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EEG delta activity: an indicator of attention to internal processing during performance of mental tasks

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Abstract

In previous papers we proposed that an increase in delta EEG activity during mental tasks might be related to an increase in subjects' attention to internal processing. In this paper we have made a narrow band analysis to detect those EEG frequencies that change selectively during the performance of a mental task that requires attention to internal processing. Two different experiments were performed: (1) a difficult mental calculation task and a control stimulus with the same physical characteristics as the arithmetical symbols were presented in random order; (2) the Sternberg paradigm for the analysis of short term memory using a memory set of 5 or 3 digits was also presented in random order. Referential recordings to linked ears were obtained in all leads of the 10/20 system. In the first experiment, the increase of power from 1.56 to 5.46 Hz was observed only during the performance of the task and not during the control condition. In the Sternberg paradigm, the increase of power from 1.56 to 3.90 Hz was greater during the difficult than during the easy condition. These results support our hypothesis that an increase in delta activity may be related to attention to internal processing during the performance of a mental task.

Keywords: Delta rhythm; Internal concentration; Attention; Internal processing; Mental task; EEG frequency analysis

1. Introduction

Vogel et al. (1968) reported a high correlation between the amount of slow waves in the EEG during the performance of a task and proficiency in the tasks' execution. In order to explain the apparent contradiction between the increase of delta waves during mental tasks and the fact that this activity is the main characteristic of slow-wave sleep, they postulated the existence of two kinds of behavioral inhibition, both represented by slow waves in the EEG. 'Class I inhibition' would refer to a gross inactivation of an entire excitatory process, resulting in a relaxed, less active state, as in sleep. 'Class II inhibition' would selectively suppress inappropriate or non-relevant neural activity during the performance of a mental task.

Subsequently, quantitative EEG analysis has been the rule for the analysis of the EEG during the

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performance of mental tasks. EEG frequency analysis has shown that during the performance of mental tasks all EEG frequency components change in relation to rest.

The most spectacular change is the decrease in alpha power, a common observation since EEG was first recorded (Adrian and Matthews, 1934; see Fernández, 1994 for a review). Two contradictory interpretations of alpha suppression exist: (1) it is related to cognitive processes since differences in alpha suppression between tasks exist (Merrin et al., 1988; Ojeman et al., 1989; Rippon, 1990) or (2) it represents a more general response related to the level of attention and the complexity of the task (Ray and Cole, 1985; Earle, 1985; Gundel and Wilson, 1992; Kaufman et al., 1991; Galbraith and Wong, 1993).

The second aspect with contradictory results is the lateralization of alpha suppression during mental activity. Klimesch et al. (1990) described lateralization during a verbal task, but not during mental calculation. Petsche et al. (1992) also observed lateralization during interpretation of paintings but not during visualization of an abstract concept. According to De Toffol and Autret (1990) this asymmetry occurs only when there is a motor response. However, in a very well controlled study, Gevins et al. (1979) demonstrated an absence of lateralization of the response.

During mental tasks the pattern distribution of theta and beta power changes, increasing and decreasing in different brain areas according to the task: an increase of theta power in frontal leads with a simultaneous decrease in the remaining leads of the 10/20 system has been reported during mental calculation (Fernández et al., 1995) and during six different tasks (including mental arithmetic) by Petsche et al. (1986). In general, an increase in theta activity has been related with task difficulty and emotional factors (Dolce and Waldeier, 1974; Lang et al., 1988; Gundel and Wilson, 1992; Inouye et al., 1993; Makeig and Inlow, 1993).

Changes in the beta band have been directly related to cognitive processes (Ray and Cole, 1985). Some authors have reported increases and decreases in beta activity in specific regions (Gevins et al., 1979, Tucker et al., 1985; John et al., 1989). We have already mentioned that Petsche et al. (1986), in the analysis of the effect of six different tasks, found the same type of changes in the theta band, but in the beta band they reported different spatial patterns of activation for each task. In an independent study, Fernández et al. (1995) described the same changes for mental calculation as those reported by Petsche et al. during arithmetic tasks. It seems as if beta-power distribution follows a specific pattern according to the given task.

Few studies relating EEG and mental activity have analyzed the delta band, due to the fact that several artifacts may be present in this band, most prominently eye movements. However, a delta increase has been reported in different types of mental tasks (Dolce and Waldeier, 1974; Tucker et al., 1985; Kakizaki, 1985; Etévenon, 1986; Valentino et al., 1993; Fernández et al., 1995).

Ray and Cole (1985) distinguished between attentional tasks that require observation of environmental stimuli (intake tasks) and those that require attention to internal processing (rejection tasks). These authors incorporated the intake-rejection dimension into EEG research, but unfortunately they analyzed EEG activity only in the alpha and beta bands. In 1993, we suggested that an increase in delta activity might be related to an increase in subjects' internal concentration during rejection tasks (Fernández et al., 1993).

In this paper, we propose that attention to internal processing should be accompanied by the 'Class II inhibition' described by Vogel et al. If this is so, during tasks that require attention to internal processing we would expect: (1) EEG delta activity would appear only during the performance of a mental task and not with the presentation of a similar physical stimulus to which the subject does not have to respond; (2) delta activity should be related to the difficulty of the task; and (3) during the performance of a task other types of stimuli unrelated to the task should be inhibited. In this paper, evidence from two different experiments supporting the first two hypotheses is presented. In a paper in progress, we shall present results supporting the third hypothesis.

Another important aspect is the frequency resolution in the experiments already performed in the literature. The great majority of the papers have examined EEG activity using broad band analysis. We were interested to know if the changes observed during mental tasks were peculiar to a specific frequency or if they covered a wider range of frequencies. For this reason, we performed a narrow EEG frequency analysis with a resolution of 0.78 Hz.

2. Materials and methods

2.1. Subjects

In the two experiments, subjects were 10 right-handed male volunteers (22–32 years old) without neurological antecedents and with a normal EEG.

2.1.1. Tasks

2.1.1.1. First experiment. Two different stimuli were presented to each subject on a videomonitor in random order and with equal probability:

1. A complex arithmetic task that the subject had to solve and give the answer to verbally, e.g. (85/5)6, (24 + 39)/9, (39 + 46)/5, and
2. A control stimulus with similar physical characteristics to the arithmetical symbols and to which no answer was expected, e.g. (&& + &&)/&.

Both types of stimuli had a duration of 4 s. EEG segments were analyzed, consisting of 1024 ms previous to the presentation of the stimulus and 3 s after the presentation of the stimulus and before the verbal response was given. The sampling interval was 5 ms. Our hypothesis was that delta activity should be observed during the performance of the task and not during the control condition.

2.1.1.2. Second experiment. The Sternberg paradigm for the analysis of short-term memory was used (Sternberg, 1966). In this experiment, a memory set of several digits was presented on a videomonitor for 1500 ms and 2 s after a single digit was displayed for 300 ms. The subject had to respond with the right button of the mouse if the digit was in the memorized set or with the left button if it was not. In this experiment, two levels of complexity were evaluated: the memory set consisted either of 3 or of 5 digits. EEG segments of 1024 ms previous to the presentation of the memory set and 2 s after the end of the memory set stimulus were analyzed. Our hypothesis was that more delta should be observed in the more complex task.

2.1.2. Recordings

In the two experiments, the EEG was recorded with reference to linked ears from Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz, Pz, and Oz of the 10/20 system. The EOG was recorded from a supraorbital electrode and from an electrode in the external canthus of the left eye. The amplifier bandwidth was set between 0.05 and 30 Hz. The EEG was sampled every 5 ms using a MEDICID 3E system and stored on a hard disk for further analysis. Subjects were seated in a comfortable chair in front of the videomonitor. Stimuli were delivered by a MINDTRACER system synchronized to the MEDICID 3E acquisition system. In order to reduce ocular movements, a fixation point on the videomonitor was presented during the whole experiment except during visual stimulation. Correct and incorrect responses during the second experiment were automatically marked in the recording. In the first experiment, as a verbal response was given by the subject, the EEG was edited offline for correct and incorrect responses.

Given that in an oddball paradigm experiment, Basar-Eroglu et al. (1992) have reported that the frequency characteristics of the Event-Related Potential (ERP) in response to the infrequent stimuli included large delta and theta components, we decided to analyze the EEG segments after the ERP. In the first experiment, EEG segments of 1024 ms from immediately before and 3 s after the presentation of the stimulus were visually edited. In the second experiment, EEG segments of 1024 ms from immediately before and 2 s after the memory set stimuli were edited. Special care was taken to reject segments with eye movements or other artifacts. Only those segments with correct responses and no artifacts were analyzed.

2.1.3. Analysis

Previous experiments have analyzed EEG frequency characteristics using broad band analysis. In this paper, we were interested to know if the changes during mental activity were peculiar to a specific frequency or if they covered a wider range of frequencies. For this reason, we performed a narrow band analysis with a resolution of 0.78 Hz.

For each monopolar lead, the Fast Fourier Transform was computed and the power in the following frequencies was obtained: 0.78, 1.56, 2.34, 3.12, 3.90, 4.68, 5.46, 6.24, 7.02, 7.80, 8.58, 9.36, 10.14, 10.92, 11.70, 12.48, 13.26, 14.04, 14.82, 15.60, 16.38, 17.16, 17.94 and 18.72 Hz.

In each subject, the power in each frequency was averaged separately across the following conditions.

2.1.3.1. First experiment.

1. EEG segments previous to the task stimuli (Calculation)
2. EEG segments 3 s after the task stimuli (Calculation)
3. EEG segments previous to the control stimuli (Control)
4. EEG segments 3 s after the control stimuli (Control)

2.1.3.2. Second experiment.

1. EEG segments previous to the memory set of 3 digits (Easy)
2. EEG segments 2 s after the memory set of 3 digits (Easy)
3. EEG segments previous to the memory set of 5 digits (Difficult)
4. EEG segments 2 s after the memory set of 5 digits (Difficult)

To achieve Gaussian distributions for statistical analysis, the ln transformation was used (Gasser et al., 1982; Pollock et al., 1991).

2.1.3.3. Statistical analysis. Repeated measures ANOVAs for each lead in each frequency were performed, taking into consideration the different types of stimuli for the first and second experiments. The two factors of the model were: stimuli (calculation vs. control for the first experiment, 3 and 5 digits in the second experiment) and the change of the EEG after the stimuli in relation to the EEG before the presentation of the stimuli (within or repeated factor). In our view, the most important result was given in the interaction stimuli * change; that is, if there was a greater change during calculation than during the control condition in the first experiment, or if the change was greater for the difficult than for the easy condition in the second experiment.

Student t-tests were also computed between the EEG after and the EEG before the presentation of the stimuli for each frequency and lead, for the arithmetic and control conditions, as well as for both levels of difficulty of the Sternberg paradigm. Maps were constructed with these t values.

Table 1
First experiment significant results of the interactions stimuli * change (change during calculation > change during control)

	Frequencies					
Leads	1.56	2.34	3.12	3.90	4.68	5.46
Fp1			0.03			
Fp2			0.03			
F4	0.005	0.04				
C3		0.009	0.0008	0.005	0.03	
C4	00.006		0.0005			
P3		0.001	0.001	0.01	0.008	
P4		0.01	0.007			
O1			0.01			0.03
F7				0.006		0.03
T3		0.05	0.002	0.0006		
T4	0.03		0.04			
T5		0.01	0.025	0.002		0.01
T6		0.01	0.05			
Fz		0.01	0.02			
Cz		0.01	0.002		0.03	0.02
Pz		0.03	0.001		0.04	0.007

Fig. 1. Topographic distribution of t values between the EEG 3 s after and the EEG before the presentation of the arithmetic task (bottom row) and the control condition (top row) in frequencies 1.56, 2.34, 3.12, 3.90, 4.68 and 5.46 Hz. Significant changes ($t < 2.76$) were observed only during the arithmetic task, being 3.12 Hz the frequency where major changes were observed. Scale of the Student t-test values is from -3 (blue) to 4 (yellow).

Fig. 2. Topographic distribution of the t values between the EEG after and the EEG before the presentation of the memory set for 1.56, 2.34, 3.12 and 3.90 Hz. Upper line: 3 digits to remember. Bottom line: 5 digits to remember. More important changes are observed in the more difficult condition. Scale of the Student t values is from -3 (blue) to 3 (white and yellow).

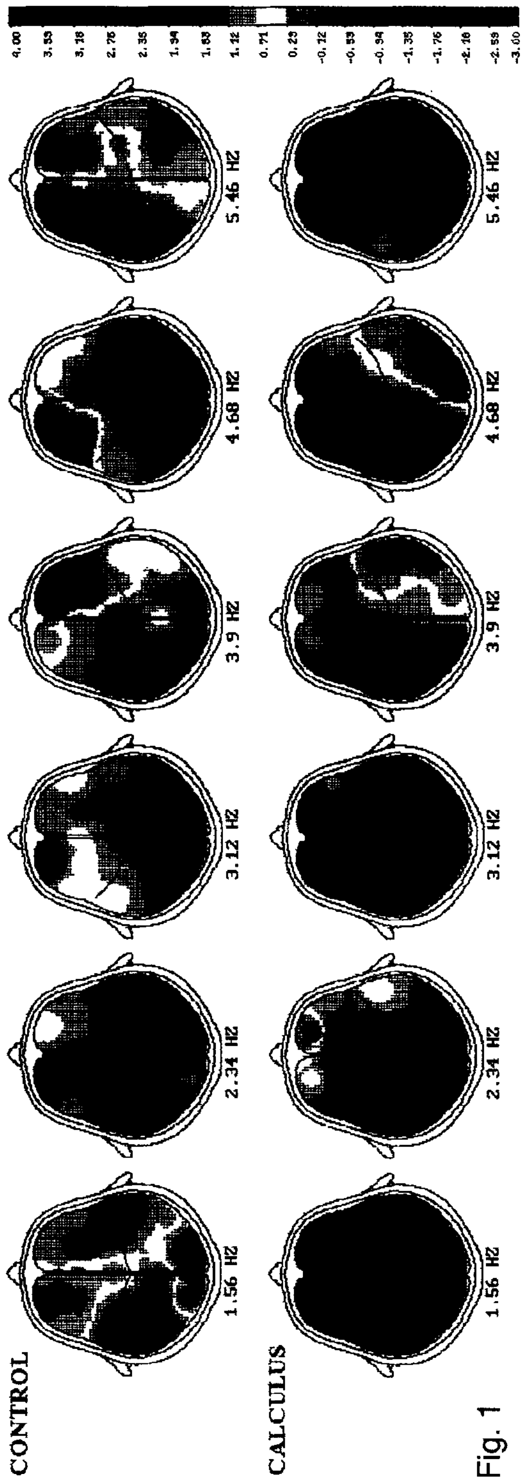
CONTROL
CALCULUS
1.56 HZ
2.34 HZ
3.12 HZ
3.9 HZ
4.68 HZ
5.46 HZ

Fig. 1

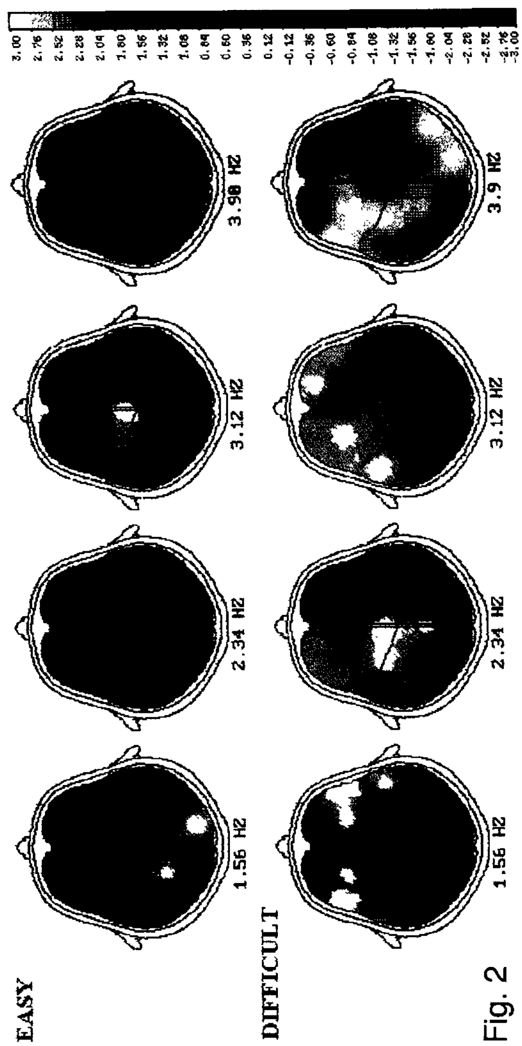
EASY
DIFFICULT
1.56 HZ
2.34 HZ
3.12 HZ
3.98 HZ
3.9 HZ

Fig. 2

3. Results

3.1. First experiment

There were no significant results in relation to the type of stimuli, as could be expected, but many significant ($P < 0.05$) results were observed for the repeated factor (EEG change) and for the interaction. Power in 1.56, 2.34, 3.12, 3.90, 4.68, and 5.46 Hz was greater for the EEG 3 s after the presentation of the stimulus than before the stimulus. However, this change was observed during the performance of the arithmetic task, and not during the control condition. Table 1 shows the significant results by lead and frequency of the interaction stimuli * change when the change for calculation was greater than for the control condition. Although this result was observed in many leads, changes in the left hemisphere appear to have been more important.

Fig. 1 shows the topographic distribution of the t values between the EEG 3 s after and the EEG before the presentation of the arithmetic task and the control stimulus. Significant values were observed only during the task in the frequencies from 1.56 to 5.46 Hz. In 7.02 and 8.58 Hz, no significant results were obtained.

Power was significantly greater before the presentation of the stimulus in 9.36 (in P3, O1, T5), 10.14 (P3, O1, T5, Cz, Pz), 10.92 (Fp1, F3, O2) and 11.70 Hz (in C4, P3, P4, O1, O2, T3, T4). No

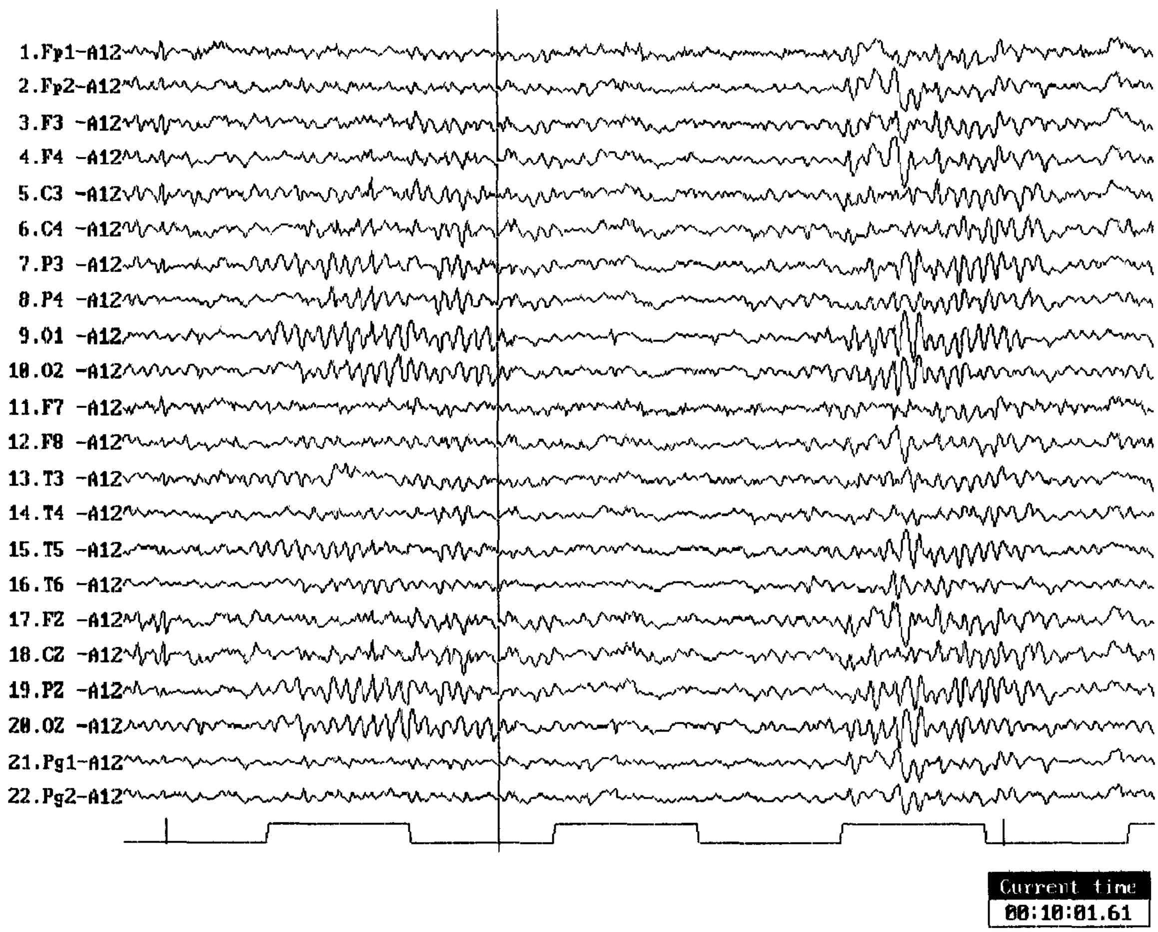

Fig. 3. EEG during the performance of the Sternberg paradigm in two different subjects. The cursor signals the onset of the memory set. In both cases, there is a clear reduction of the alpha rhythm and the appearance of slow wave shifts (A) and delta waves (B).

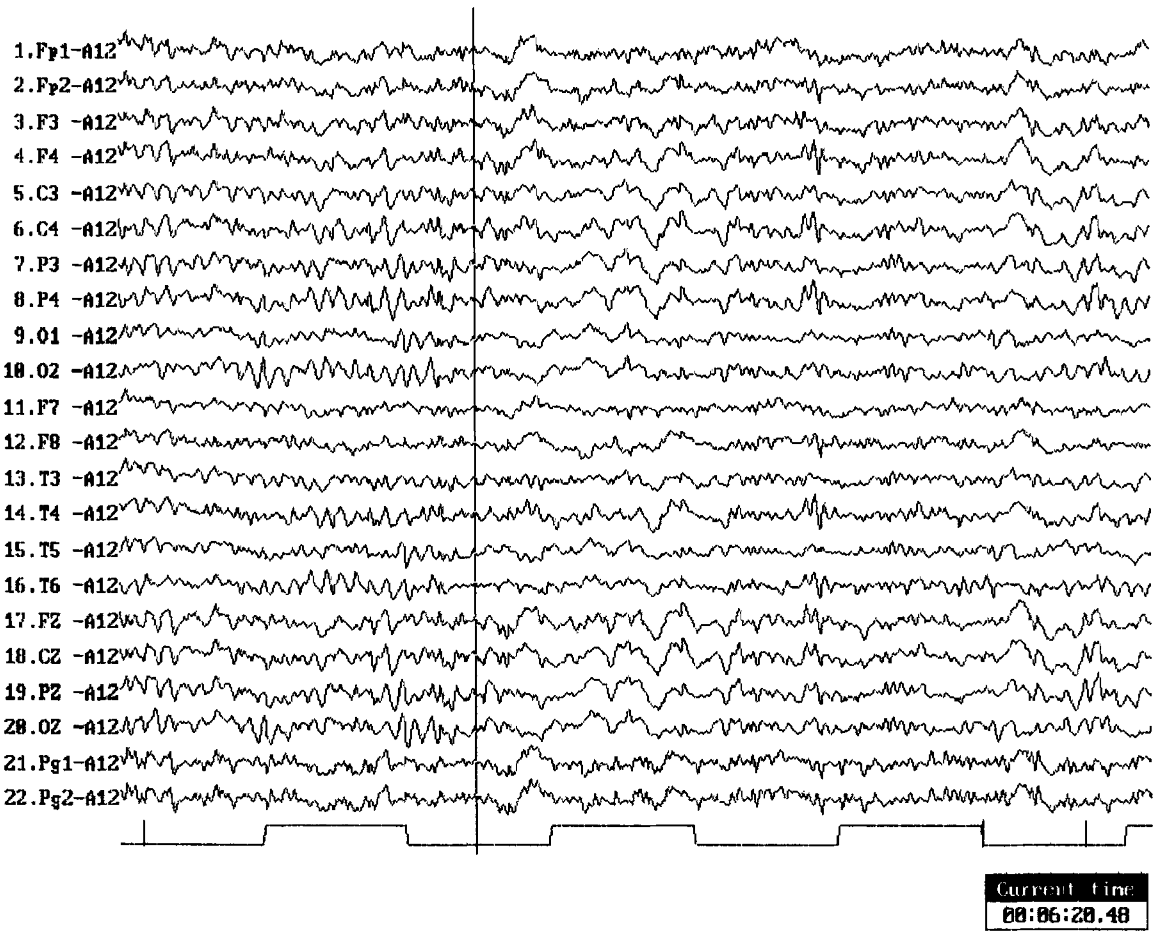

Fig. 3 (continued).

important interactions were observed, which means that power in these frequencies decreased after the presentation of both stimuli.

There was also a decrease in power after the presentation of the stimuli in 14.04, 16.38, 17.16 and 17.94 Hz in central regions (C3, C4, Cz). Significant interactions were observed in 14.04 Hz, where during the calculation task there was a more marked decrease in power during the control condition in frontal (F3) and parietal regions (P3, P4). In 16.38 Hz in F4, there was a differential effect: power decreased during the task and increased during the control condition. In 17.16 and 17.94 Hz power decreased after the stimuli in both conditions in C3, C4, Cz. No interactions were observed.

In summary, power in the delta and low theta bands (1.56–5.46 Hz) increased selectively during the task and not during the control condition, while power in the alpha band decreased after the presentation of both stimuli. In the beta band, a decrease in power from 14.04 to 17.94 Hz was also observed after the presentation of both stimuli. However, at 16.38 and 17.94 Hz, the changes observed depended on the condition.

3.2. Second experiment

Power in almost all frequencies changed. Power was higher after the presentation of the memory set than before the presentation in 1.56, 2.34, 3.12, 3.90, 4.68 and 5.46 Hz in many leads. Interactions were observed in 1.56, 2.34, 3.12, and 3.90 Hz, the difficult task (5 digits) producing a greater increase in power than the easy one (3 digits). Fig. 2 shows the topographic distribution of the t values between the EEG after and before the memory set was presented for 1.56, 2.34, 3.12 and 3.90 Hz. In the difficult condition EEG changes were more significant than in the easy one.

Fig. 3 illustrates the EEG of two different subjects during the performance of the task. After the presentation of the memory set there is a clear decrease in the alpha rhythm and an increase of slow waves.

In 6.24 and 7.02 Hz, important interactions were observed. In 6.24 Hz there was an increase in power for the difficult condition, whereas power decreased during the easy condition in Fp1, F4 and T4. In 7.02 Hz, after the memory set, power decreased in the difficult condition and increased in the easy one in C3, P3, P4, O1, T5 and Pz.

From 8.58 to 12.78 Hz, and 17.16 to 18.72 Hz, power decreased after the memory set in both conditions in almost all leads. No interactions were observed.

Interactions were observed in 14.04 (in T6), 14.82 (in P4), 15.6 (in O1) and 16.38 Hz (in C4), with an increase in power in the difficult condition and a decrease in the easy condition.

Therefore, during the second experiment power from 1.56 to 5.46 Hz was higher after the presentation of the memory set than before the presentation during the easy and difficult conditions. These frequencies were exactly the same ones in which we observed a power increase in the first experiment during calculation and not during the control condition. However, EEG changes from 1.56 to 3.90 Hz were greater during the more complex task in the second experiment.

In 6.24 and 7.02 Hz, different interactions were observed during the second experiment: while the difficult condition increases the power at 6.29 Hz, it decreases the power at 7.02 Hz. At these frequencies, no significant effects were observed in the first experiment.

From 9.36 to 11.70 Hz, power decreased after the presentation of both stimuli in both experiments. The same effect was observed at 17.16 and 17.94 Hz: power decreased in both conditions in both experiments.

At 14.04 and 16.38 Hz, specific changes were observed during mental calculation in comparison with the control condition in the first experiment. During the second experiment, there was a power reduction in the easy and an increase in the difficult condition at these frequencies.

4. Discussion

Basar-Eroglu et al. (1992) proposed that delta frequencies observed as frequency components of the P300 during an oddball paradigm were involved in signal matching, decision making and surprise. In our experiments, we selected EEG segments several seconds after the presentation of the stimulus in order not to include the ERP, and for this reason we cannot postulate that these processes are involved in the generation of the delta activity we observed.

The results for the two experiments clearly showed that there is an increase of power in the EEG frequencies from 1.56 to 5.46 Hz during the performance of mental tasks that require attention to internal processing, or what we have called 'internal concentration' (Fernández et al., 1993), since this effect was absent only in the control condition of the first experiment. This increase in power was generalized to many leads.

During memorization in the Sternberg paradigm, there was a more significant increase of power in the frequencies from 1.56 to 3.90 Hz during the most difficult task. These results support our second hypothesis, that delta power should increase more in the most complex task. Gundel and Wilson (1992) did not observe a change in the delta band according to task difficulty. However, they performed their analysis on EEG segments of 8 s of duration, including the time previous to and after the presentation of the stimuli, whereas we studied the change between the EEG activity previous to the presentation of the stimuli and the EEG during memorization, which may explain the different results.

In a previous paper (Fernández et al., 1995), we analyzed four different tasks of mental calculus – number comprehension, sign comprehension, mental calculus and the spatial component of calculus – and we observed that the higher increase of delta activity in relation to rest condition was not in the most complex task, but rather in the simplest one. We interpreted this result in relation to behavior during the tasks: in the most complex task the subject used visual feedback for a longer period than in the simplest task. Attention to the external environment decreases the amount of delta activity during internal concentration. A similar result was obtained by Giannitrapani (1971), who used different mental tasks: listening to white noise, to music, to verbal contextual material, looking at a poster, looking through diffusing goggles and silently performing mental arithmetic. He observed an increase of delta activity only in the latter task. In the other conditions, which demand attention to the external environment, he observed a decrease of delta power. Delta power increases only in those tasks which require attention to internal processing.

This increase of the slow frequencies is not due to ocular movements nor to any other artifact, as has been shown by the recording of bipolar cortical activity in epileptic patients with subdural grids during the Sternberg paradigm (Harmony et al., 1994a, Harmony et al., 1994b). In these patients, implanted in order to localize the epileptic foci, informed consent was obtained to record the EEG during different mental tasks. An increase in delta power was observed during memorization, in the scalp electrodes as well as in the cortical bipolar recordings.

Visual inspection of EEG recordings showed that during the performance of a task, alpha activity was suppressed and slow waves of low amplitude were present, sometimes as synchronous activity in 1–3 Hz and sometimes as transient slow wave shifts in the EEG. A delta increase has been reported not only in some experiments during mental tasks (Dolce and Waldeier, 1974; Etévenon, 1986; Tucker et al., 1985; Kakizaki, 1985), but also during yoga exercises that require a state of internal concentration (Roldán et al., 1980; Dostalek et al., 1983).

Normal slow waves in the frequency of the delta band are observed during slow-wave sleep (Class I inhibition). This activity was classically considered to have its origin in the cerebral cortex, because laminar analyses of these waves found vertical sink-source relationships to EEG potentials at various cortical levels (Ball et al., 1977; Petsche et al., 1984). There is now evidence that delta activity also originates in the thalamus and is transferred to cortical neurons in different layers (McCormick and Pape, 1990; Steriade et al., 1993a).

During slow-wave sleep a progressive change is observed in the EEG from alertness to sleep. These changes are produced by a decrease in the activation of thalamocortical cells due to diminished activity of cholinergic and monoaminergic neurons from the upper brainstem, posterior hypothalamus and basal forebrain and a decrease in glutamaergic activation by cortical cells (Steriade et al., 1993b). The results observed during mental tasks cannot be explained by such a progressive deactivation, since during mental tasks abrupt changes are observed. Therefore, a mechanism triggered by the mental task may exist, but it is unknown. One possibility is that during the performance of mental tasks that require attention to internal processing, the corticofugal pathway that inhibits the thalamocortical cells is activated, producing a functional disconnection of the cortex from environmental stimuli in order to selectively process the internal information. This would be the 'Class II inhibition' mentioned by Vogel et al. (1968), characterized by the presence of slow activity in the EEG.

According to several authors, theta increases with task difficulty (Petsche et al., 1986, 1992; Lang et al., 1988; Gundel and Wilson, 1992; Inouye et al., 1993). An increase of theta power during an episodic recognition task has been reported by Klimesch et al. (1994), using event-related desynchronization. However, in our experiments, the results obtained with narrow band analysis within the frequencies of the theta band showed a different behavior depending of the specific frequency. Although power in the low frequencies of the theta band, 4.68 and 5.46 Hz, was higher during the performance of the tasks (as frequencies within the delta band, from 1.56 to 3.90 Hz), these frequencies were not sensitive to task difficulty, since during memorization there was a power increase in these frequencies during both the easy and the difficult conditions. However, for 6.24 and 7.02 Hz, a contrary effect was observed in the second experiment according to task difficulty. At 6.24 Hz the difficult condition increased power while the easy condition decreased it, and at 7.02 Hz a reverse effect was observed. These results emphasized the usefulness of the narrow band analysis in applications to mental activity.

The changes observed in the frequencies within the alpha band, 9.36 to 11.70 Hz, showed a very important decrease in power after the stimuli in all conditions. No interactions were detected between this decrease in power and the complexity of the task. Although task difficulty has been reported to influence the spatio-temporal maps of event-related desynchronization in the alpha band, this effect depends on the kind of material to be remembered (Dujardin et al., 1995), and in our particular experiment the effect of complexity was not observed in the alpha band.

We explored up to 19 Hz in the beta band, finding a greater decrease in power of 14.04, 16.38, 17.16 and 17.94 Hz during calculation than during the control condition. In the Sternberg paradigm, power at 17.16 to 18.72 decreased after the memory set in both conditions. However, a differential effect of decrease or increase in power after the memory set was observed between the easy and difficult conditions in 14.04, 14.82 and 16.38 Hz. Changes in the beta band have been related to cognitive activity during the performance of several tasks (Ray and Cole, 1985; Tucker et al., 1985; John et al., 1989). Therefore, our results – although not oriented to analyzing this band – also support the findings of other authors.

To conclude, we have presented results showing that activity between 1.56 and 5.46 Hz increases only during the performance of a mental task and not after the presentation of a control stimulus and that the power increase between 1.56 and 3.90 Hz is dependent of the complexity of the task. These results support our hypothesis that an increase in delta activity may be related to attention to internal processing during the performance of a task.

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