

Persistent patterns of brain activity: An EEG coherence study of the positive effect of music on spatial-temporal reasoning

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Motivated by predictions from the structured trion model of the cortex, behavioral experiments have demonstrated a causal short-term enhancement of spatial-temporal reasoning in college students following exposure to a Mozart sonata, but not in control conditions. The coherence analysis of electroencephalogram (EEG) recordings is well suited to the neurophysiological investigation of this behavioral enhancement. Here we report the presence of right frontal and left temporo-parietal coherent activity induced by listening to Mozart which carried over into the spatial-temporal tasks in three of our seven subjects. This carry-over effect was compared to EEG coherence analysis of spatial-temporal-tasks after listening to text. We suggest that these EEG coherence results provide the beginnings of understanding of the neurophysiological basis of the causal enhancement of spatial-temporal reasoning by listening to specific music. The observed long-lasting coherent EEG pattern might be evidence for structured sequences in cortical dynamics which extend over minutes. Neurol Res 1997; 19: 107-116]

Keywords: Spatial-temporal reasoning; prefrontal cortex; temporo-parietal cortex; trion model of cortical organization; synchronization

INTRODUCTION

Predictions¹ from a structured neural model of cortex²⁻⁴ led to the testing⁵⁻⁷ of the hypothesis that music could causally enhance spatial-temporal reasoning. Based on Mountcastle's columnar^{8,9} organizational principle for cortical function, the trion model²⁻⁴ proposed that the inherent spatial-temporal firing patterns of highly structured, interconnected groups of neurons have the built-in ability to recognize, compare and find relationships among patterns⁴. This neural process may be responsible for the performance of spatial recognition tasks, such as classifying and recognizing physical similarities among objects. According to the model¹, the evolution of these relationships among neural firing patterns into specific temporal sequences for tens of seconds over large portions of cortex allows for the performance of other more complex spatial tasks requiring spatial-temporal reasoning. Spatial-temporal reasoning involves maintaining and transforming mental images in the absence of a physical model and is required for higher brain functions such as chess, mathematics and engineering.

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Music, it was argued, should also require these temporal sequences of neural activity^{1,10-11}. A fundamental property of these evolving patterns of neural activity is that they can be readily strengthened through experience or learning^{2,3}. Although higher brain functions are typically associated with specific, localized regions of cortex, all higher cognitive abilities draw upon a wide range of cortical areas¹². Leng and Shaw proposed¹ that exposure to music might excite and enhance the cortical firing patterns used in spatial-temporal reasoning, thus affecting cognitive ability in tasks that share this complex spatial-temporal neural code. Behavioral research based on these predictions found that college students scored significantly higher on spatial-temporal reasoning tasks after listening to a Mozart Sonata (K.448)^{5,6}, control groups listened to relaxation tapes, to minimalist music, to silence or to an audio-taped text. These studies established the existence of a causal relationship between music and enhanced spatial-temporal reasoning, which lasted about ten minutes. Here we study the short-term enhancement from listening to the Mozart Sonata K.448 using EEG coherence analysis.

Coherence analysis of ongoing EEG recorded during minutes of cognitive tasks especially lends itself to investigate the neurophysiological basis for this behavioral effect. It is well established that specific changes of EEG amplitude in certain frequency bands can be

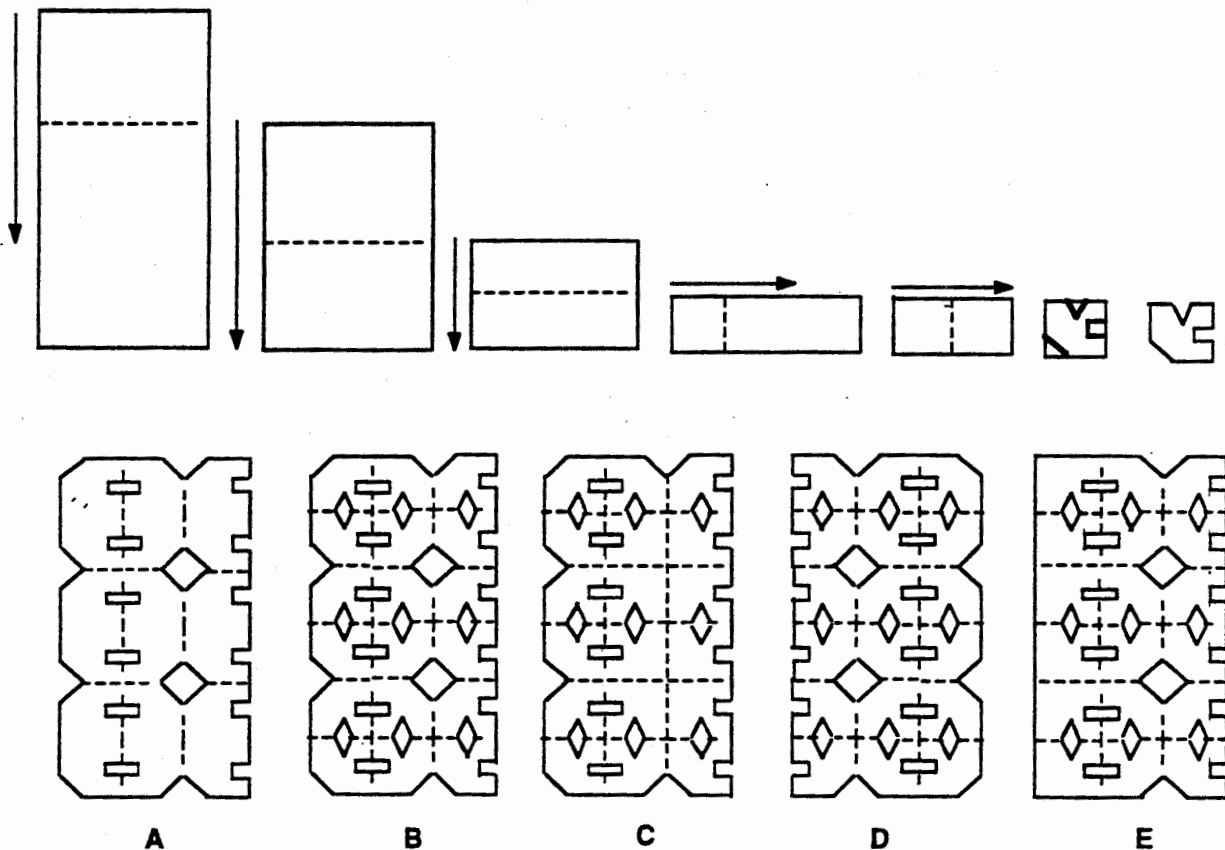


Figure 1 Example of the items of the pf&c task. Depicted is a picture of a paper before it was folded and cut (top left figure). The dotted line and straight arrows represent the location and direction of the folds. The solid lines represent cuts. Subjects had to choose which of the five choices below shows how the paper would look unfolded. The 32 items were those used in Reference 6 (this item is one of the more difficult ones)

correlated to mental processes¹³. The analysis of ongoing EEG is preferred to event-related analysis, since it is known that patterns of cortical activity are stable in their time course, but not in general time-locked to a stimulus¹⁴. Since a scalp electrode picks up the summed activity of several square centimeters of cortical tissue¹³, EEG measures only concerted activity of large scale cell assemblies and is thus well suited to detect global states of cortical function^{15,16}. The improvement of spatial reasoning capabilities by listening to music has been studied by EEG power analysis¹⁷. EEG coherence analysis has been developed as a more precise tool for the analysis of higher brain function^{18,19}. Scalp EEG coherence analysis may be related to intracortical electrophysiological findings which state that functional cell assemblies are defined by synchronous activity of their member neurons²⁰. EEG coherence may thus estimate the degree of synchrony between the activity of two brain regions. However, the exact relationship of coherence analysis to cortical activity is not known. We restrict ourselves to the statement, that a change in coherence between two adjacent electrodes reflects a change of neuronal activation in the underlying cortical

tissue. In practice, we define as a control record an idling state of the brain, when the subject is asked to fixate a point in its visual field. Plotting the spatial distribution of coherence changes leads to coherence patterns for all frequency bands. Specific patterns of coherent activity have been correlated also to several complex higher brain functions^{12,21-27}.

In the present study each subject participated in two sessions. In both sessions we recorded EEG while subjects performed a set of tasks which involve spatial-temporal reasoning, 'paperfolding and cutting' (pf&c) during a period of about one minute (see Figure 7). In the second session the pf&c tasks were preceded by listening to 10 min of the Mozart Sonata for Two Pianos in D Major (K.448). The first session thus served as a control and the second session allowed us to investigate the physiological basis of the positive effect of music on spatial-temporal reasoning^{5,6}.

We found prefrontal, parietal and temporal cortical activity during pf&c tasks manifest in the coherence patterns during both sessions for each of our seven subjects^{26,27}. This is consistent with general notions on spatial-temporal reasoning functions of the cortex.

Table 1: Demographic description of subjects

Subjects	Age/sex	Musical experience	Analytic experience	Scores	
				A	B
UW	26 F	Serious cellist	Engineering	15	16
JJ	30 F	Serious flutist	Psychology	*	13
V5	26 F	Some piano	Architecture	11	15
ME	26 F	None	Mathematics	15	10
UK	28 F	None	Computer science	15	15
AvS	34 F	Some cello	Medicine	8	10
BK	21 F	Some piano	Psychology	5	13

*score was not recorded.

During the second session, listening to Mozart induced coherence patterns of frontal and left parieto-occipital activity that were again stable over time, and even persisted after exposure to the music has ended. The patterns obtained during performance of the pf&c tasks in the second session strongly resembled those of the first session for all subjects, with a few characteristic differences. The main result of this study (found in 3 of 7 subjects) was that the additional features found during the second pf&c session were also present in the coherence patterns induced by listening to Mozart. Thus the patterns of cortical activity induced by music seemed to carry over to the subsequent task condition this might be evidence for sequences of cortical activity extending over minutes.

METHODS

Subjects

Eight healthy subjects (7 females, 1 male) volunteered for the experiment. All participants were compensated. The EEG of the male was excluded from further analysis to facilitate the comparison between subjects in an all-female group (see Table 1 for demographics; mean age = 24 ± 4 years). All subjects were clinically healthy, had not sustained any head injuries, and were not presently taking medication. All subjects had at least 12 years of formal education and were students except for one coauthor (Table 1).

Physiological recording

The subject sat with eyes open in a reclined armchair in a dimly lit, sound-attenuated room. Following the international 10-20 system^{28,29} 19 gold-disc electrodes were glued to the scalp (see Figure 2). Reference electrodes were applied to both ear-lobes. Recordings were made against the averaged signals at both ear electrodes. Using a conventional Nihon Kohden 21 channel recorder, EEG was amplified and filtered (time constant 0.3sec, low pass 35 Hz) and displayed on paper. The output of the EEG recorder was connected to a Walter Graphtek data acquisition system (sampling rate 128/sec) to store the data on hard disk for off line processing. Conspicuous artifacts were eliminated from

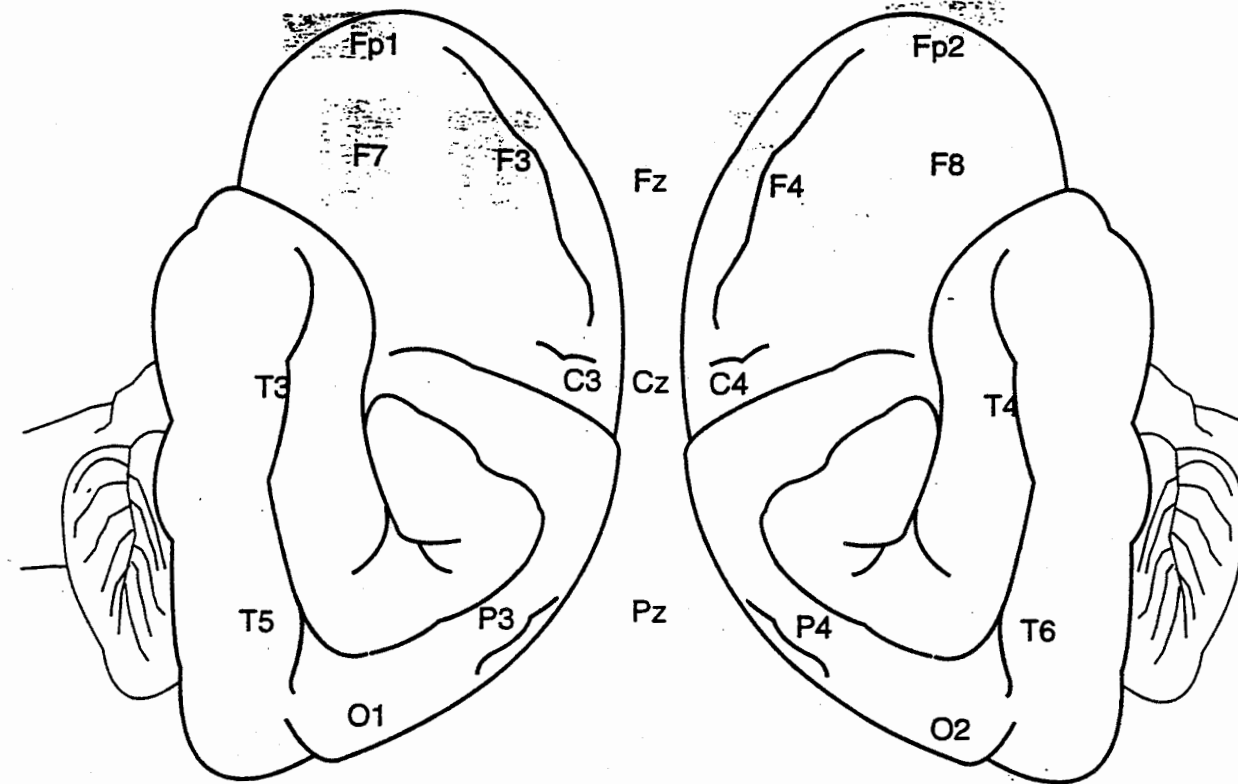
further computation by visual inspection. Each recording session began with alternating eyes open conditions and eyes closed conditions of several minutes each. During the eyes open conditions the subjects were instructed to fixate a point about 2 m in front of them in order to minimize disruptive effects of eye movements on the EEG. The corresponding EEG epochs were averaged to obtain the control record used as a baseline in the representation of the results (EEGr). During the subsequent procedure the subjects were asked to keep their eyes open. For the control records and for the test records, respectively, as many as possible artifact free 2 sec epochs were selected for further processing.

Data reduction and analysis

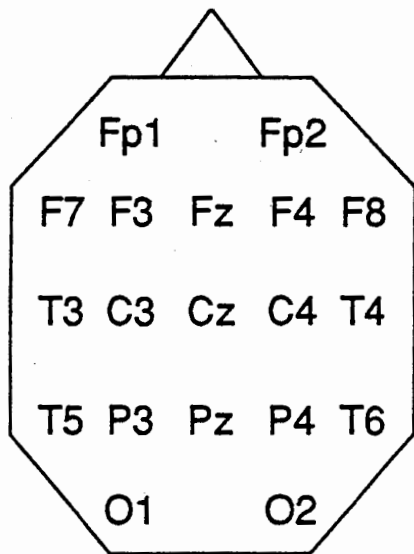
Each epoch was Fourier transformed and averaged power spectra C_{xx} and cross-power spectra C_{xy} with a frequency resolution of 0.5 Hz were computed. Data reduction of the spectra was performed by averaging adjacent spectral lines to obtain broad band parameters for six frequency bands: delta (1.5-3.5 Hz), theta (4.0-6.5 Hz), alpha1 (7.0-9.0 Hz), alpha2 (9.5-12.5 Hz), beta (13.0-18.0 Hz) and gamma (18.5-31.5 Hz). Averaged cross-power spectra were calculated between adjacent electrodes along the transverse and antero-posterior electrode rows (local cross-spectra). The final step was the computation of amplitude (square root of power) and squared coherence per frequency band^{30,31}, thus leading to 19 power spectra and 30 cross-power spectra for each recording condition.

Squared coherence K^2 describes the linear relationship of two signals x and y . It is equal to the normalized average cross power spectrum according to^{30,31} $K^2 = |C_{xy}|^2 / \{C_{xx}C_{yy}\}$. In practice, we averaged the power spectrum of all blocks that corresponded to one specific experimental condition (task, listening or resting) and then determined one coherence value for this condition. A detailed description of the method is given by Rappelsberger and Petsche¹⁹.

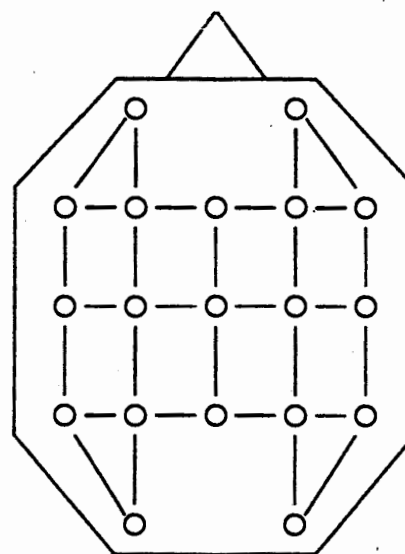
The calculation of coherence, which is defined in the frequency domain, yields the same information as calculation of the cross-correlation, which is performed in the time domain to determine the synchronization between two signals. Thus an increase of coherence signifies a synchronization between the signals recorded



A



B



C

Figure 2: Electrode positions of the international 10-20 system³². A: Location of the electrodes above the cortex as determined in an MRI study³³. B: Schema of electrode sites as used throughout this paper. C: Coherence was calculated between pairs of adjacent electrodes

at two cortical sites. Following the EEG convention, the synchronization is used here for any phase-locked signals, not only those with zero phase lag.

Presentation of results

For the evaluations of task-dependent amplitude and coherence changes the corresponding spectral parameters of the control records were used as baseline. Differences were presented in spectral parameter maps, where difference values are color coded and interpolated between electrode pairs to give a schematic view of where on the cortex coherence changes. Statistical significant changes during the tests with respect to the baseline parameters were evaluated using paired Wilcoxon tests. The obtained rank sums were converted to error probabilities and presented as topographic probability maps. In most cases a large magnitude of coherence change coincides with a significance of the change and we therefore present our data only in the color-coded difference plots which we feel are more illustrative. A detailed description of this mapping procedure can be found in References 18 and 19.

Design of the experiment

The experiment took place in two sessions for each subject, the time interval between session A and B ranging between a few hours up to several weeks. As in the behavioral experiment⁶, subjects solved two sets of 16 items derived^{5,6} from Stanford-Binet's³² Paper Folding and Cutting (pf&c) task, assessing spatial-temporal reasoning (Figure 1). Instructions for the task were presented orally prior to each session. In the first session (Session A) subjects listened to a spoken text in their native language for 3 min, followed by 1 min of a resting condition with eyes open. Next, they solved all 16 items of the first pf&c set, lasting about 1 min per item. In the second session (Session B) this procedure was repeated with the second pf&c set. However, instead of listening to the text the subjects listened to the Mozart Sonata K.448 for 10 min.

Table 1 shows the scores obtained during session A (after listening to text) and session B (after listening to the Mozart sonata). Possibly due to their analytic training three of the subjects (UW, ME and UK) obtained particularly high scores already in the first session, leaving no room for significant enhancement in session B. This made the behavioral experiment difficult to reproduce, it having shown that the highest increase in performance was achieved by participants with low initial scores (Figure 4 of Reference 6). Also participants in the behavioral experiments did not have musical training^{5,6}, the EEG experiment was carried out in Vienna, where musically-naive subjects are difficult to obtain. Unlike the behavioral studies^{5,6} which rely on the scores of the participants to study the effect of music, this paper focuses on a potential neurophysiological basis as determined by EEG coherence analysis.

RESULTS

A first result is the finding that amplitude and coherence patterns during the pf&c tasks are highly reproducible for the 16 items of the task within each session^{26,27}. This was true for each of our 7 subjects. In the following we will focus on the average coherence patterns that appeared in each session. Figure 3 shows the average coherence changes for two subjects (UW and VS.)

We will begin with subject UW (columns 1–3). The coherence patterns during pf&c in session A are shown in column 1. The main cortical sites involved in solving the pf&c tasks were right fronto-temporal (with increasing coherence in delta, theta and alpha1), right temporo-parietal (with increasing coherence in nearly all frequency ranges) and centro-parietal (with increasing coherence mainly in delta and theta). This is in agreement with the general notion of spatial reasoning tasks being performed in parietal cortex. Amplitudes during pf&c decrease in parietal cortex in the alpha bands (alpha-block) and increase in frontal amplitude in the beta and gamma bands (not shown). The coherence patterns during pf&c in session B are shown in column 2. It is interesting to note that during pf&c tasks in both sessions A and B the gross topographies of the task-related coherence patterns display many common features. We have found a similar reproducibility of patterns between sessions in most of our subjects^{26,27}.

Besides the reproducibility of the gross topography between pf&c A patterns and pf&c B patterns, some differences in well defined areas and frequency bands can be detected. There are several more cortical activations in session B than in session A; these areas are circled. Additional coherence increase appears prefrontal (gamma), left occipital (beta, gamma), and left temporal (beta, gamma and alpha2). This means that some of the features that are present unilaterally during pf&c A are found bilaterally during pf&c B. Our question was whether the additional cortical activation could be traced back to the 'Mozart listening condition' which took place before pf&c B. Column 3 shows the maps during the 'Mozart listening condition' in session B. The coherence patterns of the music listening condition are very similar to the circled patterns of the pf&c B tasks both in location and frequency band. To facilitate comparison, we drew the circles in the music patterns in the same location as in the pf&c B patterns. This suggests that the difference between pf&c B and pf&c A patterns was induced by listening to music. In a similar way, coherence between the 2 hemispheres was increased in Session B (interhemispheric coherences are not shown here). Listening to the Mozart thus appears to have an effect on patterns of cortical activation even after the exposure to the music has ended.

We will now discuss the results in subject VS (columns 4–8). During the pf&c tasks A (column 4) the main cortical sites involved were right fronto-temporal (with increasing coherence in delta, theta, alpha1) right temporal (with coherence increase in alpha2, beta, gamma) and centro-parietal (with increasing coherence mainly in alpha and beta and gamma bands). During

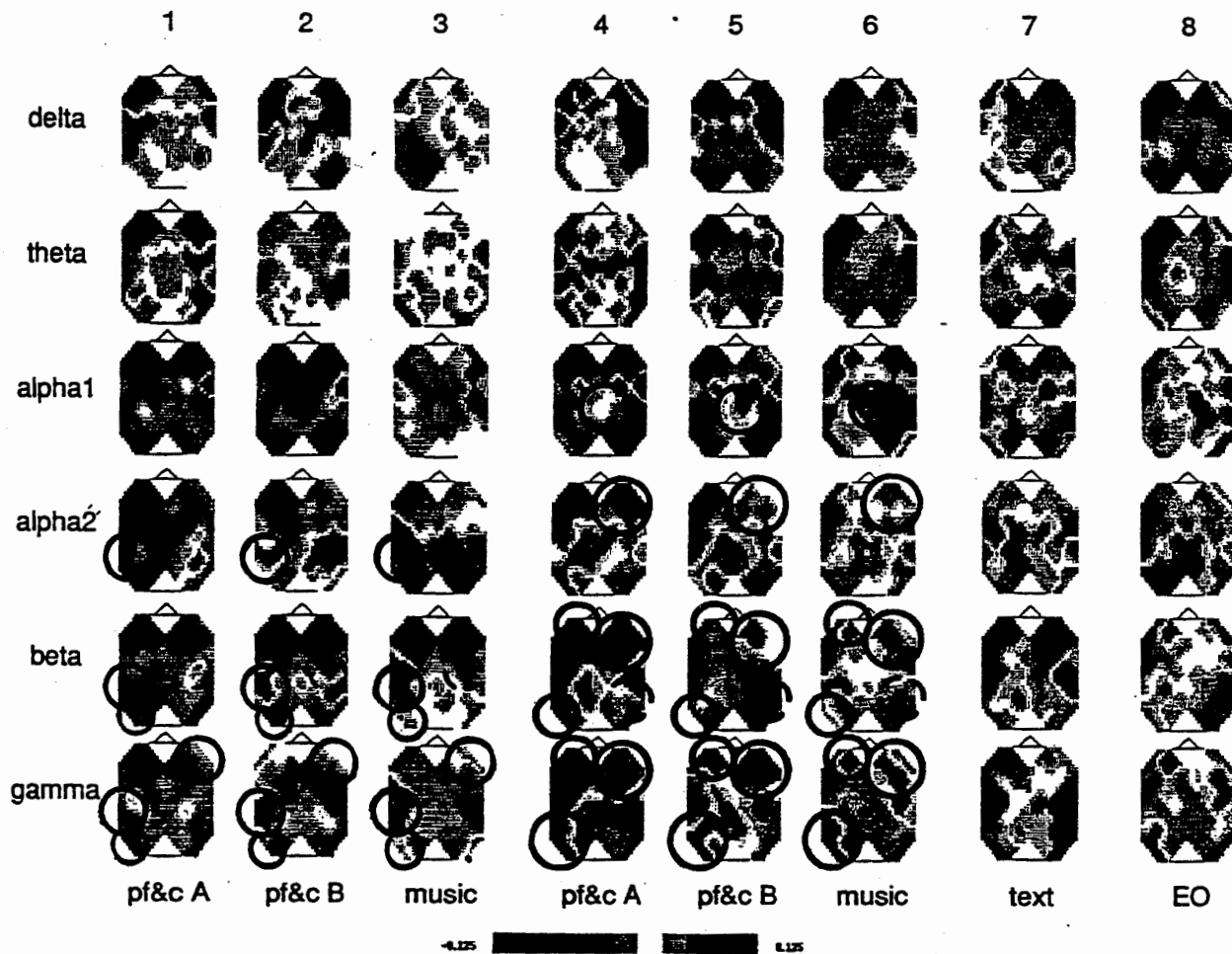


Figure 3: EEG coherence patterns during sessions A and B for two subjects (UW, columns 1–3; VS, columns 4–8). Coherence values are calculated with respect to the baseline (EEGr). The magnitude of the coherence changes is color-coded (increases are red, decreases are blue, see scale) and interpolated between electrode pairs (see Figure 2). Rows denote the frequency bands.

Subject UW: Column 1: Processing the pf&c tasks in session A. Column 2: Processing the pf&c tasks in session B. Note the reproducibility of the gross topography in columns 1 and 2. Important differences have been circled, solid (dashed) circles indicating coherence increases (decreases). The circled regions are defined with respect to differences between column 1 and column 2. The pattern pf&c B appears as a superposition of pattern pf&c A and this pattern.

Subject VS: Column 4: Processing the pf&c tasks in session A. Column 5: Processing of the pf&c tasks in session B. Column 6: Listening to the Mozart Sonata K.448 in session B before solving the pf&c tasks. The pattern here for pf&c B appears as a superposition of pattern pf&c A and this pattern. Note that the circles coincide in location and frequency bands for subjects UW and VS. Column 7: Listening to a text in session A before solving the pf&c tasks. Column 8: One minute eyes open condition after listening to the music. Comparing columns 6 and 8, we see that the patterns induced by listening to the music are sustained after exposure to the music.

pf&c B the same cortical sites are again activated. Amplitude patterns during both pf&c sessions show a similar topography; a decrease in parietal amplitude in beta and in the alpha bands (alpha-block) and an increase of frontal amplitude in beta (not shown). Again, we are interested in the differences between the patterns pf&c A and pf&c B. Additional features in the coherence patterns appear right frontal (alpha2, beta, gamma) and left prefrontal (beta, gamma) and left occipital (beta, gamma). As can be seen in column 6, these areas were

also activated while VS listened to Mozart. As in subject UW this suggests a carry-over of the brain state induced by listening to Mozart to the subsequent task condition. The finding in both subjects supports our hypothesis that additional involvement of these cortical areas improve the spatial-temporal reasoning capabilities of the subject after listening to the Mozart ('priming').

The same carry-over has also been observed for subject ME in the same areas, although less pronounced and mainly in the gamma band. ME took both sessions

in one day, reported as being tired during session B, and was the only subject to have a decrease in task performance in session B. In our other four subjects the gross topographies of the pf&c task patterns are also reproducible, but the detailed differences between the session B and A patterns cannot be attributed as easily to the 'priming' by music. We suggest that more detailed analyses, e.g., looking at the time course of the EEG coherence during the pf&c task might be informative here.

Can the additional features in pf&c B really be traced back to listening to music? As a control, we show the coherence patterns of the 'text listening condition' before solving the pf&c tasks in session A (column 7); the patterns differ appreciably from the 'Mozart listening condition'. It is, however, not clear why in this subject a language task induced strong coherence features lateralized to the right hemisphere. In a group average we find increase of coherence over left temporo-parietal cortex, in agreement with similar results of earlier work^{19,22}. The left frontal activation in the theta band may be related to working memory function necessary for language comprehension^{24,33}. To isolate the carry-over of the 'Mozart listening condition' we show the EEG patterns for VS (session B) in an eyes-open resting condition (column 8) after listening to the music and before solving the pf&c B tasks. These patterns thus occurred after column music and before column pf&c B. Coherence increases in the beta and gamma bands remain in left occipital and right frontal. These coherence increases constitute the main additional activations in pattern pf&c B with respect to pattern pf&c A.

In *Figure 4*, we focus on the duration of the carry-over. Subject JJ in an additional session (not involving the pf&c tasks) again listened to the Mozart for 10 min and subsequently relaxed for 12 min. The first column in *Figure 4* shows the coherence pattern during the exposure to music. The following four columns depict the patterns that arose during the subsequent relaxation, each period lasting about 3 min. This is evidence that the effects of listening to the Mozart, relevant to the pf&c tasks, lasts for some minutes.

DISCUSSION

According to models on cortical dynamics^{2,14} the highly interconnected, structured cortex could produce inherent spatial-temporal firing patterns, sometimes evolving over long time periods². Such sequences might be used in representing complex temporally structured stimuli such as sequences of thought as in chess or other spatial-temporal reasoning tasks. Since music also should require these temporal sequences of neural activity, it has been postulated that music might prime these evolving patterns of neural activity^{1,10-11}. An enhancement of spatial-temporal reasoning tasks by music has indeed been found^{5,6}. This study was designed to investigate possible neurophysiological bases for this effect. Using EEG frequency analysis we have investigated the cortical dynamics during both

music and a complex paper-folding and cutting task (pf&c task). The pf&c task was chosen since it is a demanding example of spatial-temporal reasoning; it involves maintaining and transforming sequences of mental images for tens of seconds even in the absence of a physical model. EEG frequency analysis seemed particularly suited since it determines stable states of coherent activity over minutes of time in the ongoing EEG. In two sessions these patterns of coherent activity were determined for a set of pf&c tasks, once when primed by listening to music, once when not. Patterns of activity were compared for the pf&c tasks among the two sessions and during listening to music. The results detailed in the previous section can be grouped into three parts:

1. Highly reproducible patterns were observed during the 16 items of the pf&c task in a given session for each subject^{26,27}. The main features were increased right temporo-parietal coherence and prefrontal amplitude. Parietal activation is consistent with the general notion of localization of spatial reasoning abilities. Prefrontal cortical function is commonly associated with working memory, which subjects recruited to keep the multiple choice solution in mind until a final decision was made. Specifically, prefrontal cortex is known to be involved in temporal sequencing of patterns³⁴ as needed explicitly in the pf&c task. The patterns of coherent activity were present across several frequency ranges, thus representing compound spatial-temporal dynamics. Thus, we have found complex activity patterns evolving in the two brain regions engaged in processing spatial-temporal sequences, parietal cortex and prefrontal cortex.

2. The patterns during the first session of pf&c tasks and the second session showed a remarkably similar topography. In three subjects in Session B, however, some additional features in the coherence patterns were observed during pf&c; these features were also present during the preceding 'Mozart listening condition'. Listening to text did not have such an evident carry-over both quantitatively and qualitatively. From this we infer that brain activation due to listening to music might carry over to the subsequent task condition and be responsible for the increase in task performance.

In detail, the carry-over of music was found in two brain regions. It is highly remarkable, that the areas coincide in both subjects UW and VS. As a first region, left temporo-parietal cortex was additionally activated; thus music induced involvement of left and right temporal lobes, as opposed to only right involvement in pf&c without music. Second, we found a strong increase of coherence in prefrontal cortex in the gamma range during pf&c after music priming. Interestingly, during pf&c in session A prefrontal cortex was also activated (subject UW), but only locally, that is with an increase in EEG amplitude (EEG amplitude reflects the degree of synchronization underneath the electrode, i.e. local synchronization, whereas coherence reflects the synchronization between different cortical sites). Thus, what appears to be added to the task after music was an increased cooperativity between different prefrontal

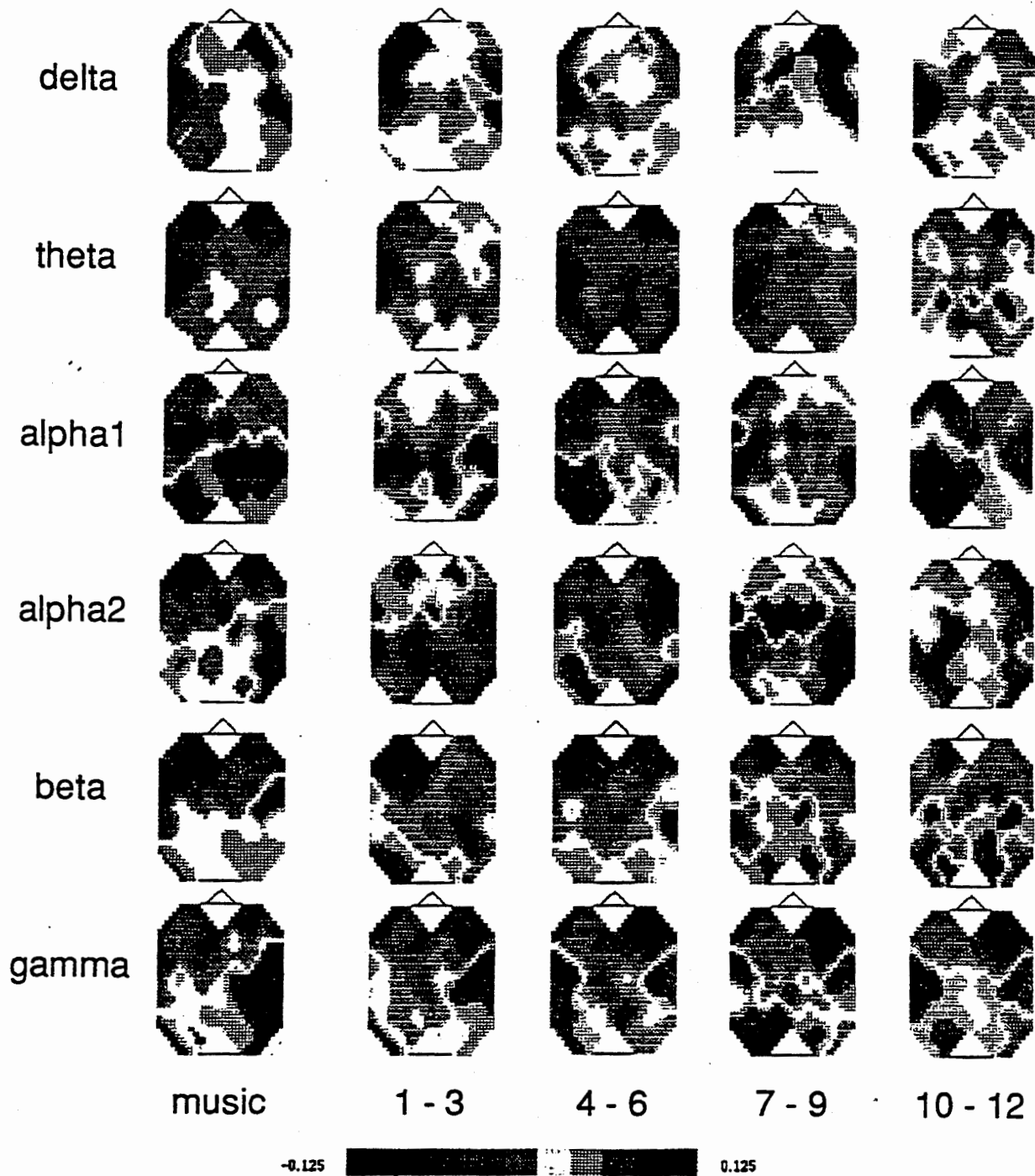


Figure 4: EEG coherence patterns of subject JJ during and after listening to the Mozart Sonata K.448. Plots as in Figure 3. Column 1: Coherence patterns while listening to the music for 10 min. Columns 2-5: Coherence patterns after exposure to the music; shown are four subsequent periods of about 3 min each. Note that several features of the patterns remain constant and similar to the patterns during the exposure to the music, several oscillate and others fade away.

sites. This gives clues on the mechanism underlying the increased task performance: instead of activating several sites independently (amplitude increase), synchronization between different cortical sites was increased (coherence increase). Since in both subjects local activity actually even decreased in Session B, we suggest that this might be a processing-mode of increased cortical efficacy. Whereas this study described the EEG correlates of short-term enhancement^{5,6} of spatial-temporal reasoning, similar effects of increased cortical efficacy have been found on a long-term basis. For example, cerebral blood flow measurements (PET) of Tetris players³⁵ and also EEG coherence studies of cube rotation tasks³⁶ both found that experience lowered brain activation during task performance.

A recent study again motivated by the mode¹ reported that music training produced long-term enhancement of preschool children's spatial-temporal reasoning⁷. The children were divided into four groups. One group of children was given private piano keyboard lessons for six months (Keyboard group), the three other groups (Singing, Computer, No Lessons) served as controls. The Keyboard group improved dramatically on an age standardized spatial-temporal reasoning task³⁷ while the control groups did not improve significantly. Tasks measuring spatial recognition did not improve significantly for any group. This enhancement lasted at least one day and thus suggests long-term modifications³⁸⁻⁴⁰ in underlying neural circuitry not primarily concerned with music. The results of the present study suggest that listening to music might enhance spatial-temporal reasoning by inducing neurophysiological effects on a short term basis, which can otherwise only be achieved by long-term training.

3. So far, the causal relationship between the additionally activated areas and music has only been assumed. To test the hypothesis that the patterns induced by music have a carry-over for long periods of time, we measured coherence in a resting condition following exposure to music. We found in subject VS that the patterns of 1 min of this condition remain very similar to those during music (Figure 3, column 8). Furthermore, we found a slow decay of coherence-patterns in several sites lasting up to 10 min after the stimulation was terminated (Figure 4). Again, there was no predominance in a certain frequency range, suggesting that we are not dealing with sinusoidal oscillatory activity but with complex spatial-temporal dynamics. On top of these patterns of coherent activity in the ms range (1 Hz to 32 Hz), slow oscillations on the timescale of minutes were evident. Although this finding definitively has to be considered preliminary, it might be a first step towards describing more complex processing sequences in time. Similar after-effects of stimulation have so far only been described for simple rhythmic stimulation like flicker-light⁴¹ or rhythmic sensory stimulation⁴². In those cases, the after-effect consists in prolonged activity in the frequency of stimulation for about 500 msec. The fact that complex and far longer lasting cortical dynamics can be induced by specific stimuli seems an interesting and promising finding,

which might shed light on higher cortical processing always evolving in time.

Suggested further experiments

1. Temporal decay of the amplitude and coherence patterns are of strong interest and not only the localization of the cortical activity induced by the stimulus material. We would expect that certain kinds of music would have longer carry-over into the resting condition and therefore greater impact on subsequent reasoning tasks. Extensive studies of this should be conducted. In addition these oscillations shown in Figure 4, if confirmed, may indicate the important effects of the long-term dynamics on reasoning.

2. The temporal oscillations noted above (see Figure 4) are on the order of some minutes. The priming thus should not only be confirmed as in 1. but we also suggest a modified series of behavioral experiments. Here one would consider as a variable the time delay inserted between the listening condition and the pf&c task looking at a peak of enhancement at nonzero time delay. One should note that in designing further behavioral experiments in this field that the task can prime itself.

3. The optimum experimental conditions might combine EEG with the higher spatial resolution of blood-flow measurements like f-MRI and PET. EEG should, however, not be entirely neglected in favor of more modern techniques, since, apart from measuring interactions between large regions of the cortex, EEG also yields information on the sub-threshold neuronal activity that could be of special importance for the priming phenomena that we are investigating.

CONCLUSIONS

In conclusion, we have found carry-over in EEG coherence from the 'Mozart listening condition' to the spatial-temporal reasoning tasks, which may be responsible for the causal enhancement found in the behavioral experiments^{5,6}. We suggest that the increased synchrony between cortical sites that was indicated may play a crucial role by increasing functional efficacy. From a more general viewpoint, we have found stable patterns of cortical activity induced by complex spatial-temporal stimuli, which persisted even after the exposure to the stimulus. This is experimental evidence for long-lasting patterns of cortical activity related to higher brain functions in humans.

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REFERENCES

- 1 Leng X, Shaw GL. Toward a neural theory of higher brain function using music as a window. *Concepts in Neurosci* 1991; 2: 229-258
- 2 Shaw GL, Silverman DJ, Pearson JC. Model of cortical organization embodying a basis for a theory of information processing and memory recall. *Proc Nat Acad Sci USA* 1985; 82: 2364-2368
- 3 Shenoy KV, Kaufman J, McGrann JV, Shaw GL. Learning by

- selection in the trion model of cortical organization. *Cerebral Cortex* 1993; 3: 239-248
- 4 McGrann JV, Shaw GL, Shenoy KV, Leng X, Mathews RB. Computation by symmetry operations in a structured model of the brain. *Physical Rev* 1994; E49: 5830-5839
 - 5 Rauscher FH, Shaw GL, Ky KN. Music and spatial task performance. *Nature* 1993; 365: 611
 - 6 Rauscher FH, Shaw GL, Ky KN. Listening to Mozart enhances spatial-temporal reasoning: towards a neurophysiological basis *Neurosci Lett* 1995; 185: 44-47
 - 7 Rauscher FH, Shaw GL, Levine LJ, Wright EL, Dennis WR, Newcomb RL. Music training causes long-term enhancement of preschool children's spatial-temporal reasoning. *Neurol Res* 1997; 19: 2-8
 - 8 Mountcastle VB. An organizing principle for cerebral function: The unit module and the distributed system. In: Edelman GM, Mountcastle VB, eds. *The Mindful Brain*. Cambridge: MIT, 1978: pp. 1-50
 - 9 Goldman-Rakic PS. Modular organization of prefrontal cortex. *Trends Neurosci* 1984; 7: 419-424
 - 10 Leng X, Shaw GL, Wright EL. Coding of musical structure and the trion model of cortex. *Music Percept* 1990; 8: 49-62
 - 11 Brothers L, Shaw GL, Wright EL. Durations of extended mental rehearsals are remarkably reproducible in higher level human performances. *Neurol Res* 1993; 15: 413-416
 - 12 Petsche H, Richter P, von Stein A, Etlinger S, Filz O. EEG coherence and musical thinking. *Music Percept* 1993; 11: 117-151
 - 13 Cooper R, Winter AL, Crow HJ, Walter W. Comparisons of subcortical, cortical and scalp activity using chronically indwelling electrodes in man. *Electroenceph Clin Neurophysiol* 1965; 18: 217-228
 - 14 Abeles M. *Corticocircuits: Neural Circuits of the Cerebral Cortex* Cambridge: Cambridge University Press, 1991
 - 15 Shaw JC, O'Connor KP, Ongley CO. EEG coherence as a measure of cerebral functional organization. In: Brazier MAB, Petsche H, eds. *Architectonics of the Cerebral Cortex*, New York: Raven Press, 1997: pp. 245-256
 - 16 Thatcher RW, Krause PJ, Hrybyk M. Cortico-cortical associations and EEG coherence: A two-compartmental model. *Electroenceph Clin Neurophysiol* 1986; 64: 123-143
 - 17 Rideout BE, Laubach CM. EEG correlates of enhanced spatial performance following exposure to music. *Percept Motor Skills* 1996; 82: 427-432
 - 18 Rappelsberger P, Pockberger H, Petsche H. Computer aided EEG analysis. *EDV Med, Biol* 1986; 17: 45-53
 - 19 Rappelsberger P, Petsche H. Probability mapping: Power and coherence analyses of cognitive processes. *Brain Topog* 1988; 1: 46-54
 - 20 Singer W. Search for coherence: A basic principle of cortical self-organization. *Concepts Neurosci* 1990; 1: 1-26
 - 21 Petsche H, vonStein A, Filz O. EEG aspects of mentally playing an instrument. *Cognitive Brain Res* 1996; 3: 115-123
 - 22 Weiss S, Rappelsberger P. EEG coherence within the 13-18 Hz band as a correlate of a distinct lexical organisation of concrete and abstract nouns in humans. *Neurosci Lett* 1996; 209: 17-20
 - 23 Johnson JK, Petsche H, Richter P, vonStein A, Filz O. The dependence of coherence estimates of spontaneous EEG on gender and music training. *Music Percept* 1996; 13: 563-582
 - 24 Samthein J, Rappelsberger P, Shaw GL, vonStein A. Synchronization between prefrontal and posterior association cortex during working memory tasks in humans, submitted 1997
 - 25 vonStein A, Petsche P. Supramodal object representation, submitted 1997
 - 26 Samthein J, vonStein A, Shaw GL, Rauscher FH, Rappelsberger P, Petsche H. EEG coherence during spatial-temporal reasoning tasks. *Soc Neurosci Abstracts* 1996; 22: 1108
 - 27 Samthein J, Rappelsberger P, Shaw GL, vonStein A. Reproducibility of EEG coherence measurements during cognitive processes, in preparation 1997
 - 28 Jasper HH. The Ten Twenty Electrode System of the International Federation. *Electroenceph Clin Neurophysiol* 1958; 10: 371-375
 - 29 Homan RW, Herman J, Purdy P. Cerebral location of international 10-20 system electrode placement. *Electroenceph Clin Neurophysiol* 1987; 66: 376-382
 - 30 Jenkins GM, Watts DG. *Spectral Analysis and its Application*, Oakland: Holden Day, 1968
 - 31 Challis RE, Kitney RI. Biomedical Signal Processing. Part 3. The power spectrum and coherence function. *Med Biol Eng Comput* 1991; 29: 225-241
 - 32 Thorndike RL, Hagen EP, Gerome MS. *The Stanford-Binet Intelligence Scale*, Chicago: Riverside Publishers, 1968
 - 33 Petrides M, Alivisatos B, Evans AC. Functional activation of the human ventrolateral frontal cortex during mnemonic retrieval of verbal information. *Proc Nat Acad Sci USA* 1995; 92: 5803-5807
 - 34 Fuster JM. Temporal processing. *Ann NY Acad Sci* 1995; 769: 173-181
 - 35 Haier RJ, Siegel BV, MacLachlan A, Soderling E, Lottenberg S, Buchsbaum MS. Regional glucose metabolic changes after learning a complex visuospatial/motor task: A positron emission tomographic study. *Brain Res* 1992; 570: 134-143
 - 36 König H, Rappelsberger P, Vitouch P, Bauer H. EEG coherence during spatial reasoning tasks, in preparation 1997
 - 37 Wechsler D. *Preschool and Primary Scale of Intelligence-Revised* San Antonio: The Psychological Corporation, 1989
 - 38 McGauch JL. Time-dependent processes in memory storage. *Science* 1966; 153: 1351-1358
 - 39 Bliss TVP, Lomo T. Long-lasting potentiation of synaptic transmission in the dentate area of the anesthetized rabbit following stimulation of the perforant path. *J Physiology* 1973; 232: 331-356
 - 40 Baudry M, Massicotte G. Physiological and pharmacological relationships between long term potentiation and mammalian memory. *Concepts Neurosci* 1992; 3: 79-98
 - 41 van der Tweel LH. Relation between the psychophysics and electrophysiology of flicker. In: Henkes HE, van der Tweel LH, eds. *Flicker*, The Hague: Junk, 1964: pp. 287-304
 - 42 Narici V, Pizella Romani GL, Torriolo G, Traversa R, Rossini PM. Evoked alpha and mu rhythms in humans: a neuromagnetic study. *Brain Res* 1990; 520: 222-231