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Journal

International Journal of Neuroscience, 116(9)

ISSN

0020-7454

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Publication Date

2006

DOI

10.1080/00207450600553232

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ALPHA EEG PREDICTS VISUAL REACTION TIME

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Studies have suggested that consciousness is encoded discretely in time and synchronously in space of the brain. The present study was to model the alpha EEG as a brain clock to carry out the functions and to test whether the quality and rate of the oscillation could predict behavioral timing. Results showed that the alpha peak frequency was correlated with the conflict reaction time, and the selectivity was associated with the simple reaction time. These findings are consistent with previous reports and support the hypothesis that alpha EEG represents excitability cycles and may serve as a brain clock for spatial synchronization.

Received 19 May 2005.

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Keywords alpha EEG, brain clock, neural encoding, perception, reaction time, synchronization

Environmental information relayed by different sensory modalities to the central nervous system are reduced in features and processed by neurons at different brain regions (Zeki, 2003). Without a proper gating system, it is difficult to imagine that all these parallel brain processors can work synchronously in time. The perception, however, is not fractional. It is thus inevitable that certain degrees of neuronal synchronization among different parts of the brain must have occurred while sensory inputs are encoded for perception. This dilemma has become central to the neuroscience as to how such dispersed information can be assembled synchronously into a holistic perception. A plausible hypothesis is the field theory where electric potential oscillations provide time signals for the spatially separated neurons to fire synchronously. Studies have suggested that neural oscillation at gamma frequency (~ 40 Hz) may play an essential role in temporal binding (Gray et al., 1989). It has also been found that coherent neural activity is phase-locked to oscillatory waves in the 30 to 100 Hz range (Contreras & Steriade, 1997; Castelo-Branco & Neuenschwander, 1998). Due to the short wavelength, the high frequency synchrony is restricted only to a few millimeters (Eckhorn et al., 2004). To represent a complex object in the cortex, it is believed that more and distant brain regions need to be coupled in time; therefore a slower and stronger carrier wave is likely to be involved. This hypothesis is supported in part by other studies (von Stein & Sarnthein, 2000) suggesting specifically that long-range interactions in the alpha and theta ranges may be involved in processing of internal mental context.

Ignored by the EEG community for more than half a century, Norbert Wiener's (Masani, 1985) speculation about brain clock at alpha frequency (~ 10 Hz) deserves another consideration. This speculation closely resembles the contemporary theory of temporal binding. He described the human brain as a control and communication apparatus, in which stored traces of past decisions are combined to give rise to present and future decisions. "For the combination of information, it is generally desirable that the pieces of information combined should arrive at substantially the same time into the combining mechanism." In his model, the rhythmic alpha EEG serves as a *clock* to carry out this function in the brain. A related theory was proposed by Lindsley (1952, 1956) that alpha activity represented an excitability cycle, in particular, aggregates of cells, and suggested that the excitability cycle provided a means of pulsing and coding sensory impulses. Compared with the gamma activity, alpha has a much longer

wavelength and thus should be able to propagate greater distance with minimal energy loss.

Behavioral studies by Efron (1970) showed that consciousness was discrete in time, parsed into sensory sampling intervals or “perceptual frames” estimated to be about 70 to 100 ms in average duration, which coincided with the duration of alpha wave. Surwillo’s early works (1963, 1972, 1975) demonstrated that human reaction time could be predicted by the frequency of alpha EEG. Recent studies showed that spontaneous alpha peak frequency was associated with performances of working memory (Clark et al., 2004), semantic memory (Klimesch, 1996), and anticipation (Basar et al., 1997).

The present study used measures of spontaneous EEG and visual perceptual reaction time to further test the alpha clock hypothesis. It was rationalized that if the alpha rhythm was a crucial part of the brain clock, then its quality and speed should predict the corresponding behavioral measures.

METHODS

Subjects

Fourteen healthy subjects (9 males and 5 females, mean age: 22.1 ± 2.4) were provided with informed consent and all agreed to participate the reaction time and EEG tests. Subjects were college students who were attending UCI in Orange County, California.

Procedure

Reaction Time. (1) *Immediate Reaction Time (IRT)* and *Movement Time (MT)*. Subject was instructed to place a stylus on a 2×2 cm yellow control square (CS) in the middle of computer screen, and then to move the stylus as quickly as possible to a lighted target square (TS) on either the left or right of the control square with equal distance (5 cm). This task provided a measure of immediate reaction time, which calculated the time interval from the appearance of the TS (or a disappearance of CS) to the moment of the stylus detachment from the screen, and a measure of movement time, the time between the stylus detachment from the CS to the moment of stylus re-attachment to the TS. The combination of IRT and MT is a simple visual reaction time. Means for each measure and the corresponding variation coefficients (s.d./mean) were calculated over ten trials.

(2) *Perceptual Reaction Time.* In the Simple Perceptual Reaction (SPR) test, subject was given two hand grips in both hands and asked to press the right-hand button with their thumb when the word “RIGHT” appeared on the screen and the left-hand button when the word “LEFT” appeared. The subject was asked to respond accurately and as fast as possible. In the Complex Perceptual Reaction (CPR) test, subject was instructed to respond by pressing the right button when they saw the word “LEFT” and the left button when they saw “RIGHT.” Total of 10 correct trials for each test were used to calculate the mean reaction times and the variation coefficients. If error occurred less than twice, five more trials would be added on to correct. In case that the errors occurred more than 3 times, the whole test would be started over again.

EEG Recording. Subjects were positioned on a hospital bed in a sound-attenuated dark room. They were instructed to relax and close their eyes throughout the testing period. An EEG electrodes (Ag-Ag Cl) was placed at Fz on subjects’ scalp according to the International 10–20 system and referenced to linked mastoids. EOGs from both outer canthus were recorded simultaneously to monitor eye movements. The impedance of each electrode was lower than 5 K Ω . EEG and EOG signals were lowpass filtered at 70 Hz and amplified with NIHON KOHDEN EEG-4321B polygraph. Two minutes of EEG epochs for each condition were collected and digitized by a 16-bit A/D converter at the rate of 256 Hz and further processed digitally by Neurodata Inc. (QND 10.2) data acquisition system.

Analysis. In the perceptual reaction time paradigm, SPR was a simple reaction time that measured the time from the onset of a visual command on the computer screen to the moment that the subject responded to it by pressing an electromagnetic switch button. CPR was a conflict perceptual reaction time, which measured the similar time intervals as in SPR with conflict command. Assuming that the times of sensory signal input and the button press within a subject were constants, the difference between CPR and SPR should be the time to evaluate the signal and execute the command across the hemispheres in the brain. This “pure” brain process time was used as an average pace of executive function to correlate with EEG parameters.

Raw EEG data were edited off-line by an experienced technician to eliminate any significant ($>3^\circ$ arc; Jin et al., 1995) eye movements and any other type of apparent artifact. Two minutes of artifact-free EEG epochs (10 s/window) were then calculated by a fast Fourier transform (FFT) routine with a 10-point smooth factor (Figure 1). Spectral data between 5 and 18 Hz

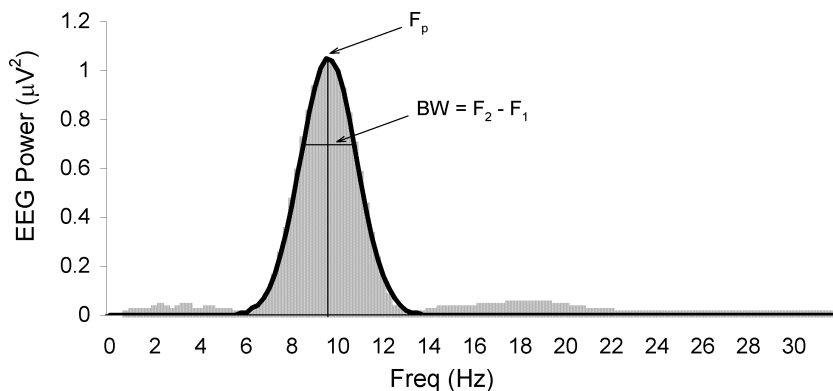


Figure 1. Power spectrum of resting EEG at Fz (shaded area). FFT with 10-s window was used to calculate the spectrum and a 10-point smoothing procedure was applied to normalize the distribution. Profile (solid line) is a curve-fitted Gaussian function used to calculate peak frequency (F_p) and quality factor ($Q = F_p/BW$). $BW = F_2 - F_1$ is half-power bandwidth at 3 db roll-off of the peak magnitude.

were further analyzed using a Gaussian function curve fitting. Two parameters were then yielded; peak frequency (F_p) measures the rate and quality factor (Q) reflects the selectivity of damping oscillation (Jin et al., 2005). Q factor was calculated using the following formula:

$$Q = F_p / (F_2 - F_1)$$

where F_p was the peak frequency, and $F_2 - F_1$ a half-power bandwidth at 3db ($1/\sqrt{2}$) roll-off of the peak magnitude. The first 10 epochs of EEG also were analyzed individually to test the peak frequency variation. Variation coefficient for each subject was calculated by dividing the standard deviation by mean.

Relationship between parameters of alpha EEG (period, amplitude, Q factor, and frequency variation) and reaction times (IRT, MT, SPR—CPR) were tested using Pearson correlation.

RESULTS

In the present study, four measures of reaction time were used, namely immediate reaction time (IRT), movement time (MT), simple perceptual reaction time (SPR), and conflict perceptual reaction time (CPR). To avoid the movement contamination, a resting EEG was recorded separately during which subjects' movements were kept to a minimum.

Table 1. Summary of correlations between EEG parameters and visual reaction times ($n = 14$). Correlation coefficients with statistical significance ($p < .05$) are displayed in bold.

| | <i>Q</i> factor | Peak freq. | Freq. Var. |
|---------|-----------------|--------------|------------|
| IRT | -0.64 | 0.47 | 0.02 |
| CPR-SPR | -0.32 | -0.61 | -0.24 |
| IRT Var | -0.51 | 0.08 | 0.15 |
| CPR Var | -0.03 | -0.49 | 0.6 |

Table 1 is a correlation matrix summarizing the relationships between the EEG parameters and reaction time measures. There was no significant correlations between the simple reaction time and any EEG measures ($|r| < 0.37$, n.s.). When the simple reaction time is fractioned into reaction time (IRT) and movement time (MT), a significant correlation was yielded between the *Q* factor and IRT ($r = -0.64$, $p < .06$; Figure 2), and the correlation between EEG and MT remained insignificant ($r = 0$, n.s.). When the simple perceptual reaction time (SPR) was subtracted from the conflict perceptual reaction time

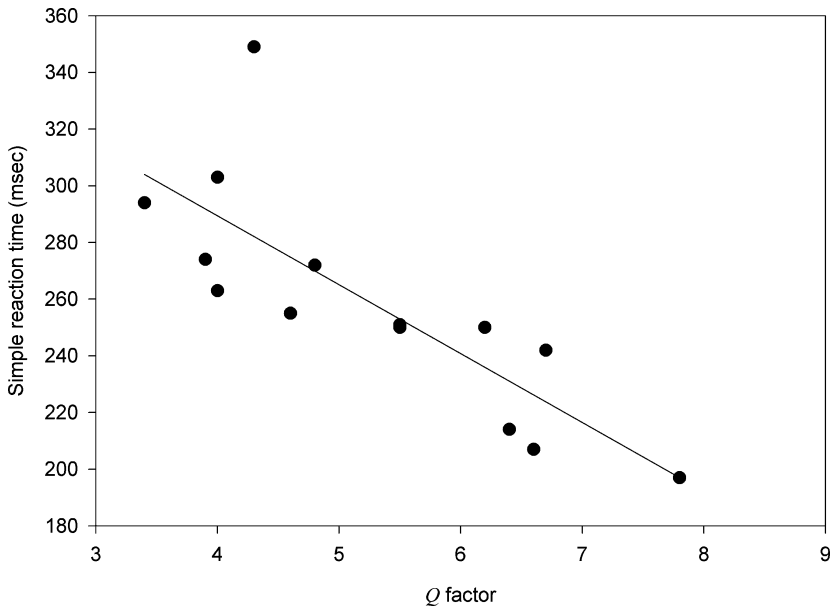


Figure 2. Relationship between immediate reaction time (IRT) and *Q* factor, a measure of selectivity of EEG in alpha frequency ($n = 14$). $r = -0.64$.

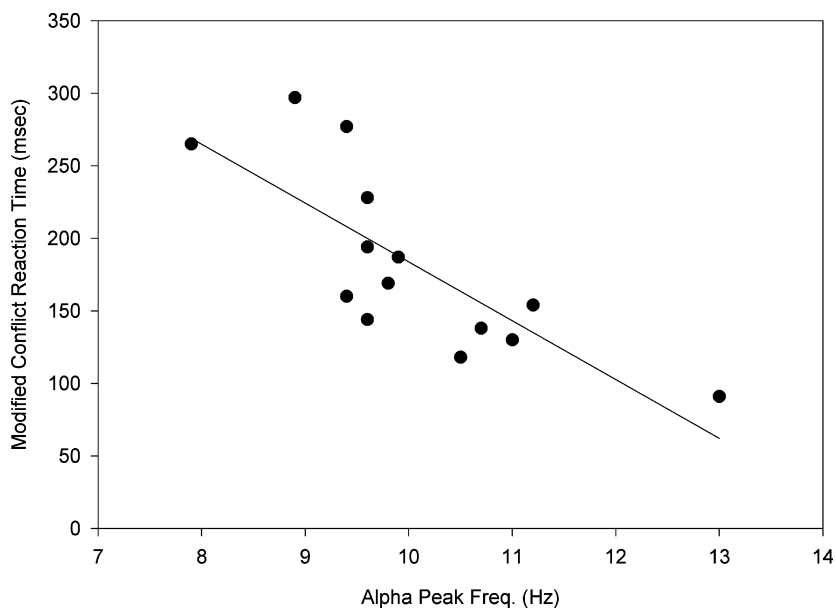


Figure 3. Relationship between peak alpha frequency and conflict perceptual reaction time ($n = 14$). Conflict reaction time was modified by subtracting simple perceptual reaction time from conflict perceptual reaction time (CPR-SPR). $r = 0.61$.

(CPR) to characterize the time delay that the brain used for conflict perception, we found that the speed of modified conflict perception (CPR—SPR) was significantly correlated with the peak alpha EEG frequency ($r = -0.61$, $p < .05$; Figure 3).

The effect of peak alpha frequency variation among EEG epochs on the reaction time variation within subject was further analyzed. It was found that the frequency variation was positively correlated with the CPR variation ($r = 0.60$, $p < .05$).

DISCUSSION

The present study used two parameters, peak frequency (F_p) and quality factor (Q) to describe the oscillatory alpha EEG activity. F_p characterizes the rate of the oscillation and Q measures the purity of the signal. Taking advantage of the high frequency resolution FFT and 10-point smoothing technique, it has been demonstrated that the alpha "hump" in the power spectrum can be modeled

reliably by Gaussian function. Q factor in this case is equivalent to the measure of standard deviation of the distribution. Smoothing for power spectral display is actually a plot of means of neighboring data points. This phenomenon of normalization could be described by the Central Limit Theorem in statistics. It states that the distribution of an average tends to be normal, even when the distribution from which the average is computed is decidedly non-normal.

Peak frequency of spontaneous alpha EEG has been found to be correlated with a number of cognitive functions, including anticipation (Basar, 1997), working memory (Clark et al., 2004), and semantic memory (Klimesch, 1996). Findings of correlation between alpha peak frequency and conflict reaction time in the present study are in agreement with Surwillo's reports (1963, 1972, 1975) and support in part the hypothesis (Lindsley, 1952, 1956) that alpha EEG may represent an excitability cycle and serves as a metronome (Masani, 1985). Comparing its effects on performance at different perceptual levels, it was found that the alpha peak frequency determines the reaction time that involves complex perception and calculation but not the simple reaction time. It is the first time to demonstrate that reaction time at lower order visual perception is predicted by the selectivity (Q factor) of the alpha activity. Q factor is a quality index of oscillatory systems. In a damping oscillation, it is a normalized measure of the bandwidth, which reflects the rate of energy dissipation per cycle and the frequency purity of the oscillation. The greater the Q is, the higher the energy conservation and frequency purity the system has. The analogy for the contrast between systems with high Q and low Q is the comparison between quartz clock and mechanical clock. Quartz has much higher Q than mechanical oscillator, and thus provides more accurate time counting than mechanical one.

If consciousness is a collection of discrete events (Efron, 1970), then the information it contains is likely to be updated discretely by the same time windows. Bearing this in mind, it was speculated that both quality and rate of the alpha wave should have effects equally on simple and conflict RT tasks. In the present study, however, it was found that Q factor was only correlated with the simple RT and F_p with conflict RT. This may be explained by the size of variance of the two correlated parameters. For a simple perceptual task, a decision is usually made during the first excitability cycle (~ 100 ms), which is not variable enough in time to count for the variance of the corresponding behavior. Quality factor of the signal, on the other hand, may play a more important role. Complex perception, such as the conflict reaction time task in the present study, tends to take more subsequent cycles to completing. Temporal variance of the cumulated multiple cycles in this task is thus likely to count for the variance of behavioral delay.

A shortcoming of the study is that EEG and RT were recorded at different states. Due to the technical difficulty, it is not known whether the EEG during activation will have the same effects on RT measures. For the similar reason, the real time correlation between the two measures could not be tested, which would be much more informative. EEG findings reported in the present study are from a single channel recording. No general conclusion can be drawn without multiple-channel recording because alpha EEG often displays phase and frequency differences between brain regions. Coherence and phase delay between distant brain regions are also interesting and should be studied in the future.

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