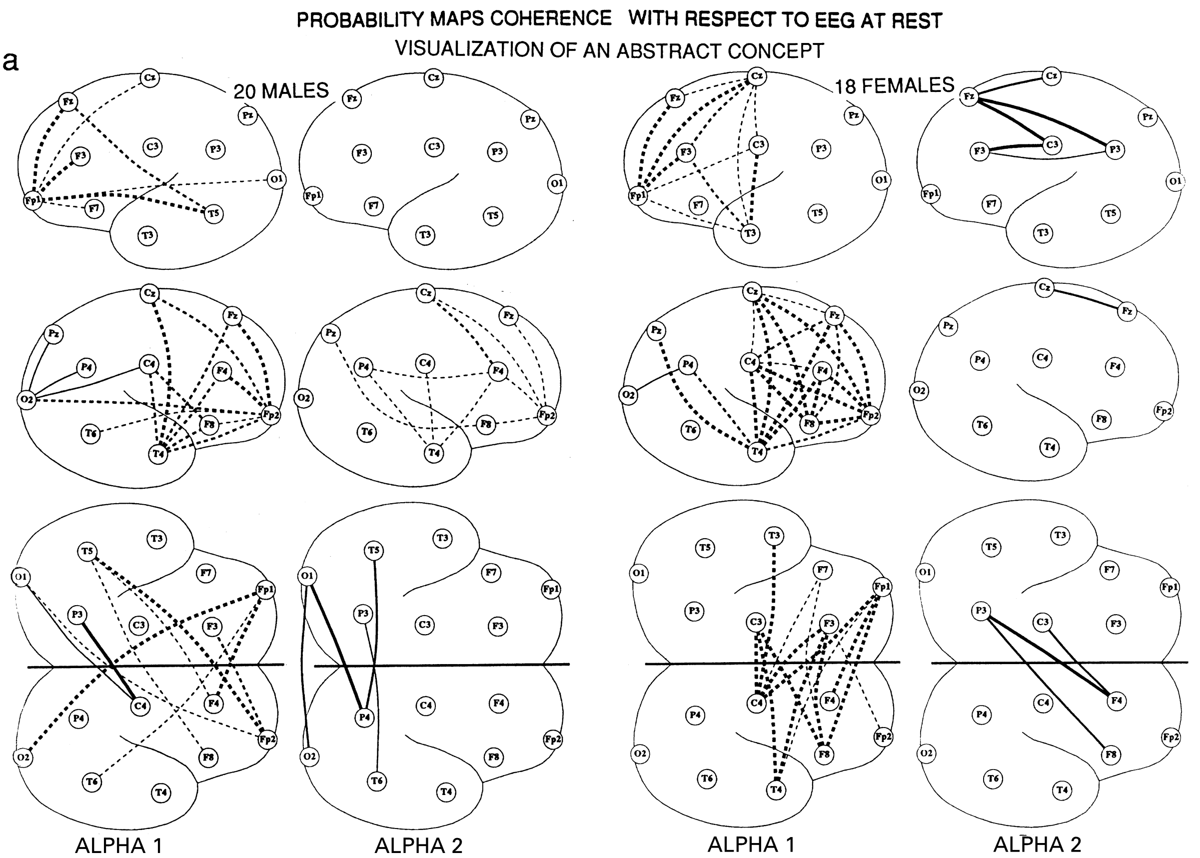
trast to their high individuality when each composer is examined for himself. Therefore, the great differences of the patterns between the alpha bands as found in individuals seem to reflect more personality-specific features of creating music, whereas, what is illustrated in Fig. 6, instead, seems to reflect more general, basic brain processes while composing music, which apparently show up more in delta, theta and in the uppermost beta ranges. In this context the fairly great number of long-range coherence increases should be emphasized.

Briefly it should also be mentioned how the two alpha bands behave during listening to music. All one can say of the two bands for composing also meets for listening to music: distinct boundaries between the two alpha bands were almost always found; each of them produced characteristic coherence patterns, part of which, however, sometimes trespassed the boundaries to adjacent bands. Besides, exactly as with composing, but in contrast to our findings in the greater part of the visual tasks, listening to music also induced considerable increases of coherence, at least in one of the two alpha bands.

Also in another series of experiments in which coherence differences between musically trained and not trained students could be detected (Petsche et al., 1988) the great variability of findings in these two bands became apparent.

3.3. Abstract mentation

Finally, a last group study is discussed that was performed in order to verify changes of coherence during two mental tasks, the visualization of



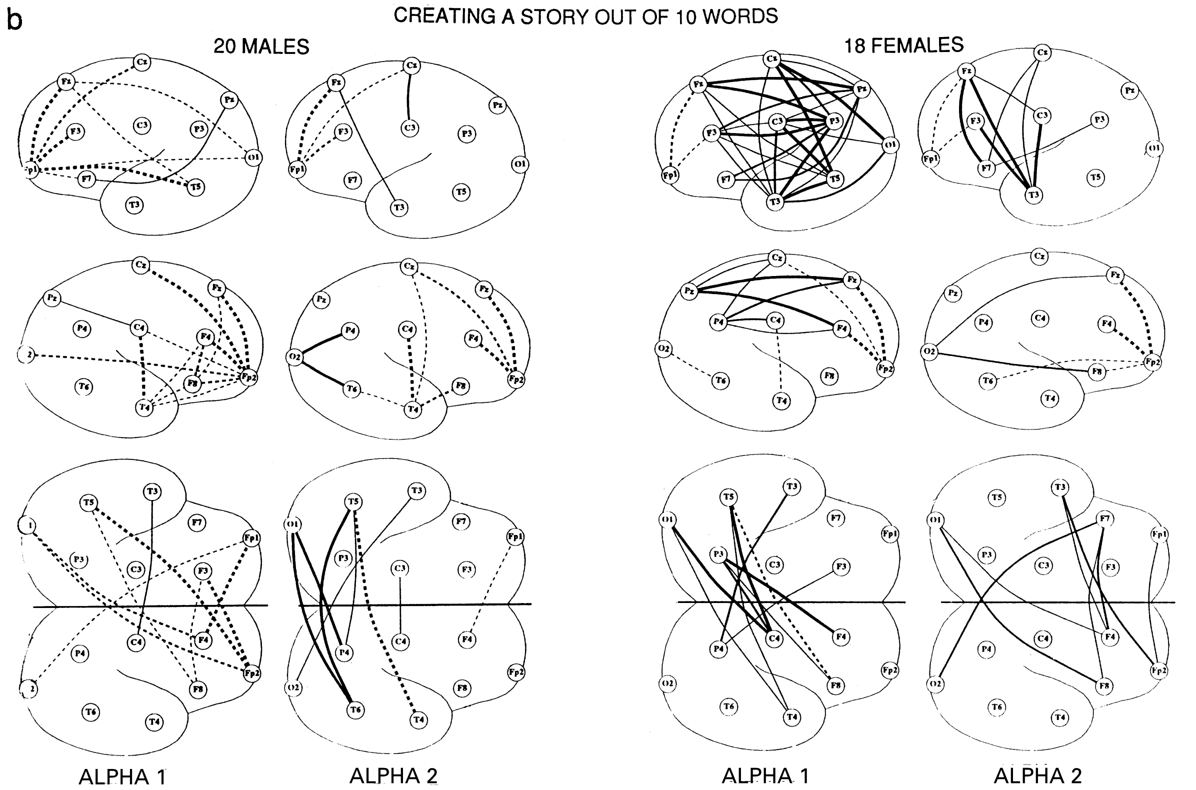


Fig. 7. Eighteen females and 20 males. Coherence changes with respect to the averaged EEG at rest. Group behaviour for both alpha bands while (a) visualizing an abstract concept, (b) creating a story out of 10 words.

an abstract concept and the creation of a text. In addition, we wanted to look for eventual correlations between coherence values determined during these two tasks and creativity scores (Petsche, 1997). This group comprised 18 females and 20 males who were pre-tested for intelligence and creativity (Schmidt-Henrich, 1990). In the first task, the subjects were asked to call an abstract concept and try to visualize it under the EEG with the aim of making a sketch of it after the EEG. In the other, the verbal task, the subjects had to invent, under the EEG, a story by using at least 10 words, they had chosen before and learned by heart. Also this study yielded impressive differences of coherence topography both between the two tasks and also between the two genders. This is shown in Fig. 7. The left pair of columns represents the findings for alpha 1 and 2 in males, the right one those in females. Considerable differences were found between the two genders.

While visualizing an abstract concept, in males, most differences between the two alpha bands were found interhemispherically, where alpha 1 was characterized by mainly long-distance coherence decreases, whereas, in alpha 2, the posterior parts of the brain tended to cooperate across the midline. In females, the differences between the two frequency bands were even more striking: alpha 1 presented only decreases within and between the frontal regions, whereas in alpha 2 left fronto–parietal regions were engaged in coherence increases, with increasing connections with right frontal regions.

It may be of interest to compare, for alpha 1, these patterns (visualization of an abstract concept) with Fig. 2 (memorizing a picture). Both tasks are similar and were performed by females

(18 in Fig. 7a and 38 in Fig. 2) though in different groups of subjects. For both tasks visual memory is required: for the task of Fig. 2, to remember a picture seen a few minutes before, for the one of Fig. 7a, to visualize an abstract concept, what is a creative act with retrieving from memory for appropriate pictorial elements in order to imagine a new picture that best fits the content of this abstract concept. In both tasks frontal regions were strongly involved by decreases: in the act of remembering a picture, only the right frontal region plus the right posterior half of the brain, but in the other, more creative act, both frontal regions were involved with even more interhemispheric dissociation.

In the other task (Fig. 7b), creating a story out of 10 words, there were even more dramatic differences between alpha 1 and 2, particularly in the left hemisphere and in females: once more, long-distance activation of coherence was found over many regions.

As gender is concerned, significant coherence differences between alpha 1 and 2 were even found in the EEG at rest: males presented higher coherences in alpha 1, whereas females showed the reverse in delta and theta bands. However, a more detailed discussion of these findings would go beyond the scope of this paper and can be found in Petsche (1997).

3.4. EEG and mood

In this study the main emphasis was put on higher cognitive processes and their possible reflections in the two alpha bands. However, electrical brain oscillations also depend on psychological conditions as was shown for the emotional situation by Machleidt et al. (1994). Therefore, the psychological condition was studied by us in 23 subjects before and after the experiments by means of the ‘Wiener Testsystem’. Also in this study the two alpha bands behaved differently: positive correlations with amplitude were found between alpha 1 and elatedness and agitation, negative correlations with coherence were found between alpha 1 and drowsiness and between alpha 2 and elatedness, respectively.

To summarize all these findings which are based on the behaviour of the alpha frequencies in cognitive and creative processes, it seems justified to postulate at least two functionally independent alpha bands; once more, studies of coherence yielded more and also more variegated results than those of amplitude. In spite of this abundance of evidences, however, no consistent conclusions as to distinct functional meanings of the two alpha bands could be drawn from our experiments.

4. Discussion

Previous papers on the significance of the alpha relate almost exclusively on amplitude. Apart from the initial idea that alpha is related to attention, Wertheim (1981) was among the first to claim that alpha depends on oculomotor functioning rather than on the quality of perception; this means that alpha blocking would be due to visual activity involving retinal feedback (Shaw, 1992). If this hypothesis were correct, differences in the degree of alpha blocking should be expected between the tasks A and D (contemplating and reading) and B and C (memorizing and creating a picture) of Fig. 1, since retinal feedback is needed only in A and D. This, however, did not happen. Moreover, the differences of the behaviour of the two alpha bands in Figs. 1 and 2 are against Wertheim’s idea of alpha being meaningless for perception. The same holds true of Mulholland (1972) who had the idea of an alpha attenuation being caused by processes of fixation, lens accommodation and pursuit tracking. Another voice against the involvement of alpha in cognition came from Gevins (1981) who considered alpha as being involved in motor activity, response preparation, task difficulty and other factors. Yet the results dealt with here are in favour of an implication of the alpha bands in mental processes.

A majority of studies concerns the connection between alpha and memory processes. Beginning with the first papers on the nature of the alpha rhythm, the idea of relationships between task demands and alpha amplitude was fostered (Berger, 1929; Martinson, 1939). A great step forward in this respect was the finding that alpha should not be considered as a fairly uniform background activity because it has strictly localized features, as among others, was recently shown by means of event-related desynchronization (Pfurtscheller and Klimesch, 1991). In addition, task-related shifts of alpha frequency were detected (Osaka, 1984). As for studies on the significance of alpha for memory, Klimesch et al. (1990) found that subjects with good memory performance had higher mean alpha frequencies than those with bad performance. From their experiments they conclude that 'alpha frequency may be a permanent factor determining the speed with which information may be retrieved from memory'. By determining the individual alpha mean frequency (IAF), the same authors were able to demonstrate (Klimesch et al., 1993) that IAF is generally higher in good than in bad memory performers and remains at this level when memory related task demands increase, whereas IAF decreases in bad performers under the same conditions. From their findings Klimesch et al. (1993) concluded that the upper alpha band seems to be essentially involved in semantic encoding. This would fit the observation that in both visual tasks in which encoding is most required, contemplating and reading, the extent of alpha 2 decrease in amplitude is largest. Moreover, encoding of episodic information would be reflected by theta amplitude, which, in our experiments, proved to be also increased by these two visual tasks. In addition, the results shown in Fig. 1 demonstrate that alpha 2 in all visual tasks became less affected by arousal in painters than in artistically non-trained subjects; therefore, painters who most likely dispose of better visual abilities than non-painters seem to need lower neuronal efforts for the visual tasks.

A few words should be said about the interpretation of these changes of coherence. First, there can be no doubt any more that information about mental processes can be extracted from the ongoing EEG which therefore makes its analysis suitable for the investigation of even long-lasting and highly complex mental processes, more complex than those which can be approached by the ERP-method which is time-locked and, thus, remains restricted to the study of brief cognitive events. By examining the mutual electric (frequency) relationships, coherence estimates seem to yield gross average aspects of the topography of mental representations in the cortex, and this in spite of the non-stationarity of the EEG and the non-linear transmission properties of the brain. The reliability of the results can be improved by using group studies and by repeating the tasks in the same experiment and at intervals of weeks. Determinations of the differences between the events during a task and the merged activity at rest turned out to be most yielding. In this respect significant increases and decreases of coherence were observed, both dependent on changes of the functional cerebral situation. Also accumulations of coherence changes in certain places have turned out to be functionally meaningful (Petsche et al., 1993). Increases indicate stronger functional connections between two brain regions, decreases indicate the opposite. The interpretation of these changes, however, depends on several accounts such as cortical region, electrode distance, task and others. Therefore, one should beware of interpreting increases of coherence as activation and vice versa, as particularly the observation during visual tasks has shown (Fig. 2), where accumulations of coherence decreases ('gravity centers of coherence decreases'), i.e. a kind of isolation of the occipital area from other cortical regions during contemplating makes it highly probable that increased processing between this area and subcortical regions takes place. On the other hand, intra- and interfrontal decreases of coherence are a common feature of visual and other mental tasks. It should also be emphasized that coherence changes are frequency-dependent. In this paper, only the two alpha bands were considered under this aspect. No clear evidence as yet exists about the functional meaning of the low- and the high-frequency bands in this respect.

Special discussion deserves the frequent occurrence of coherence increases over long distances whenever creative thinking is mainly involved in a mental task. An explanation of this fact may be found in the ideas developed by Thatcher et al. (1986). These authors reduce coherence to two separate neuronal structures, one of them being

Golgi-type-II-stellate neurons the axons of which do not surpass lengths of 17 mm at the most and terminate in the local domain. The other are type-I-pyramidal neurons with axons extending as far as 25 cm and terminating mainly at apical dendrites. The first system, called ‘B’ by Braitenberg (1978) is thought to be involved mainly in local interaction, whereas system ‘A’ with its long axons seems to serve the cooperation over long distances. From their studies on children Thatcher et al. (1986) conclude that the activation of system B goes parallel to the degree of complexity and competition between cells within a population, whereas the activation of system A with its long-distance fibres serves the information transfer over great distances. This concept is supported by our findings during creative thinking where obviously connections between many and distant regions have to be established (it should be mentioned that no conclusions can be drawn from power to coherence, which can be illustrated particularly well by mentally creating a picture, where many long-distance coherence increases were found in the alpha bands whereas power was decreased at the corresponding electrode sites; compare Figs. 1 and 2).

In the following we discuss briefly whether our results bring about any hints that the upper alpha band would better reflect task-related, the lower one non-task related processes. As the amplitudes are concerned, there are hints that the two bands behave differently under the four different tasks, but also that education-dependent features are reflected in their behaviour. However, the hypothesis that non-task-dependent cognitive processes would be reflected better by the lower band and vice versa, could not be supported by our findings as amplitude is concerned. The same holds true of coherence: each of the two bands can behave task-dependent, the most differences with respect to the neighbouring bands having been seen with contemplating, memorizing and reading and not with creating a picture. Differences with respect to artistical education were also found with contemplating, memorizing and with reading, in which pattern recognition also plays a foremost role, but not with creating a picture.

The non-uniform behaviour of the two alpha bands is particularly striking in listening to and composing music, in which the two bands often behave opposed, particularly as for coherence. Moreover, the numerous increases of coherence in one of them hints at the great significance of the involvement of either of them in the processes reflecting the composition of music. Also both experiments with the visualization of an abstract concept and creating a story out of 10 words hint at a strong involvement of one or both alpha bands in these tasks.

When presenting these results, however, it should be taken into account that these results are averages over both, time, and in mainly cases also subjects. In addition they are contingent on only the signs of changes of the parameters amplitude and coherence and on only 19 electrodes. Thus, they may represent only fairly gross and general tendencies rather than actual incidents in the complex fluctuation of the electrical events in the cortex.

There are several reasons why the use of coherence supplies more data on mental processes than the use of amplitude. Coherence may be considered as a sort of microscope to determine slight changes of the degree of synchronization. Evidence increases that the tendency of neuronal assemblies to discharge synchronously is on the basis of information processing by neurons and, as Von der Malsburg postulated (Von der Malsburg, 1985), is also the most efficient strategy to increase the saliency of responses; thus, it can be an effective code for relations among distributed neurons. In his review Singer (1993) corroborates the notions that tangential intracortical connections are the substrate for synchronization and that this process may serve perceptual binding. As was demonstrated by Dinse et al. (1994) even low-frequency events are probably involved in this process. The data dealt with by Schanze and Eckhorn (1994) give further evidence in favour of the interpretation of our coherence data: according to these authors high-frequency coupling is thought to play a more local part whereas low-frequency coupling supports integration more globally. Moreover, as Hari (1994) demonstrated, relatively few neurons seem to be sufficient for maintaining synchronization, what once more underlines the importance of neuronal mass processes for the functioning of the brain. These findings are anatomically supported by statistical studies of the fine structure of the neocortex by Braitenberg and Schüz (1991) who consider, as the main function of the cortex, the providing of a maximum possible convergence and divergence of signals.

Further support to the idea that synchronizing processes underly the so-called ‘binding problem’ of perception and action comes from clinical neurology. Evidence increases that perception is an exceedingly parcellated process that depends on activity over a large range of geographically distinct brain regions which have to be concurrently activated for the recognition and understanding of events in the environment. The study of patients with extended cortical damages contributes to this concept (Damasio, 1990).

The cooperative electric processes headed under the word ‘EEG’ are thought to represent the spatial averaging of field potentials produced by membranes of both nerve and glia cells, slurred by the spatial filter properties of CSF and tissue layers. Synchronization processes are the sine qua non for the EEG to be recorded at all. Whereas evidence accumulates that synchronization processes on the level of the neurons are an important factor in cerebral data transfer and information processing, the electric events on the macro-level did not yet find due consideration in this regard.

Under these aspects the patterns of coherence changes as described by us, though most likely being a substrate of mental processes, certainly do not reflect events in the highest hierarchical levels of cerebral data processing; more likely they are an electrophysiological correlate of specific processes related to directed attention. This term ought not to be conceived of as having to do with mere direction finding of stimuli as many psychological experiments dealing with this question would suggest; to avoid any confusion by the concept ‘directional attention’ we instead prefer the term ‘differential attention’ and understand by it a physiological property of the whole cortex which is characterized by functional states of the brain which are extremely variable, change permanently and adjust the cortex to keep abreast both with the instantaneously changing conditions induced by the environment and those, as well instantaneously changing mental conditions required for the optimum adjustment of reactions towards the environment. The electric aspects of the topographic mosaic of differential attention seem to become apparent in the pattern of coherence. This mosaic proves to be highly characteristic for tasks and, in spite of individual variations, supplies interindividually amazingly constant features in even sophisticated mental tasks.

According to Henry James, conscience, even better: awareness, consists of attention plus short-term memory. In our view, it is this kind of attention the electrophysiological aspects of which are reflected by coherence changes. The results obtained with different kinds of mental processes support the idea that the study of coherence allows for gaining insights into processes connected to both attention and memory.

Acknowledgements

This work was supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung, Project S 49-02.

References

Berger, H. (1929) Über das Elektrenkephalogramm des Menschen. Arch. Psychiatr. Nervenkr., 87: 527–570.

Braitenberg, V. (1978) Cortical architectonics: general and areal. In: M.A.B. Brazier and H. Petsche (Eds.), Architectonics of the Cerebral Cortex. Raven Press, New York.

Braitenberg, V. and Schüz, A. (1991) Anatomy of the Cortex: Statistics and Geometry. Springer, Berlin.

Damasio, A.R. (1990) Synchronous activation in multiple cortical regions: a mechanism for recall. Semin. Neurosci., 2: 287–296.

Dinse, H.R., Akhavan, A.C., Krüger, K., Spengler, F. and Schreiner, C.E. (1994) Low-frequency oscillations of visual, auditory and somatosensory cortical neurons evoked by sensory stimulation. In: E. Basar (Ed.), Alpha-activity: Cognitive and Sensory Behavior. Birkhäuser, Boston.

Gevins, A.S. (1981) The use of brain electrical potentials (BEP) to study localization of human brain function. Int. J. Neurosci., 13: 27–41.

Hari, R. (1994) Characterization of magnetoencephalographic 10- and 20 Hz rhythms. In: E. Basar (Ed.), Alpha-activity: Cognitive and Sensory Behavior. Birkhäuser, Boston.

Herrmann, W.M., Fichte, K. and Kubicki, St. (1980) Definition von EEG-Frequenzbändern aufgrund strukturanalytischer Betrachtungen. In: St. Kubicki, W.M. Herrmann and G. Laudahn (Eds.), Faktorenanalyse und Variablenbildung aus dem Elektroenzephalogramm. Gustav Fischer, Stuttgart-New York.

Klimesch, W. (1996) Memory processes, brain oscillations and EEG synchronization. Int. J. Psychophysiol. 24: 61–100.

Klimesch, W., Schimke, H., Ladurner, G. and Pfurtscheller, G. (1990) Alpha frequency and memory performance. Psychophysiology, 4: 381–390.

Klimesch, W., Schimke, H. and Pfurtscheller, G. (1993) Alpha frequency, cognitive load and memory performance. Brain Topogr., 5: 241–251.

Lindner, K., Petsche, H., Rappelsberger, P. and Schmidt, E. (1989) Denkstrategien beim Kopfrechnen: EEG-Probability-Mapping von Leistung und Kohärenz. In: H.M. Weinmann (Ed.), Aktuelle Neuropädiatrie 1988. Springer, Berlin.

Machleidt, W., Gutjahr, L. and Hinrichs, H. (1994) Die EEG-Spektralmuster der Grundgefühle: Hunger, Angst, Aggression, Trauer und Freude. EEG-EMG, 25: 81–97.

Martinson, D.M. (1939) A study of brain potentials during mental blocking. J. Exp. Psychol., 24: 143–156.

Mulholland, T.B. (1972) Occipital alpha revisited. Pschol. Bull., 78: 176–182.

Osaka, M. (1984) Peak alpha frequency during a mental task: task difficulty and hemispheric differences. Psychophysiology, 21: 101–105.

Petsche, H. (1997) Approaches to verbal, visual and musical creativity by EEG coherence analysis. J. Psychophysiol., 00: 000–000.

Petsche, H., Etlinger, S.C. and Filz, O. (1993) Brain electric mechanisms of bilingual speech administration: an initial investigation. Electroencephalogr. Clin. Neurophysiol., 86: 385–394.

Petsche, H., Lacroix, D., Lindner, K., Rappelsberger, P. and Schmidt-Henrich, E. (1992) Thinking with images or thinking with language: a pilot EEG probability study. Int. J. Psychophysiol., 12: 31–39.

Petsche, H., Lindner, K., Rappelsberger, P. and Gruber, G. (1988) The EEG — an adequate method to concretize brain processes elicited by music. Music Percept., 6: 133–159.

Petsche, H., Pockberger, H. and Rappelsberger, P. (1986) EEG topography and mental performance. In: F.H. Duffy (Ed.), Topographic Mapping of Brain Electrical Activity. Butterworths, Boston.

Petsche, H., Rappelsbeger, P. and Pockberger, H. (1987) EEG-Veränderungen beim Lesen. In: H.M. Weinmann (Ed.), Zugang zum Verständnis höherer Hirnfunktionen durch das EEG. Zuckschwerdt, München.

Pfurtscheller, G. and Klimesch, W. (1991) Event-related desynchronization during motor behavior and visual information processing. In: Event-related Brain Research. Elsevier, Amsterdam.

Rappelsberger, P. and Petsche, H. (1988) Probability mapping: power and coherence analysis of cognitive processes. Brain Topogr., 1: 46–54.

Richter, P., Petsche, H., Schmidt-Henrich, E. and Filz, O. (1993)Verbales Gestaltungsvermögen und EEG-Parameter: neurophysiologische Korrelate mentaler Begabung. Z EEG-EMG, 24: 71–80.

Schanze, T. and Eckhorn, R. (1994) Phase-coupling of stimulus-specific oscillatory events at different frequencies. In: E. Basar (Ed.), Alpha-activity: Cognitive and Sensory Behavior. Birkhäuser, Boston.

Schmidt-Henrich, E. (1990) Intelligenz und Kreativität: Erste ergebnisse der Konstruktion von Kreativitätsaufgaben zur Vorgabe während einer EEG-Untersuchung. Psychol. Österr., 3–4: 21–23.

Shaw, J.C. (1992) The ubiquitous alpha rhythm — a selective review. J. Electrophysiol. Technol., 18: 5–27.

Singer, W. (1993) Synchronization of cortical activity and its putative role in information processing and learning. Ann. Rev. Physiol., 55: 349–374.

Thatcher, R.W., Krause, P.J. and Hrybyk, M. (1986) Cortico-cortical associations and EEG coherence: a two-compartmental model. Electroencephalogr. Clin. Neurophysiol., 64: 123–143.

Von der Malsburg, C. (1985) Nervous structures with dynamical links. Ber. Busenges. Phys. Chem., 89: 703–710.

Von Stein, A., Rappelsberger, P., Filz, O. and Petsche, H. (1993) EEG-Korrelate bildlicher Vorstellung: eine Amplituden- und Kohärenzuntersuchung. Z. EEG-EMG, 24: 217–224.

Wertheim, A.H. (1981) Occipital alpha activity as a measure of retinal involvement in oculomotor control. Psychophysiology, 18: 432–439.