EEG in schizophrenic patients: mutual information analysis

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Abstract

Objective: The aim of the present study is to assess information transmission between different cortical areas in schizophrenics by estimating the average cross mutual information (A-CMI) and to characterize the dynamical property of the cortical areas of schizophrenic patients from multi-channel EEG by establishing the auto mutual information (AMI).

Methods: We recorded the EEG from 16 electrodes in 10 schizophrenic patients and 10 age-matched normal controls. We estimated the slope of the AMI to evaluate the complexity of the EEG signal from one electrode and the A-CMI values of all 16 x 16 pairs of electrodes were calculated to investigate the information transmission of different cortical areas in schizophrenic patients.

Results: In T5 and C3 electrodes, the schizophrenic patients had lower complexity than normal controls. The schizophrenic patients had significantly higher interhemispheric and intrahemispheric A-CMI values than the normal controls.

Conclusions: These results are consistent with previous findings that suggest left hemispheric hypotemporality and inter- and/or intra-hemispheric overconnectivity in schizophrenics. Our results of the left hemispheric hypotemporality and the increased interhemispheric information transmission in temporal lobe may support the hypothesis that the abnormal laterlization in temporal lobe are due to left temporal lobe deficit in schizophrenic patients. © 2002 Published by Elsevier Science Ireland Ltd.

Keywords: Information transmission; Electroencephalography; Mutual information; Schizophrenia; Functional connectivity; Complexity

1. Introduction

During the past two decades, refinements of imaging techniques have provided access to the function and structure of the human brain. EEG is the electrical potential detected at scalp electrodes so that it provides an indication of neuronal activity. Nonlinear dynamical analysis such as the correlation dimension (D2) and the first positive Lyapunov exponent (L1) has been found useful for detecting relative changes between EEGs from different brain states, that cannot be detected using conventional analytic techniques (Ruschke et al., 1993; Elger et al., 2000; Ferri et al., 2001). The application of tools for characterizing time series generated by nonlinear dynamical systems may provide a more complete description of the EEG recordings (Van der Heyden et al., 1999). It has been realized that if nonlinear analysis could be demonstrated in natural systems, it might provide a much simple explanation for the occurrence of complex behavior in such systems than the usual stochastic models (Stam et al., 1995). However, estimating the non-linear dynamical complexity of EEG using such measures as D2 and L1 is problematic (Freeman, 2000). Many of algorithms from nonlinear dynamics and theory of deterministic chaos were found chronically unreliable, often producing spurious dimension or Lyapunov exponent estimates and thus supporting false identification of dynamics existing in the observed data (Rapp, 1993; Palus, 1996a). These measures mathematically require a long time series to obtain reliable estimations. The number of data points increases exponentially with the number of variables that are need to specify the dynamics of the system (Eckmann and Ruelle, 1992). The another difficulty is that the algorithms for calculating nonlinear measures of complexity from experimental data require a very large number of computations in the embedding process (Kantz and Schreiber, 1997). The nonlinear algorithm requires also data stationarity, which cannot be achieved for biological systems. One of trials dealt with stationarity problem has done by Molnar and Skinner et al. (Molnar et al., 1999; Skinner and Molnar, 1999). They compared 3-dimensional algorithms containing Correlation...
Functional connectivity between and within brain hemispheres has been intensively studied using EEG data. There are several methods in the study of cortical connections: for example, synchronization, correlation, or coherence (Leocani et al., 1997; Shen et al., 1999; Weiss and Rappelsberger, 2000). Usually in studies on cortical connectivity the coherence method has been used. In the clinical environment, coherence analysis has been applied into the study of brain connectivity (Thatcher, 1994a,b; Holschneider et al., 1999), such as cortical and subcortical dementia, schizophrenia, and corpus callosum lesions.

In some new approaches, there are nonlinear forecasting methods (Stam et al., 1999) and various complexity measures (Wu and Xu, 1991) containing the Kolmogorov complexity (KC). KC only requires thousands of sampled points and it does not matter if the signal is chaotic or not for the calculation to characterize EEG time series for different functional states of the brain. Xu et al. (1997) suggested that it is reasonable to study the information transmission among the various parts of the human cerebral cortex by the information theory of Vastano and Swinney (1988).

Information theory measures the entropy of an input and the conditional equivocation entropy of the input given a specific output that is known or can be estimated. This estimate of the output reflects the input and the likelihood of correctly identifying the input, as measured in binary digits (bits): greater bits reflect greater likelihood. Information analysis establishes a difference between two groups at a specific time without identifying the nature of the difference. Mutual information detects linear and nonlinear statistical dependencies between time series and is used as a measure of dynamical coupling or information transmission between those time series. Mutual information has the maximum value when the two time series are completely the same and, if one system is completely independent on another, then the mutual information is zero. Xu et al. (1997) described information transmission among different cortical areas in waking and sleep states by estimating the complexity of the cross mutual information (CMI) among 8 electrodes of the EEG. Jeong et al. (2001) estimated the averaged CMI to assess information transmission between different cortical areas in Alzheimer’s disease patients and discussed in terms of cortico-cortical connection between different cortical areas.

In the present study, we investigate the information transmission between different cortical areas in both schizophrenic patients and normal controls by estimating the averaged CMI (A-CMI) between EEG electrodes. The decreasing slope of the auto mutual information (AMI) is measured to estimate the complexity of the EEG signal in both groups.

### 2. Methods

#### 2.1. Analysis

Information theory is usually discussed in terms of a communication system. Consider a process in which messages are sent to an experimenter across the channel of his instruments. Let $S$ denote the whole system which consists of a set of possible messages $s_1, s_2, \ldots, s_n$, and the associated probabilities $P_S(s_1), P_S(s_2), \ldots, P_S(s_n)$. $P_S$ maps messages to probabilities. The subscript is necessary because more than one such function will be considered at a time. If the possible messages are continuous, $S$ denotes the system, $s$ denotes a possible message, and $P_S(s)$ is the probability density at $s$.

The entropy $H$ of a system is the average amount of information gained from a measurement that specifies $S$.

$$H(S) = -\sum_i P_S(s_i) \log P_S(s_i)$$

If the base of logarithm is taken to be two, $H$ is in units of bits. We evaluated these probabilities $P_S(s_i)$ by constructing a histogram (from 4096 data points) of the variations of the measurement $s_i$. We can consider a general coupled system $(S, Q)$ and ask, “Given that $S$ has been measured and found to be $s_i$, what uncertainty is there in a measurement of $Q$?” The answer is

$$H(Q|S) = -\sum_j P_Q(q_j|s_i) \log P_Q(q_j|s_i)$$

where $P_Q(q_j|s_i)$ is the probability that a measurement of $q$ will yield $q_j$ given that the measured value of $s$ is $s_i$.

Then, by averaging $H(Q|S)$ over $s_i$, the uncertainty of $q$ for a given measurement of $s$ is

$$H(Q,S) = -\sum_{i,j} P_Q(q_j,s_i) \log [P_Q(q_j,s_i)P_S(s_i)]$$

$$= H(Q,S) - H(S)$$

where

$$H(Q,S) = -\sum_{i,j} P_Q(q_j,s_j) \log P_Q(q_j,s_j)$$

So we define the mutual information as the amount by which a measurement of $S$ reduces the uncertainty of $Q$. The mutual information is as follows:

$$I(Q,S) = H(Q) - H(Q|S) = H(Q) + H(S) - H(Q,S)$$

$$= I(S, Q)$$

This can be rewritten as

$$I(Q,S) = -\sum_{i,j} P_Q(q_j,s_j) \frac{P_Q(q_j,s_j)}{P_Q(q_j)P_S(s_j)}$$
Mutual information has the maximum value when the two time series are completely the same and if one system is completely independent of the other, then the mutual information is zero. We followed the notations in Fraser and Swinney (1986).

The principal difficulty in calculating mutual information from experimental data is in estimating the probability density $P_{SQ}(s, q)$ from histograms. If a box in the $(s, q)$ plane of size $\Delta s \Delta q$ has $N_{sq}$ points in it, we estimate $P_{SQ}(s, q)$ to be $N_{sq}/N_{total} \Delta s \Delta q$ uniformly across the box. For a given number of data, larger boxes have more points, and hence the estimate of the average probability is more accurate, but the estimates of the probability density are too flat, underestimating $I(S, Q)$. Smaller boxes allow the fluctuations that are due to small-scale structure in probability density $P_{SQ}(s, q)$, overestimating $I(S, Q)$ (Fraser and Swinney, 1986). In this study, we used 64 bins to construct the mutual information, which provided stable estimates (Jeong et al., 2001).

We computed the time-delayed mutual information

$$I(Q(t), S(t + \tau)) =$$

$$- \sum_{q(t), s(t + \tau)} P_{Q(t), S(t+\tau)}(q(t), s(t + \tau)) \log \frac{P_{Q(t), S(t+\tau)}(q(t), s(t + \tau))}{P_{Q(t)}(q(t))P_{S(t+\tau)}(s(t + \tau))}$$

If $Q$ and $S$ are same time series, then we can get the time-delayed auto mutual information (AMI), and if $Q$ and $S$ are different, we can get the time-delayed cross mutual information (CMI).

Because the decreasing slope of the AMI is positively correlated with entropy (Pompe, 1993; Palus, 1994, 1996b), we calculated the slope of the AMI profile and used it as a complexity measure of EEG. We evaluated the AMI of the EEG for 16 channels from both schizophrenic patients and normal subjects along with increasing a delay time from 0 to 500 ms. All AMI values were normalized by dividing by the AMI value at a zero time delay. Since AMI profiles were normalized, the AMI value was 1 at a time delay of zero. The decreasing rate was computed from the AMI at a zero time delay to the first minimum value of the AMI by drawing a simple straight line.

We also estimated the time-delayed CMIs between two different electrodes and averaged it over time delays of 0–500 ms. The averaged CMI (A-CMI) values of all 16 X 16 pairs of electrodes were calculated to investigate the information transmission of different cortical areas in schizophrenics and in normal controls.

For the statistical analysis, we tested the normality of the A-CMI values for both groups using the Kolmogorov-Smirnov test. Group differences of each A-CMI were analyzed using a two-way analysis of variance (ANOVA) with a group factor (patients vs. controls) and a within subject factor (electrodes). Post hoc group comparisons of A-CMI of each pair of electrodes were performed using independent Student’s $t$ tests (SPSS version 6.0). A two-tailed $P$ value of less than 0.05 was considered significant.

2.2. Subjects

The schizophrenic patients screened for inclusion in this study attended the mental health care center which is located at the Chonbuk province and funded by the Korean government. All 10 patients had undergone a thorough clinical evaluation that included clinical history, physical and neuropsychologic examination, routine tests, electrocardiogram, EEG and other tests. EEG recordings were obtained from 10 schizophrenic right-handed patients (age: 35.80 ± 5.35 years, male/female = 6 : 4) fulfilling DSM-IV (American Psychiatric Association, 1994). All patients with schizophrenia were informed of the aim and course of the study, and gave their written consent. Patients with any organic brain lesion, alcohol or drug abuse, concomitant neurologic illness were excluded. Patients were diagnosed as schizophrenics with paranoid type ($n = 7$), and with undifferentiated type ($n = 3$). The average duration of illness was 12.9 years (range: 9–22 years) and the duration of neuroleptic treatment was 10.2 years (range: 1–20 years). The patients were being treated with neuroleptic medication with one to two drugs among chlorpromazine, haloperidol, thioridazine, and memonapride. The effects of neuroleptic drugs by chlorpromazine (CPZ) equivalent doses were analysed with demographic data. The average of CPZ-equivalent doses is 228 mg with range from 60 to 667 mg.

EEG recordings were also obtained from 10 right-handed and age-matched normal controls (age: 29.05 ± 9.02 years, all males) who were healthy volunteers with no history of psychiatric or neurological diseases.

2.3. EEG recording

EEGs were recorded from 16 scalp loci (F7, T3, T5, Fp1, F3, C3, P3, O1, F8, T4, T6, Fp2, F4, C4, P4, and O2) of the international 10–20 system. With the subjects in a relaxed state and eyes closed, EEG recording was acquired and digitized using a 12-bit analog-digital converter on an IBM PC. The EEGs from 16 channels against linked earlobes were amplified on a Nihon-Kohden EEG-4412K with a time constant of 0.1 s. All data were digitally filtered with a bandpass of 0.3–60 Hz. Each EEG record was judged by inspection to be free from electrooculographic and movement artifacts and to contain minimal electromyographic activity. We used 4096 data points (16 s) with sampling frequency of 256 Hz for calculating mutual information.
3. Results

3.1. Complexity measure (AMI analysis)

Table 1 represents the means and the standard deviations of the decreasing slopes of AMI profiles in both schizophrenics and normal group. In T5 and C3 channels, the schizophrenic patients had the more slowly decreasing slope of the AMI than the normal controls, indicating the EEGs at these electrodes in schizophrenic patients are less complex than in the normal controls.

A two-way ANOVA performed on the slope of the AMI yielded significant effects for GROUP (F = 17.69, df = 1, 288; P < 0.0001) and for ELECTRODE (F = 5.39, df = 15, 288; P < 0.0001). No significant GROUP × ELECTRODE interaction was found (F = 0.38, df = 15, 288; P = 0.9831). An unpaired t test was used to compare the decreasing slopes of the AMI profiles between the schizophrenics and the normal subjects.

Table 1
Mean and standard deviations of the slopes of AMI in both schizophrenic patients and normal controls

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Normal controls</th>
<th>Schizophrenic patients</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7</td>
<td>−9.02 ± 5.52</td>
<td>−6.24 ± 5.27</td>
<td>0.26</td>
</tr>
<tr>
<td>T3</td>
<td>−15.30 ± 7.60</td>
<td>−12.63 ± 11.70</td>
<td>0.55</td>
</tr>
<tr>
<td>T5</td>
<td>−17.21 ± 6.08</td>
<td>−11.28 ± 5.91</td>
<td>0.040</td>
</tr>
<tr>
<td>Fp1</td>
<td>−7.45 ± 5.86</td>
<td>−5.58 ± 2.75</td>
<td>0.37</td>
</tr>
<tr>
<td>F3</td>
<td>−11.02 ± 5.18</td>
<td>−10.61 ± 5.74</td>
<td>0.87</td>
</tr>
<tr>
<td>C3</td>
<td>−14.56 ± 5.52</td>
<td>−7.52 ± 3.86</td>
<td>0.0039</td>
</tr>
<tr>
<td>P3</td>
<td>−15.42 ± 5.58</td>
<td>−12.87 ± 2.87</td>
<td>0.21</td>
</tr>
<tr>
<td>O1</td>
<td>−17.18 ± 6.04</td>
<td>−11.73 ± 6.66</td>
<td>0.071</td>
</tr>
<tr>
<td>F8</td>
<td>−10.27 ± 9.40</td>
<td>−5.03 ± 7.75</td>
<td>0.19</td>
</tr>
<tr>
<td>T4</td>
<td>−17.55 ± 12.58</td>
<td>−14.95 ± 7.93</td>
<td>0.59</td>
</tr>
<tr>
<td>T6</td>
<td>−16.07 ± 8.21</td>
<td>−14.34 ± 4.91</td>
<td>0.57</td>
</tr>
<tr>
<td>Fp2</td>
<td>−7.41 ± 7.73</td>
<td>−5.16 ± 2.29</td>
<td>0.39</td>
</tr>
<tr>
<td>F4</td>
<td>−12.92 ± 7.16</td>
<td>−12.09 ± 6.31</td>
<td>0.78</td>
</tr>
<tr>
<td>C4</td>
<td>−14.79 ± 6.69</td>
<td>−11.65 ± 8.18</td>
<td>0.36</td>
</tr>
<tr>
<td>P4</td>
<td>−15.50 ± 6.85</td>
<td>−13.14 ± 3.66</td>
<td>0.35</td>
</tr>
<tr>
<td>O2</td>
<td>−19.99 ± 9.21</td>
<td>−15.36 ± 5.80</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Fig. 1. Distribution of the A-CMI values between all pairs of channels in the schizophrenic patients. The numbers (1–16) correspond to F7, T3, T5, Fp1, F3, C3, P3, O1, F8, T3, T6, Fp2, F4, C4, P4, and O2. The electrode on the y-axis was time delayed. Even though the CMI is not a symmetric quantity with the time delay, the average of CMI across the time delay is nearly same whether what electrode in one pair of electrodes are time delayed.

Fig. 2. Distribution of the A-CMI values between all pairs of channels in the normal controls. The numbers (1–16) correspond to F7, T3, T5, Fp1, F3, C3, P3, O1, F8, T3, T6, Fp2, F4, C4, P4, and O2.

3.2. Mutual information transmission measure (CMI analysis)

Fig. 1 shows the distribution of the A-CMI values between all pairs of channels in schizophrenic patients. The numbers (1–16) in each axis correspond to F7, T3, T5, Fp1, F3, C3, P3, O1, F8, T3, T6, Fp2, F4, C4, P4, and O2. The electrode on the y-axis was time delayed. Even though the CMI is not a symmetric quantity with the time delay, the average of CMI across the time delay is nearly same whether what electrode in one pair of electrodes are time delayed. The CMI distribution has symmetric property, but shows different connectivity from that in the schizophrenics. In general, the schizophrenic patients had higher A-CMI values than the normal controls. For both groups, A-CMI values had normal distributions (Kolmogorov-Smirnov test: P < 0.01 for all the pairs of electrodes).

A two-way ANOVA accessed significant main effects for GROUP (F = 741.69, df = 1, 4320; P < 0.0001) and for ELECTRODE (F = 6.29, df = 239, 4320; P < 0.0001). No significant interaction for GROUP X ELECTRODE was found (F = 1.10, df = 239, 4320; P = 0.1426). The post hoc comparisons demonstrated significant increase of A-CMI values in schizophrenics. Fig. 3 shows the t-map describing the pairs where schizophrenics have significantly higher A-CMI values (P < 0.05) than normal controls. Statistical analyses showed that A-CMIs between the left temporo-parieto-occipital electrodes (significant pairs: O1-
P3, O1-T5, O1-C3, T5-C3) in the schizophrenic patients were significantly higher than those in normal controls. In the right temporoparieto-occipital brain regions, schizophrenic patients had significantly higher A-CMI value in only O2-P4 pair than normal controls. For the distant A-CMI between pairs of electrodes across the central line, the left hemispheric pairs (significant pairs: O1-Fp1, O1-F7, O1-F3, P3-F7, T5-Fp1, T5-F7, T5-F3) gave higher values in schizophrenic patients than in normal subjects. For the right distant pairs, schizophrenic patients had significantly higher A-CMI values in O2-Fp2, O2-F8, T6-F4 pairs than normal controls. No significantly different A-CMI within both left and right anterior and between anterior parts of hemispheres was observed. Schizophrenic patients had the increased A-CMIs between the left anterior and the right posterior brain regions and between the left posterior and the right anterior brain regions than normal controls (significant pairs: Fp1-T6, Fp1-C4, Fp1-P4, Fp1-O2, F7-C4, F7-P4, F7-O2, Fp2-T5, Fp2-O1, F8-T5, F8-C3, F8-P3, F8-O1). Between the left posterior and the right posterior brain regions, the pairs with the significantly increased A-CMI in schizophrenic patients were T3-O2, T5-T4, T5-T6, T5-C4, T5-P4, T5-O2, C3-T4, C3-T6, C3-C4, C3-P4, C3-O2, P4-T4, P4-T6, P4-C4, P4-P4, P4-O2, O1-T4, O1-T6, O1-P4, and O1-O2.

4. Discussion

In the present work, we showed that schizophrenic patients in waking states had slower AMI decreasing slopes at the left antero-temporal and temporal electrodes compared with controls. This means that the EEG activities at the left temporal regions in the schizophrenic brain are less complex than those of normal controls. If we consider the brain to be a non-linear dynamical system, a slower slope in AMI for the schizophrenic patients implies that the underlying neural dynamics that produce the electrical potentials of their EEGs are also less complex. Our finding of the decreased dynamical activity in the left temporal region in the schizophrenic brain is consistent with the findings of left temporal lobe abnormality reported in the studies on schizophrenia with cerebral blood flow study (Ragland et al., 2001), magnetic resonance imaging study (Rajarethinam et al., 2000; Maier et al., 2000; Sigmundsson et al., 2001), and P300 study by low-resolution electromagnetic tomography (Winterer et al., 2001).

In several nonlinear dynamical studies, schizophrenia group was shown to have a lower correlation dimension and the first Lyapunov exponent in the left inferior frontal and anterior temporal regions compared with controls (Jeong et al., 1998; Kim et al., 2000). Elbert et al. (1992) found higher dimensions of the resting EEG in schizophrenic patients at a frontal electrode position and a lower dimension at central electrode locations compared with normal control subjects. Koukkou et al. (1993) found a higher dimensional complexity for schizophrenic patients sampled their bipolar EEG between parietal-temporal and parieto-occipital electrodes compared with controls. Lee et al. (2001), however, examined and proved the non-linearity in EEGs of schizophrenia and found that schizophrenic patients’ EEGs had a lower dimension complexity compared with normal controls. The AMI abnormality noted in the left temporal region in schizophrenic patients in present study presumably reflects the loss of neurons or synapses that then contributes to less complex dynamical processing within the neural networks of their brains.

Compared with the use of nonlinear dynamical measures of complexity, the AMI analysis has practical and computational advantages such as to be available for short time series compared to nonlinear analysis, not to need other embedding process, and therefore to require a short computing time.

CMI analysis of the EEG demonstrated significantly increased A-CMI values in schizophrenic patients. We should note that A-CMI does not directly estimate axonal connection or cortico-cortical communication. However, we could understand that A-CMI quantifies information transmission in a statistical sense to mean that one can obtain information about the time series at one site from the time series at another site (Jeong et al., 2001). The increased A-CMI in schizophrenic patients was apparent for the local information transmission within left hemisphere than right hemisphere, for the distant information transmission between left anterior and right posterior and between right anterior and left posterior regions, and for the interhemispheric transmission of information between posterior parts of hemispheres. These results support the proposals that the schizophrenia may be a disorder of the integration between different brain regions.

In accordance with our increased interhemispheric A-
CMI's in schizophrenics, an increase of coherence in schizophrenic patients has been reported. Weller and Montagu (1980) reported increased interhemispheric coherences between temporal regions in the low frequency range from 2 to 6 Hz in schizophrenics compared to healthy controls. Nagase et al. (1992) compared schizophrenics and controls by using unipolar derivations, and found increased interhemispheric coherences in schizophrenic patients for the occipital and temporal regions concerning the delta and beta bands. These findings are consistent with our results of the increased interhemispheric information transmission between posterior parts of hemispheres. Although there is no report for the distant coherence between left anterior and right posterior and between right anterior and left posterior regions, our result of increased A-CMI in those pairs is consistent with the above reported findings because these pairs are also interhemispheric pairs. Moreover, our results inform the long cortico-cortical overconnections in schizophrenic patients.

Many authors reported the dysfunction in the transfer of information and abnormal patterns of neuronal connection between the two cerebral hemispheres via the corpus callosum in schizophrenic patients (Randall, 1983, 1998; Goodman, 1989; Coger and Serafetinides, 1990). David (1993, 1994) presented the callosal overconnectivity or less lateralized cerebral organization as the origin of increased interhemispheric coherence in schizophrenic patients and Coger and Serafetinides (1990) presented that the cerebral function in schizophrenics is less lateralized due to the abnormally thickened corpus callosum. However, the abnormal corpus callosum may not be the sole cause of or only explanation for the increased interhemispheric A-CMIs. Through neuroanatomical and neurochemical reviews, for example, Shirakawa et al. (2001) reported abnormality of left temporal lobe might cause the abnormal lateralization in temporal lobe in schizophrenic patients. Heidrich and Strik (1997) discussed that the structural and functional abnormalities of the left-temporal lobe may be responsible for a lateralized temporal lobe dysfunction in schizophrenics through the auditory P300 study. Our result of the left hemispheric hypotemporality and the increased interhemispheric information transmission in temporal lobe may support the hypothesis that the abnormal lateralization in temporal lobe are due to left temporal lobe deficit in schizophrenic patients.

The increased intrahemispheric A-CMIs in schizophrenic patients agrees with the results of an EEG coherence analysis of schizophrenics. Ford et al. (1986) investigated the intrahemispheric and interhemispheric coherences in psychiatric patients by using bipolar derivations. Compared with patients suffering from affective disorders and geriatric patients, schizophrenics revealed the highest coherence values. Merrin et al. (1989) found that schizophrenics revealed higher intrahemispheric and interhemispheric coherence values, which were only significant in the theta range. Wada et al. (1998) reported that the schizophrenic patients had significantly higher intrahemispheric coherence of the resting EEG for the delta band compared to controls, although no significant group differences were found for other frequency bands.

Although EEG coherence and A-CMI both quantify information transmission among different areas of the brain, the difference of two measures is that EEG coherence measures only the linear dependencies in the electrical potentials across those regions, but A-CMI considers both the linear and nonlinear dependencies of information transmission among those brain regions. If we wanted to quantify only the nonlinear dependence of electrical potentials across brain regions, we would need to compare A-CMI with coherence measure in same subjects’ EEG.

One limitation of our study was the fact that the antipsychotic medication was uncontrolled. In our study, the patients were taking neuroleptic medication with range of CPZ equivalent doses, 60–667 mg. Itil et al. (1972) reported no effect of medication on EEG activities in schizophrenic patients and Merrin et al. (1989) suggested that medication treatment was associated with clinical improvement and increases in spectral power, but not with changes in coherence values and these results confirm those obtained by earlier investigations and suggest that increased coherence reflects the presence of anomalous cortical organization in schizophrenics rather than medication effects or transient states related to acute clinical disturbance. Besides these reports, there were no correlations between CPZ equivalent dosage and the slope of AMI values nor between CPZ equivalent dosage and interhemispheric A-CMI values in the schizophrenic patients. However, our findings cannot be taken as a proof of the absence of drug effects. In future work, the comparison of MI analysis for medicated and unmedicated patients and EEG analysis during the task will be required.

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References


