Schizophrenia Research 119 (2010) 191–197

Contents lists available at ScienceDirect

Schizophrenia Research

journal homepage: www.elsevier.com/locate/schres

Dysfunctional gamma-band activity during face structural processing in schizophrenia patients

Seung-Hwan Lee [a,b,*], Do-Won Kim [b,c], Eun-Young Kim [b], Sangrae Kim [b,d], Chang-Hwan Im [c]

[a] Department of Psychiatry, Inje University Ilsan Paik Hospital, Goyang-si, Republic of Korea
[b] Clinical Emotion and Cognition Research Laboratory, Goyang-si, Republic of Korea
[c] Department of Biomedical Engineering, Yonsei University, Wonju-si, Republic of Korea
[d] Graduate Program in Cognitive Science, Yonsei University, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 20 September 2009
Received in revised form 13 January 2010
Accepted 18 February 2010
Available online 19 March 2010

Keywords:
Facial perception
Gamma-band activity
Phase synchrony
Schizophrenia
Negative symptoms

ABSTRACT

This study investigated gamma-band activity (GBA) and its phase synchrony in schizophrenia patients viewing human faces. Twenty-five schizophrenia patients were compared with 25 normal controls. Event-related potentials were recorded from all participants while they were viewing emotionally neutral faces. The spectral power and phase synchrony in the frequency band from 30 to 55 Hz were analyzed in midline electrodes (FCz, Cz, CPz, Pz, and POz). Three windows of interest, which showed discernable GBA differences between schizophrenia patients and normal controls, were selected by visual inspection: 0–100 ms (30–33 Hz), 250–300 ms (34–38 Hz), and 700–800 ms (40–45 Hz). And the phase synchrony of gamma band was analyzed. Repeated-measures ANOVA revealed that the GBA was lower in schizophrenia patients than in normal controls. Also there were significant location and time differences in GBA. GBA was significantly lower in the schizophrenia patients than in the normal controls at around 700–800 ms at the FCz electrode. The frontal (FCz) and central (Cz) GBA were significantly correlated with the number of hospitalization, and the negative symptoms of schizophrenia, respectively. The phase synchronization was significantly lower at 200–300 ms in the schizophrenia patients than in the normal controls. These findings suggest that the schizophrenia patients have impaired GBA and gamma-band synchronization during face perception. Furthermore, our results also suggest that the decreased GBA observed at the midline cortex of schizophrenia patients is closely related to their negative symptoms and disease progress.

1. Introduction

Synchronous oscillatory neural activity is a possible candidate mechanism for the coordination of neural activity between and within functionally specialized brain regions (Singer, 1999; Varela et al., 2001). It is known that the coordination of distributed neural activity is dysfunctional in people with schizophrenia (Andreasen, 1999; Friston, 1998; Phillips and Silverstein, 2003).

There are several studies showing face processing disturbance in schizophrenia patients and possible neural structures underlying this deficit (Herrmann et al., 2004; Lee et al., 2008; Onitsuka et al., 2006; Whittaker et al., 2001). They revealed that schizophrenia patients, compared with normal controls, have smaller fusiform gyrus volume and lower amplitude of N170 components with wider neuropsychological impairments.

Recent electrophysiological studies have demonstrated that functional communication between distinct brain

* Corresponding author. Department of Psychiatry, Inje University Ilsan Paik Hospital, 2240 Daehwa-dong, Ilsan-seo-gu, Goyang, Kyunggi-do, Republic of Korea.
E-mail address: lshpss@hanmail.net (S.-H. Lee).

0920-9964/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.schres.2010.02.1058

regions during neural activity relies on the oscillatory synchronization of gamma and beta frequency bands (Kopell et al., 2000). Furthermore, other recent findings have suggested that the gamma-band activity (GBA) in the human EEG is related to higher cognitive processes (Fell et al., 2001; Fiebach et al., 2005; Herrmann et al., 2004; Keil et al., 2001; Varela et al., 2001).

Several studies have shown that GBA is related to face and facial emotional processing in normal individuals (Anaki et al., 2007; Keil et al., 2001; Rodriguez et al., 1999; Zion-Golumbic and Bentin, 2007; Zion-Golumbic et al., 2008). Anaki et al. (2007) reported that induced GBA at around 150–250 ms at midline centroparietal area in healthy persons was higher while viewing an upright or familiar face than an inverted or unfamiliar one. They insisted that the effect of face inversion was found in lower gamma frequency (25–50 Hz), whereas familiarity affected amplitudes in higher gamma frequency band (50–70 Hz). Zion-Golumbic and Bentin (2007) revealed that increased GBA (25–45 Hz) was elicited in undergraduate students at midline parieto-occipital area at around 200–300 ms by full faces, but not by scrambled faces. However, they did not find significant findings in high GBA (55–70 Hz). Another study also revealed increased GBA in the middle posterior electrode cluster (Pz, POz, and Oz) at around 300 ms during face processing (Zion-Golumbic et al., 2008). Rodriguez et al. (1999) who applied ambiguous visual stimuli (perceived either as faces or as meaningless shapes) reported that GBA was prominent at ~230 ms and ~800 ms and only face perception induced long distance pattern of gamma synchronization. The enhanced GBA is also observed at occipital electrode sites in healthy subjects viewing emotional faces in rotating figures (Keil et al., 1999). Meanwhile, Matsumoto et al. (2006) revealed that GBA at the Cz and Pz electrodes for negative emotional faces at around 400–450 ms was higher in nonalexithymic subjects than in alexithymic subjects.

Face and facial emotional processing are important research areas because they are closely involved with social cognition, deficits of which may underlie the decreased functional outcomes of schizophrenia patients. To the best of our knowledge, there is currently only one published study on GBA for face-related processing in schizophrenia (Uhlhaas et al., 2006); the study reported the deficits in Gestalt perception in schizophrenia patients were associated with reduced phase synchrony in the band (20–30 Hz), whereas induced spectral power in the band (40–70 Hz) was mainly intact. But they found schizophrenia patients are impaired in the long-range synchronization of neural responses, which may reflect a core deficit in the coordination of neural activity. GBA in schizophrenia patients processing real human faces is thus worthy of evaluation. Furthermore, face structural processing and emotional processing should be assessed separately since they are likely to involve different brain resources (Lee et al., 2008).

We hypothesized that the schizophrenia patients will show the decreased GBA and gamma synchronization during the face structural processing compared to the normal controls. As a first stage of exploration about GBA dysfunction of face processing in schizophrenia patients, this study has examined the face structural processing while viewing emotionally neutral face.

2. Methods

2.1. Participants

Twenty-five patients with schizophrenia and 25 normal controls were recruited for this study. The schizophrenia patients were recruited from the Psychiatry Department of Inje University Ilsan Paik Hospital, and they were diagnosed based on the Structured Clinical Interview for Diagnostic and Statistical Manual of Mental Disorders, 4th edition (DSM-IV) Axis I Psychiatric Disorders (First et al., 1996b). Their psychiatric symptoms were evaluated using the Positive and Negative Syndrome Scale (PANSS) (Kay et al., 1987). None of the patients had a history of central nervous system disease, alcohol or drug abuse, electroconvulsive therapy, mental retardation, or head injury with loss of consciousness. All patients were of stable state and taking atypical antipsychotic medication (olanzapine, $n=12$ and risperidone, $n=13$).

Normal controls were recruited from the local community through local newspapers and posters. An initial screening interview excluded subjects if they had any identifiable neurological disorder or head injury, any personal history of psychiatric disease, and a family history of psychiatric illness. After the initial screening, potential normal controls were interviewed using the Structured Clinical Interview for DSM-IV Axis II Psychiatric Disorders (First et al., 1996a), and were excluded if they had any of these disorders.

All subjects had normal or corrected-normal vision and were right-handed. Handedness was determined by asking which hand the subject tended to use for writing and other precise motor skills. All subjects signed a written informed consent form that was approved by the Institutional Review Board of Inje University Ilsan Paik Hospital prior to their participation in the study. The demographics of the two groups are given in Table 1, which indicates that there were no significant group differences in gender distribution, age, and education.

Table 1
Demographic data and symptom ratings for schizophrenia patients and normal controls. Data are mean ± SD values.

	Schizophrenia patients ($n=25$)	Normal controls ($n=25$)	p
Age (years)	34.6 ± 12.6	38.9 ± 12.4	0.225
Males:females	12:13	12:13	1.000
Education duration (years)	12.5 ± 2.5	12.9 ± 3.0	0.605
Illness duration (years)	6.1 ± 5.6		
Number of hospitalizations	1.8 ± 1.5		
PANSS total score	82.4 ± 24.8		
Negative symptoms score	18.6 ± 7.2		
Positive symptoms score	20.6 ± 7.6		
Antipsychotics dosage (chlorpromazine equivalents, mg)	398 ± 103		

PANSS: Positive and Negative Syndrome Scale.

2.2. Procedures

Participants were presented with two types of human face: emotional (happy and fearful) and neutral. The presented images were selected from the "Chaelee face," which is a standardized set of pictures of a Korean face (Lee et al., 2004). The pictures of faces comprised the whole face structure including the hair. The luminance and contrast were made the same in all of the images. Stimuli were presented on a 17-inch (approx. 43-cm) CRT monitor positioned 1 m in front of the participants, and which subtended a maximum visual angle of 4°×4°.

Face stimuli were presented repeatedly in random order but at the same frequency of presentation for a total of 288 trials, comprising 96 neutral faces and 192 emotional faces. The trials started with a fixation cross presented for 100 ms followed by a black screen for 500 ms. Face stimuli were then presented for 500 ms and followed by a black screen displayed for 900–1100 ms; the total time of sequence of an event was 2000–2200 ms, and this was changed randomly in each trial so as to avoid habituation. The entire recording session for each subject lasted approximately 15 min.

All participants were requested to push a button using their right thumb when they saw an emotional face; recognition of emotional faces requires greater cognitive processing than that of neutral faces in this task. Since the aim of this study was to examine face structural processing, we only analyzed data obtained from the subjects while viewing neutral faces.

2.3. EEG recording

Stimulus presentation and data synchronization with the EEG were accomplished with E-Prime (Psychology Software Tools, Pittsburgh, USA). The EEG was synchronized to the onset of face-stimulus presentation. EEG activity was recorded and amplified using a NeuroScan SynAmps amplifier (Compumedics USA, El Paso, TX, USA) and 64 Ag–AgCl electrodes mounted in a Quick Cap using a modified 10–20 placement scheme. The vertical electrooculogram (EOG) was recorded using two electrodes, one located above and one below the right eye. The horizontal EOG was recorded at the outer canthus of each eye. EEG data were recorded with a 1- to 100-Hz band-pass filter at a sampling rate of 1000 Hz. The ground electrode was placed on the forehead and the reference was located at electrode Cz.

EEG data were initially processed using Scan 4.3. EEG data were rereferenced offline to an average reference. Gross movement artifacts were removed by visual inspection. Eye blinks were removed from the data using established mathematical procedures (Semlitsch et al., 1986). Trials were rejected if they included significant physiological artifacts (amplitude exceeding ±70 μV) at any site over all 64 electrode sites. After artifact removal, baseline correction was conducted by subtracting the mean of 300 ms of prestimulus data from the poststimulus data for each trial. Data were then epoched to 300 ms prestimulus and 1000 ms poststimulus.

All participants showed a sufficient number of accepted event-related potential (ERP) epochs for neutral faces, and the averaged acceptance rate did not differ significantly between the groups [schizophrenia patients 96.1% (accepted epoch $n=94.1$) vs. normal control 92.3% (accepted epoch $n=89.0$), $P=0.06$].

2.4. Time frequency analysis

Event-related spectral perturbation (ERSP) analysis which measures the dynamic change of spectral power over time has been increasingly used in EEG studies to observe narrow-band event-related desynchronization and synchronization (Delorme and Makeig 2004; Makeig, 1993; Tanji et al., 2005). In this study, ERSP was calculated using functions implemented in a well-known MATLAB toolbox EEGLAB (http://sccn.ucsd.edu/eeglab/) (Delorme and Makeig 2004). The ERSP maps were calculated using the short-time Fourier Transform method. The spectral power was computed for every 5 ms by a Hanning window of 250 ms and the results were averaged across all trials. After the calculation of the average spectral power for each subject, the average baseline (−300~0 ms) power was subtracted from each spectral estimate, which resulted in the baseline-normalized ERSP maps. The time–frequency map of each midline channel (FCz, Cz, CPz, Pz, and POz) was obtained by averaging the ERSP values across all epochs and subjects.

The choice of midline electrodes was based on previous study findings. Most of the previous studies using the cortical EEG method have found that the GBA was mainly higher at the midline cortical area (posterior>anterior) for face-related processing (Anaki et al., 2007; Keil et al., 2001; Matsumoto et al., 2006; Zion-Golumbic and Bentin, 2007; Zion-Golumbic et al., 2008). One intracranial EEG study of epileptic patients found a higher GBA in the face-specific fusiform gyrus (Lachaux et al., 2005). However, other cortical EEG studies have failed to find any significant lateral GBA. Furthermore, we did not analyze the Fpz, Fz, and Oz electrodes because these electrodes can be easily contaminated by muscle artifacts (Vialatte et al., 2008). Here we focus on and discuss the recordings from five midline channels (FCz, Cz, CPz, Pz, and POz).

2.5. Phase synchrony analysis

To determine the degree of synchronization between a pair of EEG time series, we computed event-related phase coherence (ERPCOH) (Delorme and Makeig 2004). The ERPCOH is defined by,

$$ERPCOH^{a,b}(f,t) = \frac{1}{n}\sum_{k=1}^{n}\frac{F_k^a(f,t)F_k^b(f,t)^*}{|F_k^a(f,t)F_k^b(f,t)|},$$

where f and t represent frequency and time, respectively, a and b represent two selected channels, and n is the number of epochs. $F_k^a(f,t)$ is the spectral estimate of channel a for a kth trial and was calculated by short-time Fourier transform with the same parameters used for the ERSP calculation. $F_k^b(f,t)^*$ is the complex conjugate of $F_k^b(f,t)$ and $||\cdot||$ operator represents the complex norm. ERPCOH has a value between 0 and 1, where 0 indicates complete absence of phase synchronization between two signals a and b at a given frequency f in the time window centered on t; whereas 1 indicates perfect synchronization. For the sake of simplicity, we chose 19 electrodes (Fp1, Fp2, Fz, F3, F7, F4, F8, Cz, C3, T7, C4, T8, Pz, P3, P7, P4, P8, O1, and O2) based on the international 10–20 electrodes system. For the visualization of meaningful synchrony between the channels, lines were connected between two electrodes only when the ERPCOH between the electrodes

showed statistically significant increment or decrement ($p<0.0003$, Bonferroni-corrected two-tailed t-tests) compared to the baseline activity (Uhlhaas et al., 2006).

2.6. Statistical analysis

A map of differences in GBA between schizophrenia patients and normal controls was produced. By visual inspection, the discernable area of GBA differences was examined statistically. The data were analyzed by repeated-measures ANOVA with group (patients vs. controls) as the between-subjects factor, and time [three time windows: 0–100 ms (30–33 Hz), 250–300 ms (34–38 Hz), and 700–800 ms (40–45 Hz)], and location (five electrodes: FCz, Cz, CPz, Pz, and POz) as the within-subjects factors. The Greenhouse–Geisser epsilon value was obtained in all cases in which the repeated-measures data failed the sphericity test (Greenhouse and Geisser, 1959). When a significant effect was found, the Bonferroni-corrected t-test for multiple comparisons was applied. The number of t-test was five, which we considered to calculate the resulting threshold. The threshold of significant synchrony lines (probability $p<0.0003$, two-tailed t-tests) was chosen by Bonferroni correction whilst considering that there was a total of 171 synchrony lines. The Spearman correlation coefficient was calculated between GBA and symptomatic and demographic variables.

3. Results

3.1. Behavioral data

Hit rate was defined as the percentage of correct responses. There were no significant differences in hit rate for happy (89.4 ± 15.4 vs. 91.2 ± 18.8, $t=-0.338$, $p=0.737$) and fearful faces (88.9 ± 21.5 vs. 81.9 ± 32.6, $t=0.811$, $p=0.422$) between schizophrenia patients and normal controls. However, the false alarm rate for neutral faces was significantly higher in schizophrenia patients than in normal controls (23.2 ± 21.1 vs. 6.7 ± 9.9, $t=3.175$, $p=0.004$).

3.2. Spectral power of the gamma band

The difference map, in which the ERSP map of the schizophrenia patients is subtracted from that of the normal controls, revealed three time windows of GBA: 0–100 ms (30–33 Hz), 250–300 ms (34–38 Hz), and 700–800 ms (40–45 Hz). These time windows became the focus of this study. Fig. 1A depicts the GBA values of the three time windows at five midline electrodes, and Fig. 1B shows the ERSP map at three prominent electrodes (FCz, Cz, and CPz).

Repeated-measures ANOVA revealed a significant main effect for group [$F(1, 48)=7.95$, $p=0.007$], location [$F(4, 45)=13.661$, $p=0.000$], and time [$F(2, 47)=3.692$, $p=0.029$]. Furthermore, there was a significant interaction between time and location [$F(8, 41)=4.799$, $p=0.000$; Fig. 1A].

In the 0- to 100-ms time window we found that the GBA was significantly higher in the normal controls than in the schizophrenia patients, especially at the POz region ($t=-2.279$, uncorrected $p=0.027$; Fig. 1). However, this effect disappeared after Bonferroni correction. In the 250- to 300-ms time window we found that the GBA was significantly higher in the normal controls than in the schizophrenia patients, especially at the CPz region ($t=-2.047$, uncorrected $p=0.046$, Fig. 1). This effect also disappeared after Bonferroni correction. In the 700- to 800-ms time window, a Bonferroni-corrected t-test revealed that GBA was significantly higher in the normal controls than in the schizophrenia patients, especially at the FCz region ($t=-3.215$, corrected $p=0.01$; Fig. 1B).

3.3. Phase synchrony of the gamma band

The synchrony lines have displayed in Fig. 2. The normal controls showed increased synchrony lines among the frontal, temporal, and parieto-occipital electrodes from 100 ms, peaking at the 200- to 300-ms time window. Compared with normal controls, schizophrenia patients exhibited weak patterns of significant synchrony lines. All subjects did not produce any decreased synchrony lines. Group comparisons of phase coherence between two groups were analyzed using chi-square statistics for each time bin (Spencer et al. 2003). The result showed that the phase coherence distribution is significantly different between the groups across time bins.($\chi^2_{(4)}=18.8$; $p=0.0008$).

3.4. Correlation between GBA and the symptomatic demographic and behavioral data

The Spearman correlation coefficients were calculated between GBA and the symptomatic and demographic data. Significant correlations were found between GBA at 700–800 Hz and several variables: number of hospitalizations (at FCz, $\rho=-0.455$, $p=0.022$), score for negative symptoms on the PANSS (at Cz, $\rho=-0.435$, $p=0.03$; at CPz, $\rho=-0.628$, $p=0.001$; at Pz, $\rho=-0.404$, $p=0.045$). However, we did not find any significant correlation between GBA and the score for positive symptoms on the PANSS. The neutral faces may not be viewed as 'neutral' by patients with schizophrenia (Horley et al. 2001). However, the false alarm rate of neutral faces was not significantly correlated with the GBA in schizophrenia patients.

3.5. Induced GBA or evoked GBA

The question of whether the observed GBA is induced or evoked was addressed by calculating the mean intertrial PLVs for each subject during this period (Zion-Golumbic and Bentin, 2007). The PLV is bounded between 0 and 1. A PLV of 1 corresponds to perfect phase-locking. The results confirmed that low level of PLVs were present during the time window of interest in all participants (at POz between 0–100 ms, mean = 0.11, SD = 0.03; at CPz between 250–300 ms, mean = 0.19, SD = 0.08; at FCz between 700–800 ms, mean = 0.10, SD = 0.03). These GBAs can therefore be regarded as being induced.

4. Discussion

The goal of the present study was to clarify the characteristics of face structural processing in schizophrenia patients by analyzing the spectral power and phase synchronization of the gamma band. We found three windows of

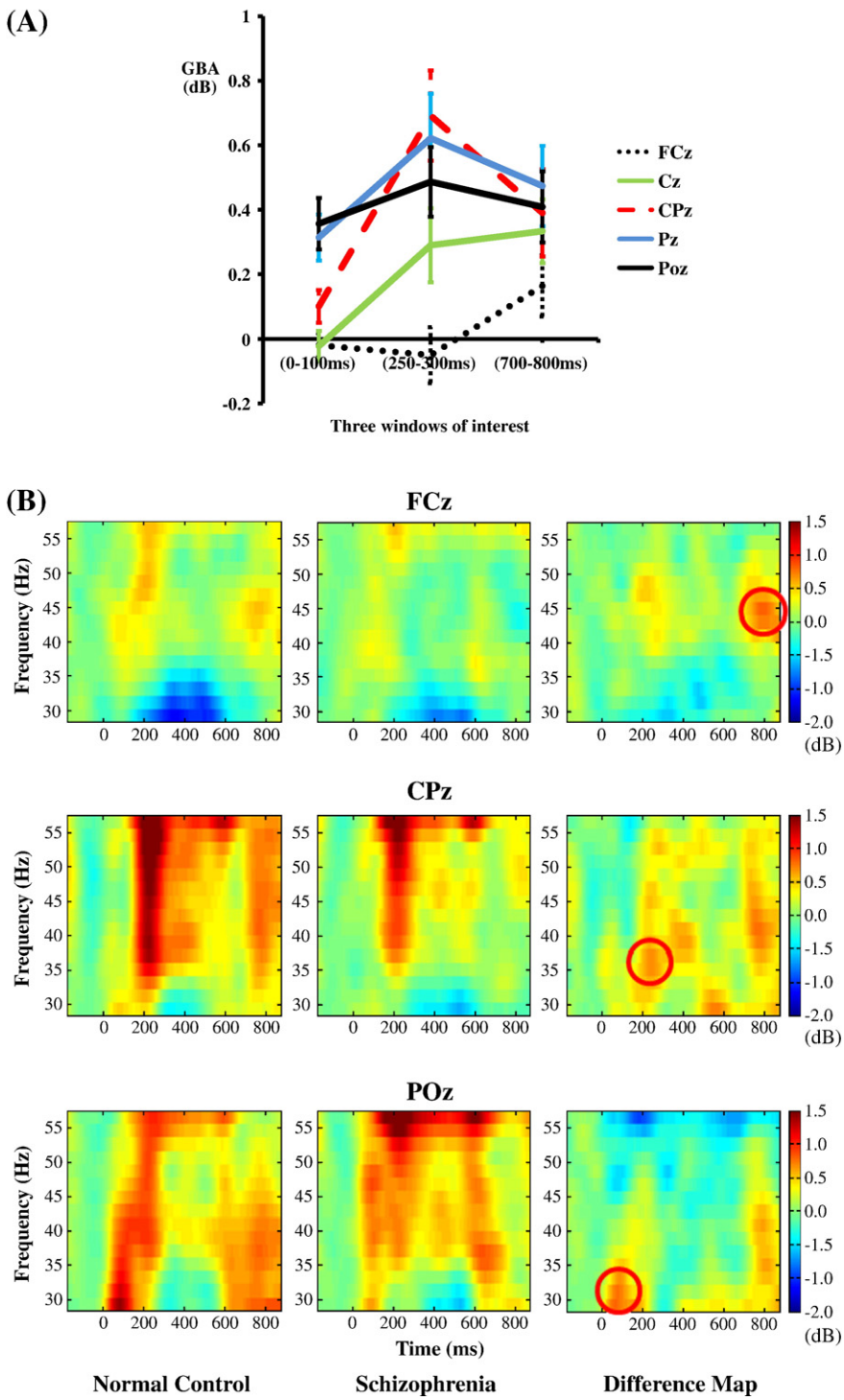

Fig. 1. Comparison of gamma-band activity (GBA) between schizophrenia patients and normal controls. A: Patterns of GBA in three windows of interest at five electrodes sites from all subjects (schizophrenia patients and normal controls). The GBA was highest at the occipital electrode (POz) in the period 0–100 ms, and at frontal electrode (FCz) in the period 700–800 ms. The standard errors were presented. B: Event-related spectral perturbation (ERSP) from electrodes FCz, CPz, and POz. The difference map was calculated by subtracting the schizophrenia ERSP map from that of the normal controls. Red circles indicate the three windows of interest for which there are significant differences between normal controls and schizophrenia patients. After Bonferroni-corrected *t*-tests, only the FCz region (corrected $p = 0.01$) remained as a significantly activating region in the normal controls relative to the schizophrenia patients.

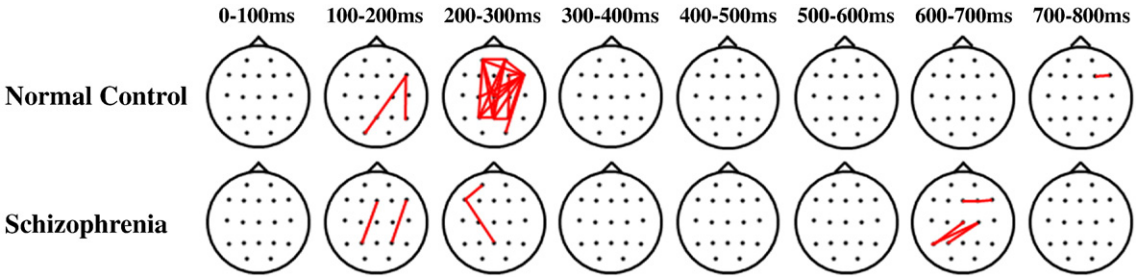

Fig. 2. Topography of phase synchrony for neutral face processing. Synchrony between electrodes is indicated by lines, which are drawn only where there is a synchrony value beyond a two-tail probability of $p<0.0003$. Gamma-band phase synchronization was significantly increased (red) at 200–300 ms, and was lower in schizophrenia patients than in normal controls.

interest among the midline electrodes from our data set, and found that the GBA was significantly lower in schizophrenia patients than in normal controls.

Even though we found some interesting GBA dysfunction at around 0–100 ms at POz and at around 200–300 ms at CPz. These GBA differences disappeared after Bonferroni correction. So, we will concentrate on the third time window (700–800 ms, 40–45 Hz) which has still shown the significant difference after considering multiple comparisons.

We also found increased GBA at around 700–800 ms at the FCz region. Rodriguez et al. (1999) reported that two gamma peaks appear at around 800 ms and 230 ms after seeing a "Mooney" face. However, no previous study has demonstrated frontal GBA during facial processing. The predominant frontal GBA at this late period may be associated with postperceptual top-down processing of faces. The relatively decreased frontal GBA observed in schizophrenia patients might reflect decreased frontal-lobe function during face processing (Fig. 1B). There existed the scarcity of theoretical knowledge about the specific cognitive mechanisms normally involved in face processing during this interval. Thus, our finds need to be further evaluated in future study.

Detailed spatiotemporal information is provided by the regional distribution of GBA and phase synchrony over the scalp (Fig. 2). The pattern of gamma activity first occurred at around 100–200 ms, peaked at around 200–300 ms, and reappeared at around 600–800 ms. These findings are similar to those of Uhlhaas et al. (2006) demonstrating that gamma activity peaked at around 300–400 ms when normal controls processed Mooney faces. There is some debate as to whether the gamma synchrony computed from scalp EEGs is the result of spurious synchronization resulting from volume conduction (Menon et al., 1996). However, our results show that multiple significant synchronies were established between distant electrodes. It is thus conceivable that distant synchronization could result from a powerful deep source that diffuses widely over the scalp. The average reference can produce artifactual GBA. However, in the present data, referencing the present data linked to the mastoid did not affect the statistical significance of topographic effects regarding ERPs and GBA. We can therefore conclude that the GBA we measured was not significantly produced from reference-related artifacts.

We have found that the GBAs of frontal, central and parietal areas were negatively correlated with the score for negative symptoms on the PANSS, and the number of hospitalization in schizophrenia patients. Our results suggest that the GBA during face structural processing is reduced in schizophrenia patients with dominant negative symptoms as well as the higher number of hospitalization. The significant correlations found only at 700–800 ms would suggest dysfunctional top-down processing in schizophrenia patients, and a functional relationship between GBA and schizophrenia patients.

Our study has a limitation: all of the schizophrenia patients were taking antipsychotic medications, and we are unable to exclude the drug effects on our findings. However, our data still revealed that there is a deficit in the GBA and synchrony during the processing of neutral human faces in schizophrenia patients. In addition, the results from neutral face can be influenced, at least in part, by emotional content of the paradigm and/or inhibition of motor response to low-probability neutral stimuli. However, as you can see in Fig 1 (B), the baseline activities of gamma were well stabilized. It could be evidenced that our data contain neutral face processing without confounding effects of emotional content of the paradigm and/or inhibition of motor response to low-probability neutral stimuli. Even though we can not know what kind of emotion the schizophrenia patients perceived when they did the false alarm for neural faces, no significant association between GBA and false alarm rate indicated that inhibition (no-go) during processing of neutral stimuli had minimal effects on GBA in this study.

To our knowledge, this is the first study to show dysfunctional GBA in schizophrenia patients viewing pictures of real human faces. These findings are in line with the previous studies that used ambiguous figures of faces, which also suggested a deficit of cognitive face processing in schizophrenia patients. We will continue to use the same cohort to explore the relationship between gamma activity and emotional processing in schizophrenia patients.

Role of funding source

This work was supported by a grant from the Korea Science and Engineering Foundation (KOSEF), funded by the Korean government (MOST; no. M10644000005-06 N4400-00510).

The KOSEF had no further role in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

Contributors

Seung-Hwan Lee designed the study and wrote the protocol. Do-Won Kim calculated gamma-band activity and synchronization from data set. Eun-Young Kim and Sangrea Kim managed the literature searches and analyses. Chang-Hwan Im undertook gamma-band analysis and the

statistical analysis. All authors contributed to and have approved the final manuscript.

Conflict of interest

All the authors declare that they have no conflicts of interest.

Acknowledgments

The authors thank Eung-Kyung Jo and Jeong-In Kim for their assistance with data collection.

References

Anaki, D., Zion-Golumbic, E., Bentin, S., 2007. Electrophysiological neural mechanisms for detection, configural analysis and recognition of faces. Neuroimage 37, 1407–1416.

Andreasen, N.C., 1999. A unitary model of schizophrenia: Bleuler's "fragmented phrene" as schizencephaly. Arch. Gen. Psychiatry 56, 781–787.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134, 9–21.

Fell, J, Klaver, P., Lehnertz, K., Grunwald, T, Schaller, C., Elger, C.E., Fernández, G., 2001. Human memory formation is accompanied by rhinal–hippocampal coupling and decoupling. Nat. Neurosci. 4, 1259–1264.

Fiebach, C.J., Gruber, T., Supp, G.G., 2005. Neuronal mechanisms of repetition priming in occipitotemporal cortex: spatiotemporal evidence from functional magnetic resonance imaging and electroencephalography. J. Neurosci. 25, 3414–3422.

First, M.B., Gibbon, M., Spitzer, R.L., Williams, J.B.W., 1996a. Structure Clinical Interview for DSM-IV Axis II Personality Disorder. Biometrics Research, New York State Psychiatric Institute, New York.

First, M.B., Gibbon, M., Spitzer, R.L., Williams, J.B.W., 1996b. Users Guide for the Structured Clinical Interview for DSM-IV Axis I Disorders — Research Version (SCID-1, Version 2.0, February 1996 Final Version). Biometrics Research, New York State Psychiatric Institute, New York.

Friston, K.J., 1998. The disconnection hypothesis. Schizophr. Res. 30, 115–125.

Greenhouse, S.W., Geisser, S., 1959. On methods in the analysis of profile data. Psychometrika 24, 95–112.

Herrmann, M.J., Ellgring, H., Fallgatter, A.J., 2004. Early-stage face processing dysfunction in patients with schizophrenia. Am. J. Psychiatry 161, 915–917.

Horley, K., Gonsalvez, C., Williams, L., Lazzaro, I., Bahramali, H., Gordon, E., 2001. Event-related potentials to threat-related faces in schizophrenia. Int. J. Neurosci. 107, 113–130.

Kay, S.R., Fiszbein, A., Opler, L.A., 1987. The positive and negative syndrome scale (PANSS) for schizophrenia. Schizophr. Bull. 13, 261–276.

Keil, A., Muller, M.M., Ray, W.J., Gruber, T., Elbert, T., 1999. Human gamma band activity and perception of a gestalt. J. Neurosci. 19, 7152–7161.

Keil, A., Muller, M.M., Gruber, T., Wienbruch, C., Stolarova, M., Elbert, T., 2001. Effects of emotional arousal in the cerebral hemispheres: a study of oscillatory brain activity and event-related potentials. Clin. Neurophysiol. 112, 2057–2068.

Kopell, N., Ermentrout, G.B., Whittington, M.A., Traub, R.D., 2000. Gamma rhythms and beta rhythms have different synchronization properties. Proc. Natl. Acad. Sci. U. S. A. 97, 1867–1872.

Lachaux, J.P., George, N., Tallon-Baudry, C., Martinerie, J., Hugueville, L., Minotti, L., Kahane, P., Renault, B., 2005. The many faces of the gamma band response to complex visual stimuli. Neuroimage 25, 491–501.

Lee, W.H., Chae, J.H., Bahk, W.M., Lee, K.U., 2004. Development and its preliminary standardization of pictures of facial expressions for affective neurosciences. J. Korean Neuropsychiatr. Assoc. 43, 552–558.

Lee, S.H., Im, W.Y., Kim, J.H., 2008. Neurobiology of facial perception and facial affect recognition. J. Korean Neuropsychiatr. Assoc. 47, 113–118.

Makeig, S., 1993. Auditory event-related dynamics of the EEG spectrum and effects of exposure to tones. Electroencephalogr. Clin. Neurophysiol. 86, 283–293.

Matsumoto, A., Ichikawa, Y., Kanayama, N., Ohira, H., Iidaka, T., 2006. Gamma band activity and its synchronization reflect the dysfunctional emotional processing in alexithymic persons. Psychophysiology 43, 533–540.

Menon, V., Freeman, W.J., Cutillo, B.A., Desmond, J.E., Ward, M.F., Bressler, S. L., Laxer, K.D., Barbaro, N., Gevins, A.S., 1996. Spatio-temporal correlations in human gamma band electrocorticograms. Electroencephalogr. Clin. Neurophysiol. 98, 89–102.

Onitsuka, T., Niznikiewicz, M.A., Spencer, K.M., Frumin, M., Kuroki, N., Lucia, L.C, Shenton, M.E., McCarley, R.W, 2006. Functional and structural deficits in brain regions subserving face perception in schizophrenia. Am. J. Psychiatry 163, 455–462.

Phillips, W.A., Silverstein, S.M., 2003. Convergence of biological and psychological perspectives on cognitive coordination in schizophrenia. Behav. Brain. Sci. 26, 65–82 discussion 82-137.

Rodriguez, E., George, N., Lachaux, J.P., Martinerie, J., Renault, B., Varela, F.J., 1999. Perception's shadow: long-distance synchronization of human brain activity. Nature 397, 430–433.

Semlitsch, H.V., Anderer, P., Schuster, P., Presslich, O., 1986. A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. Psychophysiology 23, 695–703.

Singer, W., 1999. Neuronal synchrony: a versatile code for the definition of relations? Neuron 24 (49–65), 111–125.

Spencer, K.M., Nestor, P.G., Niznikiewicz, M.A., Salisbury, D.F., Shenton, M.E., McCarley, R.W., 2003. Abnormal neural synchrony in schizophrenia. J. Neurosci. 23, 7407–7411.

Tanji, K., Suzuki, K., Delorme, A., Shamoto, H., Nakasato, N., 2005. High-frequency gamma-band activity in the basal temporal cortex during picture-naming and lexical-decision tasks. J. Neurosci. 25, 3287–3293.

Uhlhaas, P.J., Linden, D.E., Singer, W., Haenschel, C., Lindner, M., Maurer, K., Rodriguez, E., 2006. Dysfunctional long-range coordination of neural activity during Gestalt perception in schizophrenia. J. Neurosci. 26, 8168–8175.

Varela, F., Lachaux, J.P., Rodriguez, E., Martinerie, J., 2001. The brainweb: phase synchronization and large-scale integration. Nat. Rev. Neurosci. 2, 229–239.

Vialatte, F.B., Solé-Casals, J., Cichocki, A., 2008. EEG windowed statistical wavelet scoring for evaluation and discrimination of muscular artifacts. Physiol. Meas. 29, 1435–1452.

Whittaker, J.F., Deakin, J.F., Tomenson, B., 2001. Face processing in schizophrenia: defining the deficit. Psychol. Med. 31, 499–507.

Zion-Golumbic, E., Bentin, S., 2007. Dissociated neural mechanisms for face detection and configural encoding: evidence from N170 and induced gamma-band oscillation effects. Cereb. Cortex 17, 1741–1749.

Zion-Golumbic, E., Golan, T., Anaki, D., Bentin, S., 2008. Human face preference in gamma-frequency EEG activity. Neuroimage 39, 1980–1987.