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 brain 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 neuropsychophysiological 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 four 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 neuropsychophysiological 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. Neurosci Res 1997; 19: 107-116.

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

INTRODUCTION

Predictions from a structured brain model of the cortex1-3 led to the testing6 of the hypothesis that music could causally enhance spatial-temporal reasoning. Based on Mountcastle's columnar5,6 organizational principle for cortical function, the brain model1-3 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 patterns1. 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.

Music, it was argued, should also require these temporal sequences of neural activity.1-3,6-7. A fundamental property of these evolving patterns of neural activity is that they can be readily strengthened through experience or learning1-3. Although higher brain functions are typically associated with specific, localized regions of cortex, all higher cognitive abilities draw upon a wide range of cortical areas1-2. 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 common 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.44886, control) groups listened to relaxation tapes, to minimalist music, to silence or to an audio-taped test. 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 neuropsychophysiological basis for this behavioral effect. It is well established that specific changes of EEG amplitude in certain frequency bands can be
correlated to mental processes. 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 stimulus. Since a scalp electrode picks up the summed activity of several square centimeters of cortical tissue, EEG measures only concerted activity of large scale cell assemblies and is thus well suited to detect global states of cortical function. The improvement of spatial resolving capabilities by listening to music has been studied by EEG power analysis. EEG coherence analysis has been developed as a more precise tool for the analysis of higher brain function. Scalp EEG coherence analysis may be related to intracortical electrophysiological findings which state that functional cell assemblages are defined by synchronous activity of their member neurons. 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. Placing 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. In the present study each subject participated in two sessions. In each session the subject was asked to perform a set of tasks which involve spatial-temporal reasoning, paper folding and cutting (p&f&c) during a period of about one minute (see Figure 1). In the second session the p&f&c tasks were preceded by listening to 10 min of the Mozart sonatas for two pianists 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. We found prefrontal, parietal and temporal cortical activity during p&f&c tasks manifest in the coherence patterns during both sessions for each of our seven subjects. This is consistent with general notions on spatial-temporal reasoning functions of the cortex.
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 pt16 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 pt16 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 included 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 reclining armchair in a dimly lit, sound-attenuated room. Following the international 10-20 system, 19 gold-disc electrodes were gazed to the scalp (see Figure 2). Reference electrodes were applied to both earlobes. 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 0.3 sec, low pass 35 Hz) and displayed on paper. The output of the EEG recorder was connected to a Walter Crystek data acquisition system (sampling rate 128Sec) to store the data on hard disk for off line processing. 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 (EEGc). 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 Cw and cross-power spectra Cw, with a frequency resolution of 0.5 Hz were computed. Data reduction of the spectra was performed by averaging adjacent spectral bins to obtain broad band parameters for six frequency bands: delta (1.5–3.5 Hz), theta (4.5–6.5 Hz), alpha (7.0–9.0 Hz), beta 1 (13.0–16.0 Hz) and gamma (18.5–31.5 Hz). Averaged cross-power spectra were calculated between adjacent electrodes along the transverse and anterior-posterior electrode rows (local cross spectra). The final step was the determination of amplitude (square root of power) and squared coherence per frequency band, thus leading to 19 power spectra and 30 cross-power spectra for each recording condition. Squared coherence Kg describes the linear relationship of two signals x and y. It is equal to the normalized average cross power spectrum according to

Kg = [Cw(xy)]²/[Cw(x)xwCw(y)]

In practice, we averaged the power spectrum of all blocks that corresponded to one specific experimental condition (task, listening or resting) and then determined overall coherence value for this condition. A detailed description of the method is given by Rappelberger and Fetscher. 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

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Figure 2: Electrode positions of the international 10-20 system\textsuperscript{2}. A: Location of the electrodes above the cortex as determined in an MRI study\textsuperscript{3}. B: Schematic diagram of electrode sites as used throughout this paper. C: Coherence was calculated between pairs of adjacent electrodes.

\textsuperscript{2} Neurological Research, 1997, Volume 19, April
Results

A first result is the finding that amplitude and coherence patterns during the pfAc 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).

You will begin with subject UW (columns 1-3). The coherence patterns during pfAc in session A are shown in column 1. The main cortical sites involved in solving the pfAc tasks were right fronto-temporal (with increasing coherence in delta, theta, and alpha1), right temporoparietal (with increasing coherence in nearly all frequency ranges) and centro-parietal (with increasing coherence in beta, gamma, and alpha2). In agreement with the general notion of spatial reasoning tasks being performed in parietal cortex. Amplitudes of pfAc 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 pfAc in session B are shown in column 2. It is interesting to note that during pfAc 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 pfAc A patterns and pfAc 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 preferential (gamma, left occipital (beta, gamma), and left temporal (beta, gamma and alpha2). This means that some of the features that are present unilaterally during pfAc A are found bilaterally during pfAc B. Our question was whether the additional cortical activation could be traced back to the ‘Mozart listening condition’ which took place before pfAc 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 pfAc B tasks both in location and frequency band. To facilitate comparison, we drew the circles in the music pattern in the same location as in the pfAc B patterns. This suggests that the difference between pfAc B and pfAc 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 pfAc 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 alpha), 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 UV and VS. Columns 1-3: VS; columns 4-6: UV. Coherence values are calculated with respect to the baseline (EEG3). The magnitude of the coherence changes is color-coded (increases are red, decreases are blue; see scale) and represented between the corresponding sites. Line Figure 2 shows the frequency bands.

Subject UV: Column 1: Processing the p300 tasks in session A; Column 2: Processing the p300 tasks in session B. Note the reproducibility of the gross topography in columns 1 and 2. Important differences have been marked, solid (dashed) circles indicating coherence increases (decreases). The circles have also been drawn in column 3 to guide the eye. Column 3: Listening to the Mozart Sonata K.448 in session B before solving the p300 tasks. The circled regions are defined with respect to differences between columns 1 and 2. The pattern p300 A appears as a superposition of pattern p300 B and the pattern. Subject VS: Column 4: Processing the p300 tasks in session A; Column 5: Processing the p300 tasks in session B; Column 6: Listening to the Mozart Sonata K.448 in session B before solving the p300 tasks. The pattern has a similar pattern to pattern p300 B appears as a superposition of pattern p300 A and the pattern. Note that the circles indicate locations and frequency bands for subjects UV and VS, Column 7: Listening to a test in session A before solving the p300 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.

p300 B, the same cortical sites are again activated. A specific pattern was observed during both p300 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 p300 A and p300 B. Additional features in the coherence patterns appear right frontal (alpha2), beta, gamma) and left parietal (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 UV, 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 reorganizing capabilities of the subject after listening to 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 pfc task patterns are also reproducible, but the detailed differences between the session B and A patterns cannot be attributed at 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 pfc task might be informative here.

Can the additional features in pfc B really be traced back to listening to music? As a control, we check the coherence patterns of the "antit listening condition" before solving the pfc task 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-polar cortex, in agreement with similar results of earlier work[12,14]. The left frontal activation in the "best brand may be related to working memory function necessary for language comprehension[24,25]. To isolate the carry-over of the "Mozart listening condition" we show the EEC patterns for VS (session 1B) in an eyes-open writing condition (column 8) after listening to the music and before solving the pfc B tasks. These patterns thus occurred after column music and before column pfc 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 pfc B with respect to pattern pfc A.

In Figure 4, we focus on the duration of the carry-over. Subject 1 is an additional session (not involving the pfc task) 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 2 min. It is evidence that the effects of listening to the Mozart, relevant in the pfc B tasks, lasts for some minutes.

DISCUSSION
According to models or cortical dynamics[24,25] the highly interconnected, structured cortices could produce inherent spatial-temporal firing patterns, sometimes evolving over long time periods[4]. 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[4,24]. An enhancement of spatial-temporal, reasoning task by music has indeed been found[8]. This study was designed to investigate possible neurophysiological cues for this effect. Using EEG frequency analysis we have investigated the cortical dynamics during both music and a complex paper-folding and counting task (pfc task). The pfc 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 if 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 pfc A tasks when primed by listening to music, once when not. Patterns of activity were compared for the pfc A tasks among the two sessions and during listening to music. Each subject's music might be detailed in the previous section can be grouped into three parts:

1. Reproducible patterns were observed during the 16 items of the pfc A task in a given session for each subject[8]. The main features were increased right temporo-polar coherence and prefrontal amplitude. Parietal activation is consistent with the general notion of localization of spatial reasoning abilities. Parietal 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 patterns[24] as noted explicitly in the pfc A 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 pfc A 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 pfc A; 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 pfc A without music. Secondly, we found a second increase in coherence in prefrontal cortex in the gamma range during pfc A music priming. Interestingly, during pfc A in session A prefrontal cortex was also activated (subject UW), but only locally, that is with an increase in EEG amplitude (EEG amplitude reflect the degree of synchronization underneath the electrode, e.g. local synchronization, whereas coherence reflects the synchronization between different cortical sites). Thus, what appears to be added in the task after music was an increased cooperativity between different prefrontal
Figure 4: EEG coherence patterns of subject 8 during and after listening to the Mozart Sonata K.444. 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 oscillating elements fade away.
sities. This gives clues on the mechanisms underlying the increased task performance: instead of activating several sites independently (amplitude increase), synchroniza-
tion 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 EGG correlates of short-term enhancement of spatial-temporal reasoning, unlike effects of increased cortico-thalamic efficacy have been found on a long-term basis. For example, cerebro blood flow measurements (PET) of Teglia et al. [20] and also EEG coherence studies of the rotation task [21] both found that experience lowered brain activation during task performance.

A recent study again motivated by the model reported that music training produced long-term enhancement of preschool children's spatial-temporal reasoning [22]. 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 (SingIn, Computer, No Lessons) served as controls. The Keyboard group group improved dramatically on a pure standardized spatial-temporal reasoning task [23] 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 modifications 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 III). 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 coherence activity in the ms range (1 Hz to 3 Hz), slow oscillations on the timescale of minutes were evident. Although the 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-light [24] or rhythmic somatosensory stimulation [25]. In those cases, the after-effect consists in prolonged activity in the frequency of stimulation for about 500 ms. 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 inspect that certain kinds of music would have longer carry-over into the resting condition and therefore greater impact on subsequent reasoning tasks. Explorative 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 confined 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 tact 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 EGG with the higher spatial resolution of brain-flow measurements like fMRI and PET. EGG 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 subthreshold 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 '30-20 Hz range of the EEG, which is of interest for the study of spatial-temporal reasoning tasks, which may be responsible for the causal enhancement found in the behavior.

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