Beta oscillations in face recognition

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Received 4 May 2004; received in revised form 3 June 2004; accepted 8 June 2004
Available online 5 August 2004

Abstract

This report presents an analysis of the brain’s beta oscillations in face recognition. We performed experiments on 26 subjects with a strategy consisting of two types of stimulations: (1) the picture of an elder anonymous lady (unknown face) and (2) the picture of the subject’s own grandmother (known face). The subjects were healthy, young people between the ages of 15–32 years. Data were analyzed by means of amplitude frequency characteristics and digital filtering. Our results show the significant role of beta response in face recognition and the differentiation of known and unknown faces. Furthermore, this report supports our former view that the presentation of grandmother face evokes selectively distributed multiple oscillations in the brain. Together with the scope of other frequencies (e.g., delta, theta, and alpha), this method can serve as a tool for research studies or clinical studies in memory and cognition.

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Keywords: Beta; Delta; Alpha; Theta; Oscillations; ERP; Face recognition; Semantic; Episodic; Memory; Laterality; Prolongation

1. Introduction

The aim of the present study is to investigate the role of beta oscillations in face recognition. In our long-standing work, we have empirically shown that the integrative brain functions are manifested with the superposition of multiple oscillations. In order to give further experimental support to this working hypothesis, we recently have started measurements with facial stimuli and described that delta, theta, and alpha responses of the brain have clear differentiation upon presentation of known and unknown faces (Ba şar et al., 2001, 2004; Ba şar, 2004).

According to some authors, face selective activity takes place in fusiform gyrus, which has also been known as face fusiform area (Klopp et al., 1999; Kanwisher et al., 1998). However, a number of studies suggest that not only the occipito-temporal areas but
also other areas in the brain are activated during face recognition (Begleiter et al., 1995; Schweinberger et al., 2002; Eimer, 2000).

The brain’s beta oscillatory responses remained in the shadow of the analyses in the gamma band. These oscillations, however, merit important consideration. As the present study clearly shows, the distributed beta oscillatory responses play an essential role in face recognition and the differentiation of known and unknown faces.

2. Materials and methods

2.1. Experimental strategy

We used a strategy consisting of application of three different types of stimulation:

1) A simple light stimulation as control signal: its luminance was approximately at the same level of stimulations 2 and 3 described in the following (approximately 30 cd/m²).
2) The picture of an unknown face (an anonymous elder lady)
3) The picture of the ‘known face’: the subject’s own grandmother.

A total of 26 subjects in the age range of 15–36 years (17 females and 9 males) participated in the study. They had normal or corrected-to-normal binocular visual acuity and were right-handed. The pictures of the faces of the subjects’ own grandmother were prepared prior to measurements. The pictures were black and white (17×17 cm) and were displayed on a screen located at a distance of 120 cm from the subjects. The stimulus duration was set to 1000 ms with intervals varying between 3.5 and 7.5 s. The subjects, who were instructed to minimize blinking and eye movements, sat in a sound-proof and dimly illuminated echo-free room.

2.1.1. Data recording set

All three stimulations described above have been applied in a random sequence. Seventy-five stimulation signals have been applied with approximately the same distribution of each type of stimulation. Following the recordings, grandmother’s (known) face, unknown face, and light responses have been divided into subsets. In all experiments, subjects reported that they clearly recognized and differentiated the face of their own grandmother.

2.1.2. Electrophysiological recording

The electroencephalogram (EEG) was recorded from F3, F4, Cz, C3, C4, P3, P4, O1, and O2 locations according to the 10–20 system (Jasper, 1958). For the recordings, an EEG-CAP was used. For the ears, electromyogram (EMG) and electro-olfactogram (EOG) recordings with Ag/AgCl electrodes were used. Linked earlobe electrodes (A1+A2) served as reference. The EOG medial upper and lateral orbital rim of the right eye was also registered. The EEG was amplified by means of a Nihon Kohden EEG-4421 G apparatus with band limits 0.1–100 Hz, 24 dB/octave. The EEG was digitized on-line with a sampling rate of 512 Hz and a total recording time of 2000 ms, 1000 ms of which served as the prestimulus baseline and was stored on the hard disc of the computer.

2.2. Data Analysis

Before the averaging procedure, the epochs containing artifacts were rejected by an off-line technique. The frequency responses of the system were determined using the amplitude frequency characteristics (AFC) method (for a more detailed explanation of AFC method, please see Başar et al., 2001; Karakaya et al., 2000).

According to the general systems theory, all information about the frequency characteristics of a linear system is contained in the transient response of the system and vice versa. In other words, knowledge of the transient response of the system allows one to predict how the system will react to different stimulation frequencies if the stimulating (input) signal is sinusoidally modulated. If the step response \( c(t) \) of the system—in our case, the ERP—is known, the frequency characteristics \( G(jω) \) of this system can be obtained with a Laplace (or one-sided Fourier) transform of the following form:

\[
G(jω) = \int_{0}^{\infty} \exp(-jωt)d\{c(t)\}
\]
where \( G(j\omega) = \) frequency characteristics of the system; \( c(t) = \) step response of the system; \( \omega = 2\pi f = \) angular frequency, and \( f = \) frequency of the input signal.

The frequency characteristics, including the information on amplitude changes of forced oscillations and the phase angle between the output and the input, are also called the frequency response function. It is a special case of transfer function and is, in practice, identical with the transfer function.

For numerical evaluation, a fast Fourier transform (FFT) is used. Let \( X_n \) be a discrete time series \( X_n = X(n\Delta t), T = ((N-1)\Delta t) \). Then the Fourier transform \( Y_k \) of \( X_n \) is:

\[
Y_k = Y(\omega_k) = \sum_{n=0}^{N-1} X_n \exp(-i2\pi N^{-1}nk);
\]

\[
\omega_k = 2\pi k T^{-1}
\]

where \( Y_k = a_k + ib_k \) are the complex Fourier coefficients, the geometric mean of which is the amplitude spectrum.

The AFC is expressed in relative units and reflects the amplification in the studied frequency channels. The presence of a peak in the AFC thus reveals the frequency selectivities of the system, and these are interpreted as its most preferred oscillations when responding to stimuli. The AFC method has also the advantage of showing the status of all frequencies in a combined manner.

2.2.1. Algorithm for evaluation of prolongation of oscillations

We performed an analysis to evaluate the magnitudes and prolongations of the beta responses: the maximum peak-to-peak (pp) amplitude and the latency (lat) of the beta responses were measured. In order to assess the duration and the damping of these responses, the time periods for reaching half (1/2 lat) and third (1/3 lat) of the maximum pp amplitudes of the responses have been measured. This measure revealed the temporal characteristics of the oscillations, as the onset, duration, and damping of these responses. The same procedures were repeated for all sets and locations.

The Wilcoxon matched pair test was used as a statistical procedure in order to constitute the distinction between responses to grandmother and unknown faces.

3. Results

3.1. Beta responsiveness in the frequency and time domains

Fig. 1 shows the grand average AFC obtained from responses to grandmother and unknown faces at F4. It is noteworthy that the relative amplitude of beta response to the unknown faces is higher in comparison to grandmother faces. This AFC is also useful to choose limits of filters for determination of beta responses in the time domain. As illustrated in Fig. 1, the frequency response to facial stimuli had more prominent and distinct maxima in the beta range, peaking around 22 Hz, in comparison to the gamma range. Accordingly, we recommend the use of frequency characteristics in order to determine optimum filter limits (15–30 Hz) instead of using given templates.

3.2. Beta responses from single subjects and grand average responses

Beta (15–30 Hz) responses of individual subjects to grandmother and unknown faces were recorded at all electrode sites. These responses were similar to the results obtained from grand averages of 26
subjects. In regard to this similarity, Fig. 2 illustrates beta responses to unknown face (upper curve) and grandmother face (lower curve) of a single subject (subject 16) and (B) grand average responses to grandmother and unknown faces are illustrated. In this illustration, the global linear envelopes of oscillatory responses are also indicated. The prolongation time PT is the time difference between the decay of responses to grandmother face and the anonymous face. Latencies evaluated firstly with the maximal pp response and also with the minimum of the dampening amplitude, as vertical dashed lines indicate. Note the smaller amplitude and prolonged character of the lower curves (beta responses to grandmother face). The responses to the unknown face have larger amplitudes and are less prolonged. Furthermore, the responses to grandmother faces showed prolonged oscillations in comparison to the responses to unknown faces.

3.2.1. Topography of beta responses

In Fig. 3, the topographical distribution of grand average beta responses to grandmother and unknown faces is shown. Please note that the responses to grandmother faces are more prolonged than the responses to unknown faces at the frontal and central areas. The latencies of beta responses to grandmother faces varied between 150 and 220 ms in different recording sites. Similarly, the latencies of beta responses to unknown faces varied between 130 and 190 ms in different recording sites.

3.2.2. Amplitudes of beta responses

Statistical analysis showed that amplitudes of beta responses to unknown face stimuli were significantly larger than the amplitudes of beta responses to grandmother stimuli at F3, F4, Cz, and P3 recording sites \( (P<0.05) \). Accordingly, at the F3 recording site, the amplitude of beta response to grandmother face was 0.98 \( \mu V \) pp and the amplitude of beta response to unknown face was 1.32 \( \mu V \) pp, which was significantly larger \( (P=0.023) \).

At the F4 recording site, the amplitude of beta response to unknown face (1.40 \( \mu V \) pp) was significantly larger \( (P=0.035) \) than the amplitude of beta response to grandmother face (0.98 \( \mu V \) pp). At the Cz recording site, the amplitude of beta response to unknown face (0.93 \( \mu V \) pp) was significantly larger \( (P=0.020) \) than the amplitude of beta response to grandmother face (0.63 \( \mu V \) pp). Also, at the P3 recording site, the amplitude of beta response to unknown face (0.74 \( \mu V \) pp) was significantly larger \( (P=0.023) \) than the amplitude of beta response to grandmother face (0.36 \( \mu V \) pp).

According to the statistical analysis, the amplitudes of beta responses to grandmother and unknown face stimuli were not significantly different at the recording sites of P4, O1, and O2.

3.2.3. Laterality at parietal electrodes

The beta response amplitudes were also compared in between two hemispheres for each stimulation and
location. This analysis was significant only for the beta response to grandmother stimuli at parietal locations: there was significant difference between the amplitudes of beta responses to grandmother face at P3 and P4 recording sites ($P=0.017$).

3.2.4. Prolongation of beta responses

An important feature of the results is the significant differentiation of beta responses along time axis. In Fig. 4, the prolongations of beta responses in different recording sites are indicated. As this figure shows, the
responses to grandmother faces are more prolonged in comparison to responses to unknown faces at F3, F4, and Cz.

Accordingly, at the F3 recording site, the time period for reaching a third of its pp amplitude (1/3 lat) of beta response to unknown face was 255 ms and to grandmother face was 400 ms. Thus, the beta response to grandmother face was significantly more prolonged than the beta response to unknown face ($P=0.004$). Similarly, at F4, the beta response to unknown face was prolonged to 275 ms and the beta response to grandmother face was prolonged to 400 ms. At this recording site, there was significant prolongation in favor of beta response to grandmother face ($P=0.006$). The largest prolongation (575 ms) was of the beta response to grandmother face at Cz, which was also significantly more prolonged than the beta response (260 ms) to the unknown face ($P=0.028$).

The other recording sites did not show significant changes of prolongations of beta responses to grandmother and unknown faces.

4. Discussion

4.1. Selectively distributed beta responses

Several research groups have reported differentiated ERP components during face presentation localized at temporal areas (Bötzell et al., 1989; Bentin and Golland, 2002; Eimer, 2000; Zhang et al., 2001). Only a few papers are related to the frontal regions during face recognition. Bötzell et al. (1995) showed that for recognition of familiar faces, both the temporal and frontal regions are involved. Schweinberger et al. (2002) also reported that only for the familiar faces, responses were recorded from parietal, central, and prefrontal areas.

Our results showed that the beta responses to both grandmother faces and unknown faces were widely distributed at all recording sites. At F3, F4, Cz, and P4 areas, the maximal amplitudes of beta responses to grandmother faces were smaller than the maximal amplitudes of responses to unknown faces. However, at P4 and O2, the beta responses to grandmother faces were larger than unknown face responses. The selective distribution of beta responses in all recording sites is suggestive that not only temporo-parietal regions but also the cortex are involved during the processing of faces.

4.2. Beta responses in time domain

A major part of the papers indicated the presence of face-specific responses in the range of 120–210 ms (Bötzell et al., 1989; Linkenkaer-Hansen et al., 1998; Bentin and Golland, 2002). In a recent study, potentials specific to familiar faces extending to 400–600 ms were recorded as the largest at midline electrodes (Eimer, 2000). It was suggested that those results might reflect the activation of stored representations of familiar faces.

Our data show that the beta responses to known faces vary between 150 and 220 ms and beta responses to unknown faces are between 130 and 190 ms. These results are in agreement with earlier findings reporting face specific activity between 120 and 210 ms (Bötzell et al., 1989; Linkenkaer-Hansen et al., 1998). Beta responses to grandmother faces had prolonged oscillations in comparison to beta responses to unknown faces at F3, F4, and Cz. Furthermore, beta response prolongations (extending to 575 ms) do occur with the same latency of the late evoked potential components (400–600 ms) that are specific to familiar faces (Eimer, 2000).
4.3. Laterality of responses

In a study of interhemispheric cooperation, Mohr et al. (2002) obtained a highly significant familiarity by visual field interaction showing that, only for familiar faces, a bilateral advantage was obtained. Schutter et al. (2001) reported parietal asymmetry in beta frequency.

Our results indicate that the amplitudes of responses to grandmother faces (but not to unknown faces) show significant differences only between P3 and P4 recordings. Our results are in accordance with studies of Schutter et al. (2001) who showed asymmetries in the beta range.

4.4. Multiple functions of beta oscillations

Various functions have been assigned to beta such as visual attention (Marrufo et al., 2001; Wrobel, 2000), movement-related changes (Müller et al., 2003), excitation–inhibition (Whittington et al., 2000), sensory memory (Haenschel et al., 2000), cognitive tasks (Ray and Cole, 1985), and recollection and familiarity (Burgess and Ali, 2002). Recently, linkage and linkage disequilibrium between beta frequency and a GABA receptor gene have been reported (Porjesz et al., 2002). Rangaswamy et al. (2002) reported enhanced beta power in the resting EEG of alcoholics.

4.5. Multiple oscillations in face recognition

Polich and Kok (1995) emphasized the factors that contribute to neuroelectric activity related to cognitive processes besides attention allocation and immediate memory. In a study of cognitive processing, Klopp et al. (1999) analyzed face-selective spectral changes of ERPs. They concluded that phase locking of event-related spectral power took place not within a narrow frequency band but across a broadband of frequencies from 5 to 45 Hz, thus including the beta range and also the other major frequency bands.

In most of the face-related reports, only the amplitudes and latencies of conventional evoked potentials were mentioned. The sensory and cognitive processes related to facial stimuli of the brain would need to be more complicated. The whole brain and all oscillations are activated during recognition or remembering of one’s own grandmother and an anonymous face. The ensemble of responses behaves like a three-dimensional construct, consisting of temporal, spatial, and frequency spaces (Başar, 2004). The responses to an anonymous face or to a grandmother face are not represented solely by one location and a unique frequency or at the same position along the temporal axis, as differentiated delay and prolongation of multiple oscillations that are selectively distributed on the whole cortex show (Başar et al., 2004).

Although beta responses have larger amplitudes upon presentation of unknown faces, there is more prolonged activity in the beta range upon presentation of grandmother faces. On the contrary, theta responses are larger and less prolonged to grandmother faces in comparison to theta responses to the unknown faces (Başar, 2004).

Klimesch et al. (1994) and Sauseng et al. (2002) showed the possibility of differentiating the role of alpha and theta oscillatory activities during memory tasks. Alpha activity has been also correlated with phyletic memory, as well as episodic and semantic memories, and selectively distributed over several cortical areas (Başar, 1999, 2004).

In the delta frequency range, significant amplitude increases were observed in posterior areas to responses upon grandmother and unknown face stimuli, but not in frontal areas (Başar et al., 2004). The differentiation of the two types of facial stimuli is more distinct in beta responses than alpha and delta responses especially at the frontal and central areas, thus showing the important role of beta oscillations in face recognition.

5. Conclusion

(1) During activation of episodic memory (grandmother picture) and semantic memory (anonymous face), the topologic distribution of beta responses is significantly differentiated by showing varied degrees of amplitude enhancements and prolongations.

(2) These results support and extend the concept that integrative brain functions are based on multiple
oscillations selectively distributed in the whole brain.

(3) During face recognition, which is also involved in memory differentiation, a parallel processing in the beta frequency range takes place. Laterality, prolongation of oscillations, and topological selectivity belong to the manifestations of this parallel processing.

(4) Besides the parallel processing in beta frequency range, the superposition of oscillations in delta, theta, and alpha frequency windows indicates that the recognition of faces is manifested with a multifold of oscillatory activities including prolongation of oscillations.

(5) This high degree of differentiation in recognition of faces, which is reached by the present analysis, cannot be realized by conventional ERP analysis.

Acknowledgements

The experiments of this collaboration study were supported by TÜBITAK-DFG grant 446 TUR 112/14/01, DEÜ 02 KB.SAG.012/ 027-03.KB.SAG.064.

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