Increased frontal phase-locking of event-related alpha oscillations during task processing

Vasil Kolev a,*, Juliana Yordanova a, Martin Schürmann b, Erol Başar b, c

a Institute of Physiology, Bulgarian Academy of Sciences, Acad. G. Bonchev str., bl. 23, BG-1113 Sofia, Bulgaria
b Institute of Physiology, Medical University of Lübeck, D-23538 Lübeck, Germany
c Brain Dynamics Research Unit, Tübitak, Ankara, Turkey

Abstract

Recent findings substantiate the view that electroencephalographic (EEG) alpha rhythm (7–13 Hz) is functionally involved in cognitive stimulus processing. Our previous results have shown that enhanced alpha responses to auditory task stimuli can be well synchronized with stimulus until 800–1000 ms. The present study analyzed the effect of perceptual uncertainty and difficulty in decision making on event-related alpha oscillations in single auditory event-related brain potentials (ERPs). EEG was recorded from Fz, Cz and Pz electrodes in 10 subjects participating in two experimental sessions, in which auditory stimuli with equal physical parameters were presented under passive and task instructions. Separate measurements of single alpha response amplitude and phase-locking were performed and statistically analyzed for consecutive time windows in the post-stimulus epoch. Major results show that, during the cognitive task, the phase-locking of alpha oscillations at the frontal site is significantly increased in the time window of 500–1000 ms after stimulation. Thus, the involvement of enhanced and synchronized frontal alpha activity in higher brain processes is strongly emphasized. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Brain oscillations; Event-related potentials; Single-sweep analysis; Phase-locking; Frontal alpha rhythm; EEG; Cognitive

1. Introduction

New results obtained by means of different approaches and paradigms substantiate the notion that the electroencephalographic (EEG) alpha rhythm (7–13 Hz) is more than just a spontaneous or ‘idling’ rhythm of the brain (Mulholland, 1995; Niedermeyer, 1997). The EEG alpha activity recorded at various scalp locations and in different conditions is now referred to as the prototype of dynamic process related to a large ensemble of integrative brain functions (Başar et al., 1997).

Recently, increased attention has been focused on the association of alpha oscillations with cog-
nitive operations (Klimesch, 1996, 1997; Başar, 1998). Since earlier studies, mental efforts engaging attention and memory processes have been reported to elicit both long- and short-lasting suppressions of the ongoing EEG alpha activity (Berger, 1930, 1932; Van Winsum et al., 1984; Sergeant et al., 1987; Pfurtscheller and Klimesch, 1991, 1992; Boiten et al., 1992; Klimesch, 1996, 1997). Interestingly, task demands can produce not only suppressions but also augmentations of alpha oscillations. Başar et al. (1989) have observed that during attentive expectation of relevant stimulus omission, enhanced and well synchronized alpha oscillations are generated just before the omitted signal. A prolongation until 800–1000 ms after auditory task stimulus has also been described for phase-locked alpha and theta responses Kolev and Schurmann, 1992. In addition, mental task conditions with increased attention (Mulholland and Runnals, 1962; Ray and Cole, 1985; Spencer and Polich, 1999), goal-directed concentration (Shaw, 1996), and working memory activation (Krause et al., 1995) have been demonstrated to cause significant enhancements of EEG alpha activity. Hence, while there is evidence for the association between alpha oscillations and higher brain functioning, the precise mechanisms of this relationship are not definitely known.

The present study was designed to analyze the effect of task demands imposing extensive perceptual and decision making processing (Kolev and Schürmann, 1992) on event-related alpha oscillations. To describe precisely oscillatory alpha responses: 1 several distinct approaches were implemented to verify the presence of event-related alpha activity (Yordanova and Kolev, 1998); and 2 analyses were performed at the level of single sweeps, with alpha response phase-locking in consecutive time windows quantified independently of amplitude effects (Kolev and Yordanova, 1997; Yordanova and Kolev, 1998). The results show that, during task processing conditions, the phase-locking of frontal alpha oscillations is significantly increased within 500–1000 ms after stimulation, thus emphasizing the role of enhanced and synchronized frontal alpha activity in higher brain processes.

2. Experimental setup, data recording and analysis

Ten healthy volunteers (five female) from the Sofia Medical University, 18–30 years of age, served as subjects. There were two recording conditions, passive and task. In the passive listening condition, event-related brain potentials (ERPs) were elicited by identical 2000-Hz tones. In the task condition, the subjects were instructed to count mentally rare 1950-Hz tones randomly distributed among frequent 2000-Hz tones. In a preceding short training session, the two stimulus types were demonstrated to the subjects to make sure that they differentiated them. However, despite the instruction, the first experimental sequence of identical tones was repeated in the task condition. All stimuli presented in each of the two conditions (n = 80) were with equal physical parameters, frequency of 2000 Hz, duration of 1000 ms, intensity of 60 dB SPL (τ/f 10 ms), and inter-stimulus intervals randomly varying between 3.5 and 6.5 s. The instruction to differentiate between two slightly different stimuli was given to induce extensive perceptual uncertainty and difficulty in decision taking. During the recording sessions subjects kept their eyes closed.

EEG data (filter cut-off 0.1 and 70 Hz) were recorded at Fz, Cz, and Pz with linked-mastoids as a reference, and digitized with a sampling frequency of 250 Hz/12 bit. EEG segments contaminated with ocular or muscular activity, or exceeding ±50 µV, were excluded from further analysis. For each subject and experimental condition, the first 50 artifact-free sweeps were processed.

3. Verification of event-related alpha activity

Unfiltered averaged ERPs are depicted in Fig. 1a and show that the parietal late positive activity within the P300 range was larger to task than to passive stimuli. The presence of event-related alpha activity in ERPs was verified by: (a) calculation of amplitude–frequency characteristics (AFCs) (Başar, 1980; Röschke et al., 1995); and (b) estimation of event-related power changes in
the alpha range (for methodological details see Kalcher and Pfurtscheller, 1995; Yordanova and Kolev, 1998).

3.1. AFCs

Fig. 1b shows that the AFCs of both passive and task ERPs at three locations were characterized by a major prominent peak at approximately 10 Hz that was more pronounced for the task ERPs at Fz and Cz. Within the alpha range too, a second clear peak was observed at 7–8 Hz at Fz and Cz. A pronounced component was detected at the three locations in the theta (3–6 Hz) band that was also larger for the task ERPs. The presence of peaks in the AFCs indicates that oscillatory EEG activity within the limits of alpha band was generated and enhanced in a resonant manner during stimulus processing (Başar, 1980).

3.2. Alpha power changes

Fig. 1c demonstrates that an increase occurred for the EEG alpha activity after each stimulus type. For the early post-stimulus epoch (0–250 ms), the increase was most prominent at the central site. For the late epochs (500–1000 ms), alpha power increase was expressed only for the task ERPs and at the frontal and central locations. Because amplitude changes (enhancement or damping) of the post-stimulus relative to the ongoing EEG is a reliable indicator of the presence of event-related response in a given frequency channel (Başar, 1980; Kalcher and Pfurtscheller, 1995), these observations provide evidence for the stimulus-related responsiveness in the alpha-frequency channel. It is also demonstrated that this responsiveness is different for the task and passive stimuli.

4. Single-sweep analysis

Alpha activity was analyzed after single EEG responses were filtered in the 7–13-Hz band with zero phase shift (Başar and Ungan, 1973; Wastell, 1979). For amplitude analysis, root mean square (rms) amplitudes were calculated and measured.
for the time windows 0–250, 250–500, 500–750, and 750–1000 ms (Fig. 1d). For statistical evaluation, individual means of single alpha rms amplitude were computed. For quantitative evaluation of phase-locking, the single-sweep wave identification (SSWI) method was applied (Kolev and Yordanova, 1997). A histogram of the number of phase-locked single-sweep alpha waves (SSWI histogram) was obtained, normalized, and quantitatively assessed by calculating the sums of absolute SSWI histogram values for the same consecutive time windows of 0–250, 250–500, 500–750, and 750–1000 ms (Fig. 1e).

Alpha rms amplitude and phase-locking measured for each subject, experimental condition, time window, and electrode site were subjected to a three-way repeated-measures analysis of variance (ANOVA) task (passive vs. task) × electrode (Fz, Cz, Pz) × time window (0–250, 250–500, 500–750, 750–1000 ms). The Greenhouse–Geisser correction was applied to the analyses with repeated measures factors with more than two levels. The original degree of freedom (d.f.) and corrected probability values are reported throughout the text.

5. Task effects on single alpha response parameters

Fig. 1d illustrates that task stimuli tended to produce larger alpha activity in the whole 1 s post-stimulus epoch as compared to passive stimuli (task, $F_{1,9} = 3.8, P = 0.08$). Fig. 1e demonstrates that the phase-locking of alpha activity was stronger at central and frontal sites than at the parietal location (electrode; $F_{2,18} = 5.94, P < 0.01$). Significant interactions between task and electrode ($F_{2,18} = 7.08, P < 0.01$) were obtained because task stimuli produced stronger alpha phase-locking only at the frontal location (simple task effect at Fz: $F_{1,9} = 6.66, P < 0.05$; Cz and Pz: $F_{1,9} < 0.27, P > 0.61$). It can be observed in Fig. 1e that a frontally localized difference between the phase-locking of task and no-task stimuli is mostly expressed in the later post-stimulus epochs, e.g. later than 500 ms. This observation is verified additionally by the significant electrode × time window interaction ($F_{5,54} = 3.98, P < 0.01$). While the early alpha responses were best phase-locked at the central location, this topography effect was absent for the time periods later than 250 ms. Only for the 500–1000-ms epoch was the frontal phase-locking significantly stronger to task relative to passive stimuli as revealed by the task × electrode interactions found for the time windows 500–750 ms and 750–1000 ms ($F_{2,18} > 5.92, P < 0.05$). The phase-locking was strongest for the early post-stimulus epoch (0–250 ms) (time window: $F_{3,27} = 27.73, P < 0.001$).

6. Task-related alpha activity

Results of the present study demonstrate that auditory event-related alpha oscillations in a task processing condition are substantially different from those generated in a passive processing condition. One difference was that the alpha oscillations tended to be more enhanced to task than to passive stimuli. More important, actively processed task signals produced a significantly higher phase-locking of frontal alpha oscillations. These findings strongly indicate that enhanced and well organized patterns of EEG alpha activity accompany cognitive stimulus processing induced by perceptual uncertainty and difficulty in decision making.

6.1. The alpha response

Stimulus-related augmentation of alpha oscillations has been analyzed primarily in the context of the brain alpha response appearing as enhanced and time-locked alpha oscillations in the first 250 ms after sensory stimulus presentation (Başar, 1980; Başar and Schürmann, 1996; Schürmann et al., 1997). As reported previously for auditory passive and task conditions (Schürmann and Başar, 1994; Yordanova and Kolev, 1996, 1997), the present results showed that event-related alpha oscillations were most enhanced and best synchronized in the first 250
ms of the analysis epoch at the central scalp location. Hence, the alpha oscillations observed here for the 0–250-ms period can be identified with the auditory alpha response. As described in the results and in previous studies, neither the amplitudes nor the phase-locking of the early 7–13-Hz oscillations differentiated significantly task from non-task processing (Sterman et al., 1996; Quian Quiroga and Schürmann, 1999). However, differences in the early alpha (7–9 Hz) responses were detected between good and poor memory performers (Sterman et al., 1996), which, together with the present observation of slightly enhanced early alpha oscillations to task stimuli (Fig. 1c,d), leaves open the possibility that the alpha response within 0–250 ms may be related with task stimulus evaluation.

6.2. Task-related increase in alpha activity

In the present study, task effects on event-related alpha oscillations were obtained for the time epochs later than 250 ms and lasted as long as 1 s after stimulus onset. Since the discovery of alpha-blocking (Berger, 1930, 1932), the alpha EEG suppression to effortful mental tasks has been repeatedly reasoned as a marker of the activation of functionally involved brain areas. However, despite the classical view, the alpha blocking responses to mental tasks has been demonstrated to be inconsistent and to depend on the specific cognitive strategies employed by the subjects (Creutzfeld et al., 1969; Niedermeyer et al. 1989; Niedermeyer, 1997). Furthermore, Ray and Cole (1985) have found increased alpha activity during internal attentional processes (rejection taskwork), which was accepted to index a mechanism permitting more efficient processing of cognitive tasks. Shaw (1996) also describes a number of conditions requiring goal-directed concentration whereby an increase of the EEG alpha activity was found. Intensive activation of working memory processes such as stimulus set memorization and retrieval from memory, has been found to produce a substantial and widely distributed increase in the power of fast and slow alpha activity lasting as long as 3 s (Krause et al., 1995). These findings indicate that there exist cognitive brain functions (or cognitive states) that are associated with long-lasting enhancement of EEG alpha activity.

By quantifying short-lasting changes in the ongoing EEG rhythms referred to as event-related desynchronization (ERD) for power decrease and synchronization (ERS) for power increase (Pfurtscheller and Aranibar, 1977; Pfurtscheller et al., 1988, 1996), it has been found that during verbal and memory processes, the occipital cortical areas manifest alpha ERD while at the same time the alpha activity at the anterior regions is synchronized (Pfurtscheller and Klimesch, 1991, 1992; Krause et al., 1994, 1995, 1997). A most recent study has demonstrated that within 1 s after auditory stimulation, alpha power increases with increase in task demands (Spencer and Polich, 1999). Topography-specific enhancements of event-related alpha activity (or alpha ERS) observed in relation to task processing may occur alone or may accompany alpha ERD in other regions. As anterior areas often display task-dependent alpha ERS, the augmentation of alpha activity may reflect specific cognitive operations rather than cortical state at rest (Pfurtscheller et al., 1996). The present findings are consistent with such an assertion, because: (1) the amplitudes of event-related alpha oscillations tended to be higher for task than to passive processing especially in the late (500–1000 ms) latency epoch at anterior (frontal and central) sites (Fig. 1c,d); and (2) frontal alpha oscillations were better synchronized to task stimuli.

6.3. Cognitive alpha responses

The present observation of better synchronized and organized alpha patterns within 500–1000 ms after stimulus onset over the frontal cortical areas may be discussed in the context of prolonged or cognitive alpha response. First, it is possible that the initially generated alpha response is prolonged to targets but not to passive stimuli. Within this proposal, it may be expected that: (1) the topographic distribution of the alpha oscillations should be similar for each of the consecutive time
windows of the analysis epoch; and (2) no substantial changes in phase-locking to targets would occur over time of prolongation. However, the present study found that while the early alpha oscillations were maximal and better synchronized at the central electrode site, the late (500–1000-ms) oscillations were best phase-locked at the frontal location. Also, late alpha oscillations manifested a significant reduction in phase-locking as compared to the early (0–250-ms) oscillations. Hence, the effects of task processing on late frontal alpha oscillations can not be simply explained in terms of prolongation of the alpha response. Second, the task effect on the phase-locking of late frontal alpha oscillations may be proposed to reflect a cognitive alpha response. The term cognitive alpha response is suggested to be used to emphasize the fact that the event-related alpha oscillations are not merely enhanced as in the case of ERS, but they are also better synchronized. The stronger phase-locking with stimulus indicates that these alpha oscillations occur in relation to specific stimulus processing rather than to processing of task in general. The experimental design employed in the present study imposes extensive and prolonged evaluation of each stimulus because a decision about signal appearance cannot be readily taken. Processes of stimulus feature analysis and matching with target memory trace are likely to be continuously carried out during the recording epoch. It is thus demonstrated that the additional activation induced by perceptual uncertainty and difficulty in decision making may produce synchronized frontal alpha oscillations.

It is noteworthy that task processing also has been consistently associated with enhanced frontal theta activity (Mizuki et al., 1980; Demiralp and Başar, 1992; Başar-Eroğlu et al., 1992; Klimesch et al., 1994; Stermán et al., 1996; Yordanova and Kolev, 1998). As both EEG alpha and theta oscillations appear to be functionally involved in higher brain functioning, it will be a matter of future research to establish whether these two as well as other frequency bands are interrelated during cognitive stimulus evaluation and how this association may depend on the specific task demands.

Acknowledgements

The present study was supported by the National Research Fund by the Ministry of Education and Science, Sofia, Bulgaria (B-703/97 and B-812/98), the Deutsche Forschungsgemeinschaft, Bonn, Germany (436-BUL-113/105), and James S. McDonnell Foundation (98-66 EE-GLO.04).

References

Klimesch, W., Schimke, H., Schwager, J., 1994, Episodic and


