Alpha Frequency, Cognitive Load and Memory Performance

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Summary: EEG-signals were recorded from subjects as they performed a modified version of Schneider's and Shiffrin's memory search paradigm. The hypothesis was tested whether individual (centre of gravity) alpha frequency, termed IAF, is related to memory performance and/or attentional demands. The results show that memory performance exerts the strongest effect on IAF. As compared to a resting period, the difference in IAF between age-matched good and bad memory performers reached a maximum when subjects were actually retrieving information from their memory. During retrieval, the IAF of good performers is 1.25 Hz higher than for bad performers. Attentional and task demands also tend to reduce IAF, but - as compared to memory performance - to a much lesser degree. The results of amplitude analyses demonstrate further that during retrieval, alpha desynchronization is more pronounced for bad performers than for good performers. Taken together, the results indicate that a decrease in IAF is always related to a drop in performance.

Key words: Alpha frequency; Event related desynchronization; Memory performance; Encoding; Retrieval; Attention.

Introduction

In this paper we discuss evidence for a close relationship between EEG-alpha correlates and memory performance. The term alpha is used for rhythms within the alpha band, including alpha rhythms, the mu rhythm and others. We start with a brief review of experiments dealing with alpha correlates and cognitive processes and then refer to the results of recently performed experiments (Klimesch et al. 1990b) in order to explain the design of the present study.

The vast majority of experiments studying alpha correlates and cognitive performance is not concerned with memory processes. The general view here is that in comparison to a resting period, task demands tend to attenuate or desynchronize the alpha band rhythms and increase their frequencies at the same time (Berger 1929 and Martinson 1939). There are important exceptions to this role, however, depending e.g., on the recording site and the type of task. But as the results of early studies (e.g., Adrian and Matthews 1934) have already indicated, alpha band activity is selectively suppressed in that hemisphere which is dominant for a particular type of task (also Donchin, Kutas and McCarty 1977; Kinsbourne and Hiscock 1983). More recently, Pfurtscheller and his coworkers have repeatedly demonstrated that event-related desynchronization of alpha band activity can be used as an indicator of localized brain activation (Pfurtscheller and Klimesch 1991) in a variety of different perceptual and motor tasks. Special cognitive tasks such as reading, classification and recognition as well as attentional demands tend to reduce the power within the alpha band (Klimesch et al. 1990a).

As compared to the abundance of experiments dealing with alpha power measurements, relatively few studies focused on task related shifts in alpha frequency. Those studies adopting this measure indicate that mental tasks (Knott 1938; Hadley 1941) and task difficulty in particular lead to an increase in alpha frequency (Osaka 1981, 1984). The results of Osaka (1984) showed further that only for difficult but not for easy tasks, alpha frequency increases selectively in that hemisphere which is dominant for a particular task. A localized increase in alpha frequency was also reported as a response of visual and auditory stimulation (Pfurtscheller, Maresch and Schuy 1977). Clinical results also are in support with the view that cognitive performance may be related to alpha frequency. There is evidence that alpha frequency decreases with age (e.g., Köpruner 1984; Saletu and Grünberger 1985) and is lower in demented subjects as compared to age matched normals (e.g., Coben, Danzinger and Storandt 1985). These results are also in good agreement

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with the observation that interhemispheric frequency differences of more than 0.2 Hz are usually associated with a pathological process in one hemisphere. As an example, after an ischemic attack of one hemisphere the frequency in the affected side is lowered.

The level of attention and alertness also seems to be related to alpha frequency. Arguments against this view come from an interesting study of Treisman (1984) who has shown that fluctuations in alpha frequency are too small to account for fluctuations in attention. However, when interpreting shifts in alpha frequency with respect to shifts in cognitive and/or attentional demands, care must be taken not to assume a simple linear relation. Studies focusing on power related frequency shifts demonstrate a rather complex relationship between alpha amplitude and frequency (Kawabata 1972). Earle (1988) has shown that under certain circumstances alpha frequency becomes even slower when task difficulty is increased.

Despite the variety of studies using alpha band activity as an indicator of cognitive performance and despite the evidence outlined earlier, no consistent reports on a relationship between alpha band activity and memory can be found in the literature (cf. Bauer 1976; Andersen and Andersson 1968; Saletu and Grünberger 1985). However, clear evidence for a positive relationship between memory performance and mean alpha (center) frequency was reported by Klimesch et al. (1990b). The results of this study have shown that alpha frequency varies as a function of memory performance.

As interesting as this relationship between alpha frequency and memory performance is, the question arises whether an increased alpha frequency does not simply reflect a higher level of attention and/or arousal and that as a consequence of this, memory performance is better as well. One way of testing whether alpha frequency varies as a function of memory performance or unspecific task demands (such as attention, and cognitive load) is to vary both variables in one and the same task. This was done in the present experiment which is a modified version of Schneider's and Shiffrin's memory search paradigm (Schneider and Shiffrin 1977). In each trial subjects view a string of 5 or 10 numbers and letters (termed "memory set") which they are asked to retain in memory. Then, several seconds later a single letter or number appears (termed frame). If the frame is a member of the memory set, it is called a target, otherwise a distractor. Subjects are asked to respond with "yes" to a target and with "no" to a distractor. Attentional demands are varied by using either the same memory set across a series of trials (termed consistent mapping condition) or different memory sets with different characters (termed varied mapping condition). Under the consistent mapping condition, subjects know which characters the memory set on the next trial will contain. Under the varied mapping condition, on the other hand, each memory set contains new characters. Thus, when deciding whether a frame is a target or distractor, subjects must be careful not to confuse characters between the current and the previously shown memory set. According to Shiffrin and Schneider, selective (or focused) attention refers to those control mechanisms which allows a subject to encode a sensory input into short-term memory. The concept of selective attention is closely linked to that of limited capacity. If processing capacity is overloaded, attention becomes divided and performance is reduced. As an example, if the memory set comprises only a single character, attention is "focused" on the target. But with increasing memory set size, attention also becomes increasingly "divided" and processing capacity overloaded.

Schneider and Shiffrin's design allows us to vary attentional demands (as manipulated by the two mapping conditions) and task difficulty (as manipulated by memory set size) in an orthogonal design and to use selected groups of good and bad memory performers as subjects. If we proceed from the hypothesis that the higher alpha frequency of good memory performers is primarily due to a superior attention performance rather than better memory performance per se, we would expect alpha frequency to vary primarily with attentional demands and/or task difficulty. On the other hand, if we adopt the hypothesis that alpha frequency reflects memory performance, we must assume that the manipulation of attentional demands and/or task difficulty does not blur or abolish the frequency difference between good and bad memory performers.

Finally, let us consider some methodological issues which refer to the measurement of alpha frequency. It is well known that alpha frequencies vary over the scalp, and that central mu rhythms have a frequency which is somewhat lower than occipital alpha rhythms. Different types of tasks (e.g., sensory and cognitive tasks) will also have a differential effect on alpha frequencies at various recording sites. Consequently, in the experiment reported below, frequency shifts (as well as amplitude shifts) are calculated separately for different recording sites.

Peak frequency and center of gravity frequency are the most commonly used measures to calculate alpha frequency. However, these two measures focus on different aspects of rhythmic alpha band activity. Peak frequency reflects only that frequency which has the highest power value, but ignores other aspects such as the shape of the alpha peak. Center of gravity frequency, on the other hand, is sensitive to the entire shape of the alpha peak and reflects the central tendency of alpha power within a selected frequency window f1 - f2 (f1 being the lower and f2 the upper frequency limit). Thus, as compared to peak frequency, gravity frequency may be considerd a more global measure.

When choosing between the two measures, it is important to consider the type of mental activity which should be studied. If alpha frequency is studied during a resting period, a pronounced alpha peak can be expected and peak frequency would be an appropriate measure to reflect alpha activity. If, however, alpha frequency is to be calculated during a period in which subjects perform a difficult mental task, alpha power will drop drastically and as a consequence, no or only a rudimentary broad "peak" will be observed. It is obvious that under these conditions, the calculation of peak frequency would be inappropriate. The calculation of gravity frequency, on the other hand, offers a reasonable alternative. Because the memory search paradigm used in the present study imposes considerable cognitive load, gravity frequency was selected in order to calculate alpha frequency. Inspection of the power diagrams also have shown that during the test interval, no clearcut alpha peak could be detected in most of the cases.

The accuracy of frequency estimates improves with the length of the test interval. Consequently, it would be desirable to use long test intervals of several seconds. However, as is well known from the literature dealing with reaction times and event related brain potentials, cognitive processes (such as the classification and recognition of complex stimuli) are very fast, lasting not much longer than several hundred milliseconds only. On this basis, it would not make much sense to use long intervals of several seconds when calculating task dependent shifts in alpha frequency. Thus, even at the risk of getting only approximate frequency estimates, we use test intervals of 1 second, allowing gravity frequency resolution of only 1 Hz. In an attempt to compensate for this low resolution, individual frequency estimates were averaged over a large number of trials and over several leads.

Methods

Subjects

Subjects were 16 right-handed graduate students (12 males and 4 females) who participated voluntarily in the experiment reported below. Their mean age was 27.6 years. Handedness was controlled by a questionnaire with 10 questions about hand preference in different tasks such as handwriting, tooth brushing, throwing a ball, etc. A subject was considered right-handed if he/she indicated the right hand for all of these different tasks. Furthermore, only subjects with a clearly detectable alpha peak were selected.

Stimuli and Experimental Design

The experimental design consisted of a modified version of Schneider and Shiffrin's (1977) memory search paradigm. In contrast to their original paradigm, frame set size was kept constant and consisted of only one character (letter or number). Memory set size was either 5 or 10 (abbreviated M5 or M10 respectively).

A set of 15 characters (the numbers 1, 2, ... 8 and the consonants B, C, F, H, K, L, R) was used to construct a total of 240 memory sets which were subdivided into 4 groups with 60 memory sets each. The 4 groups originated from the orthogonal combination of two factors, which were "mapping condition" (varied and consistent mapping, abbreviated VM and CM) and "memory set size" (M5 and M10). In the varied mapping condition each character of each memory set was randomly drawn from the above described set of 15 characters. However, the following two sampling restrictions were used. First, in each subgroup each character had to occur with equal frequency (hence the use of 15 characters). Second, half of the characters in each memory set had to be numbers, the other half letters (In the M5 condition half of the 60 memory sets had 3 numbers und 2 letters, whereas the other half had 2 numbers and 3 letters). In the consistent mapping condition, 6 blocks with 10 memory sets were used. Within a single block, the characters and their ordering remained identical for 10 subsequent trials. Between the blocks, the characters varied. They were selected according to the same principles as in the VM condition.

With the exception of the following restrictions, the frames were randomly drawn from the same set of 15 characters from which the memory sets were constructed. First, within each of the 4 subgroups, each frame had to occur with equal frequency. Second, half of the frames in each subgroup required a yes response (i.e., was contained in the memory set), the other half required a no response (i.e., was not contained in the memory set). Third, the set of frames (but not their order) was identical for all of the four subgroups.

Each trial started with the presentation of the memory set. The characters of the memory set were presented as a string of letters and numbers which appeared for 2000 msec in the middle of a computer-controlled video terminal. After an interval of another 2000 msec, the frame (target or distractor) appeared an the screen for 250 msec. A warning signal, appearing 1750 msec after the offset of the frame, reminded the subject to respond. The time between the onset of the warning signal and the onset of the memory set of the following trial was 5000 msec.

Subjects were instructed to respond verbally with "yes" if the letter or number of the frame was contained in the memory set and with "no" if it was not contained in the memory set. In an attempt to avoid muscle artefacts, subjects were asked to wait with their response until the warning signal appeared.

Each subject was tested under all of the four experimental conditions. Presentation sequence was counterbalanced between subjects in such a way that in the entire sample of 16 subjects, each of the four conditions appeared with equal frequency in each of the four experimental sessions. Let us denote the four conditions with "A", "B", "C" and "D". Presentation sequences then were: A, B, C, D; B, A, D, C; C, D, A, B and D, C, B, A.

Each of the four experimental session was preceded by a practice session of 10 trials. Memory sets and frames were constructed in the same way as described for the experimental conditions, but none of the memory sets of the training session was identical with any of the 240 memory sets of the experimental session. The data of the training session were not used for data analysis.

The character strings of the memory set and the characters of the frames appeared at the centre of the screen of a computer controlled video terminal. Characters (words or numbers) were 3 cm in height. The length of a 10 character-string was 23 cm. Subjects sat at a distance of 1.4 m from the video terminal.

Test Performance

All of the subjects had to perform all 6 subtests of the Lern and Gedächtnis Test-3 (LGT-3) as well as 4 subtests (logical thinking, memory span, visual memory and associative memory) of the Wechsler Memory Scale.

Apparatus, Acquisition and Processing of EEG-data

A modified "electro cap" with 29 scalp electrodes was used to record the EEG. Seventeen of these electrodes were placed according to the International Electrode (10-20) Placement-system, at F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1 and O2. From the remaining twelve electrodes, 4 electrodes were placed over parieto-occipital areas (PO3, PO1, PO2, PO4), 4 electrodes were placed over centro-parietal areas (CP5, CP1, CP2, CP6), and 4 electrodes were placed over fronto-central areas (FC5, FC1, FC2, FC6). All data were recorded monopolarly against linked ears. Before they were converted to a digital format via a 32-channel A/D converter, EEG-signals were amplified by a 32-channel biosignal amplifier system (frequency response: 1.5 to 30 Hz) and then subjected to an anti-aliasing filterbank (cut-off frequency: 30 Hz, 120 dB/octave). Sampling rate was 64 Hz. The data were processed by a PDP 11/73 computer system.

The length of a single trial was 11 sec. At the beginning of the 2nd second, the memory set and at the beginning of the 6th second, the frame set was presented. The warning signal (inviting the subject to respond) appeared at the beginning of the 8th second. EEG was sampled only during the first 8 seconds of each trial.

After the experimental sessions and a pause of 5 minutes, subjects were asked to relax with eyes closed for a resting period of 2 minutes. During this resting period the EEG was recorded and segmented into 30 epochs of 4 seconds.

EEG was displayed online on a high resolution color monitor and stored on disk. All of the 4 x 60 experimental epochs (as well as the 30 resting epochs) were checked individually for artefacts (eye blinks, muscle artefacts etc.). After excluding epochs containing artefacts as well es erroneous epochs (in which subjects responded "yes" to negative trials requiring a "no" response and vice versa), an average of 36 epochs remained for data analysis in each of the four experimental conditions.

EEG-data were subjected to frequency and to amplitude analyses. For both types of analyses the following two periods each with a length of 1000 ms were selected. The first period, termed "memory period", immediately followed the presentation of the memory set, whereas the second period, termed "retrieval period", immediately followed the presentation of the frame set. Furthermore, the first 1000 ms of each epoch were used as a reference period. For the amplitude analysis, an interval of 800 ms immediately preceding the presentation of the memory set was used as reference interval.

Frequency Analysis

The procedure to determine the individual mean frequency by calculating the centre of gravity within the (extended) alpha band - termed simply "individual alpha mean frequency" or "IAF" in the following - was already used in an earlier study (Klimesch et al. 1990). In a first step, Fast Fourier Transformation was applied to each of the selected epochs. Then, the spectra were averaged over all of the selected epochs in order to improve the accuracy of spectral estimates. Finally, the IAF was calculated individually for each subject according to the formula: IAF = (Sum (a(f) x f))/(Sum a(f)). Power spectral estimates at frequency f are denoted a(f) and the index of summation is in the range of f1 to f2.

The frequency window f1 - f2 was determined individually for each subject. By using the data of the resting period, the power spectra for each subject and each of the 29 electrodes were calculated within the total frequency range of 1.5 - 30Hz. Then, by visual inspection, the bandwith of the alpha peak was determined for each lead i and each subject j: f1(i,j) marks the beginning of the "ascent" and f2(i,j) the end of the "descent" of the alpha peak for electrode i and subject j. This was done for all of those electrodes, showing a clearly detectible alpha peak. According to this procedure, an average of 19.3

electrodes could be used in calculating f1(j) and f2(j). Averaging the selected values f1(i,j) and f2(i,j) over the electrodes gives the window f1(j) - f2(j) for calculating IAF in the experimental epochs. Note that according to this procedure the values f1(j) and f2(j) vary between subjects. Averaged over the sample of 16 subjects, f1 was 6.0 Hz and f2 was 14.44 Hz. Thus, the term "extended alpha band" instead of "alpha band" is more appropriate to denote the frequency range from 6 - 14 Hz.

Amplitude Analysis

The amplitude analysis is based on the measurement of "event-related desynchronization" or "ERD" in the specified frequency band. The quantification of the ERD was introduced by Pfurtscheller and Aranibar (1977) and Pfurtscheller et al. (1988). According to this procedure, ERD is the percentage band power decrease (or increase) in a test interval (here the memory or retrieval period) as compared to the reference interval (here: the interval 200ms to 1000ms after the beginning of an epoch). It is calculated according to the following formula: ERD = (((band power, reference interval) - (band power, test interval))/(band power, reference interval))*100.

The method of processing single epochs was described in detail elsewhere (Pfurtscheller et al. 1988) but will be outlined briefly below. The data for each epoch and each of the 29 channels were digitally band-pass filtered, squared and averaged over trials within each of the 4 experimental conditions. Then, based on the averaged data, power values were calculated for the reference interval, the memory period and the retrieval period. Finally, the ERD-values were calculated for each of the 29 electrodes.

It is important to emphasize that the alpha band was determined individually for each subject and within the same range f1 - f2 as this was done for the frequency analysis. Because the results of earlier performed studies (Klimesch et al. 1988; Klimesch et al. 1990) have shown that the lower and the upper alpha band reflect different cognitive processes, two different (extended) alpha bands were used in this study. Furthermore, in order to get compatible results with the frequency analysis, the same frequency range was used for the amplitude analysis. Thus, for each subject the lower band is defined between f1 and (f1 + f2)/2, whereas the upper band is defined between (f1 + f2)/2 and f2.

Statistical Analyses

The frequency and ERD-data were subjected to several different ANOVA (analyses of variance). ANOVA-rest, ANOVA-t1, -t2 and -t3 use IAF, measured in the resting period (ANOVA-rest), and during different time intervals (t1, t2 and t3) of the experimental epochs: the reference interval (ANOVA-t1) the encoding interval (ANOVA-t2) and the retrieval interval (ANOVA-t3). ANOVA-E uses ERD-values. The factorial design comprises several treatment factors and one grouping factor.

All of the treatment factors are repeated measures factors. Factors of this type having three or more levels carry an additional assumption known as sphericity or circularity. Violation of this assumption results in positively biased tests (cf. Games 1976; Vasey and Thayer 1987). In order to compensate for this effect, the Greenhouse-Geisser procedure for adjusted degrees of freedom is used. For repeated measures factors with more than two levels, the adjusted tail probabilities p′ will be reported together with the respective F-values.

The treatment factors and their levels are: mapping condition (CONVAR), consistent versus varied mapping; number of items to remember (NITEM), 5 versus 10 items; hemisphere (HEMI), left and right side of the scalp; localization (LOC), frontal (f), central (c), parietal (p), temporal (t) and occipital (o) recording sites; the frequency band (FREQ), upper and lower band and different time intervals (TIME), t2, t3. Factor FREQ and TIME is used only for ANOVA-E which is based on ERD data.

The grouping factor (MEMORY) refers to the distinction between subjects with good (M+) and those with bad memory (M-). The mean summary score of the LGT-3 was used to cut the sample of 16 subjects into two halves. The first half, denoted M- (bad memory) contains those subjects falling below the mean score of the sample, whereas the other half, denoted M+ (good memory) contains the remaining subjects falling above the mean score. Grouping factor MEMORY with the two levels M+ and M- remains identical for all of the different ANOVA reported below.

Results

ANOVA-rest comprises grouping factor MEMORY and the treatment factors HEMI and LOC. Significant effects were found for LOC ($F(4,56) = 18.76$; $p' < 0.001$), as well as the interactions MEMORY X LOC ($F(4,56) = 4.46$; $p' < 0.017$) and HEMI X LOC ($F(4,56) = 3.81$; $p' < 0.028$). The results are summarized in figure 1 and 2 and show that the difference in IAF between good and bad performers is more pronounced at anterior as compared to posterior recording sites and that there is a tendency for a left hemispheric superiority at frontal and occipital leads (cf. figure 2).

ANOVA-t1 consists of grouping factor MEMORY and the treatment factors HEMI, LOC, CONVAR and NITEM. A significant main effect was found for LOC ($F(4,56) = 8.97$; $p' < 0.001$). Inspection of the respective means shows that as compared to anterior recording sites, posterior leads exhibit IAF's which are about 0.4 Hz

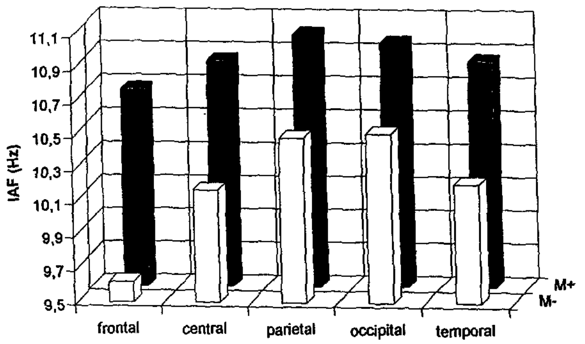

Figure 1. IAF, resting period: Interaction between factor MEMORY and LOCATION.

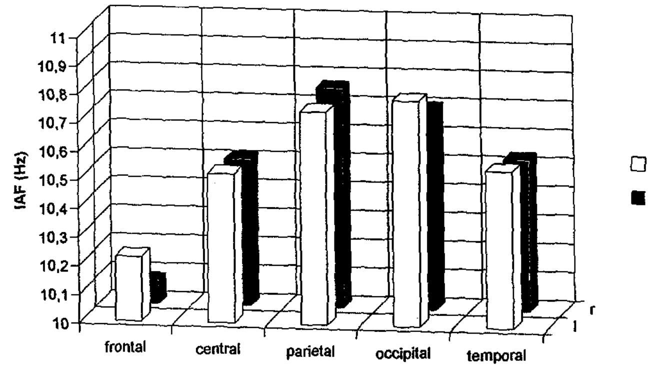

Figure 2. IAF, resting period: Interaction between factor HEMI and LOCATION.

higher. Out of the 25 interactions only HEMI X LOC ($F(4,56) = 5.52$; $p' < 0.004$) and NITEM X HEMI ($F(1,14) = 10.72$; $p < 0.006$) reached significance. Inspecting the respective means for interaction NITEM X HEMI reveals a left hemispheric superiority for M = 5 items but not for M = 10 Items. Interaction HEMI X LOC is shown graphically in figure 3. Note that different scales are used for figures 2 and 3 and note that in the reference interval t1 (figure 3) IAF is much lower on the average than in the resting period (figure 2).

ANOVA-t2 comprises the same factors as ANOVA-t1. As for ANOVA-t1, factor LOC ($F(4,56) = 6.39$; $p' < 0.003$) shows a clearly significant effect, indicating an increase in IAF from frontal to central, temporal and parietal recording sites. However, in contrast to ANOVA-t1, occipital leads show a pronounced drop in IAF (figure 4 in contrast to figures 2 and 3). Grouping factor MEMORY is only marginally significant ($F(1,14) = 4.00$; $p < 0.065$). As the respective means indicate, the IAF of good performers is higher than that of bad performers. The only significant interaction is HEMI X LOC ($F(4,56) = 4.02$; $p' < 0.01$) which is shown in figure 4. Comparing the data of figure 4 with those of figures 2 and 3 shows that the weak left hemispheric superiority (figure 2 and 3) gives way to a weak right hemispheric superiority.

ANOVA-t3 comprises also the same factors as ANOVA-t1 and ANOVA-t2. Most interestingly - and in contrast to the resting period, the reference interval (t1) and the encoding interval (t2), - only in the retrieval interval (t3) factor MEMORY ($F(1,14) = 5.13$; $p < 0.039$) exceeded the 5%-level of significance. Comparing the respective means for good (M+) and bad performers (M-) in the different intervals (resting period: M+ = 10.88, M- = 10.21, diff = 0.67; reference interval t1: M+ = 10.67, M- = 9.78, diff = 0.89; encoding interval t2: M+ = 10.74, M- = 9.69, diff = 1.05; retrieval interval t3: M+ = 10.77, M- = 9.52, diff = 1.25) reveals two interesting effects (cf. figure 5). First, the difference between good and bad performers reaches a maximum when subjects are retrieving information from memory. Here, this difference is about twice as big as compared to the resting period. Second, the drop in IAF from the resting period to t1, t2 and t3 is negligibly small for good performers but pronounced for bad performers.

Besides factor MEMORY, ANOVA-t3 shows two other significant main effects, one for NITEM ($F(1,14) = 4.94$; $p < 0.043$), the other for LOC ($F(4,56) = 7.04$; $p' < 0.002$). Inspecting the respective means for NITEM indi-

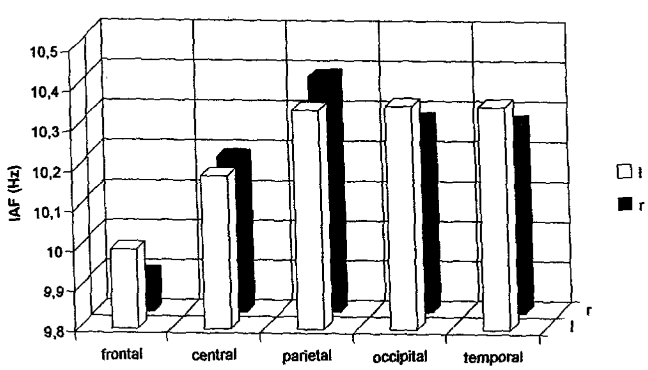

Figure 3. IAF, reference interval (t1): Interaction between factor HEMISPHERE and LOCATION.

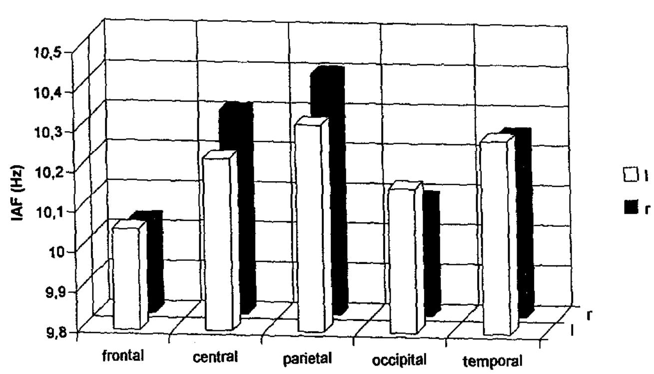

Figure 4. IAF, encoding interval (t2): Interaction between factor HEMISPHERE and LOCATION.

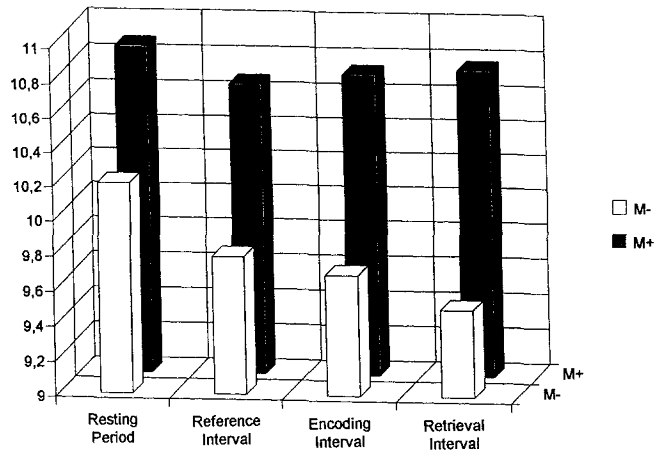

Figure 5. The differences in IAF between good and bad memory performers.

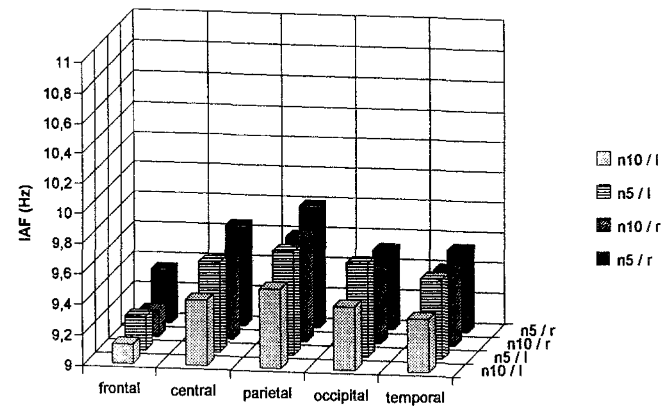

Figure 6. IAF, retrieval interval (t3): Interaction between the factors CONVAR, NITEM, HEMISPHERE, LOCATION and MEMORY; displayed for bad memory performers (M-) under the varied mapping condition (var).

cates that frequency decreases with increasing memory load. The significance of factor LOC is due to an increase in IAF from frontal, central, temporal to parietal leads. As was found for the encoding interval, the IAF shows a drop at occipital leads.

The significant higher order interactions CONVAR X NITEM X LOC (F(4,56) = 3.83; p' < 0.02), NITEM X HEMI X LOC (F(4,56) = 3.60; p' < 0.02) and CONVAR X NITEM X HEMI X LOC (F(4,56) = 6.02; p' < 0.00) form part of the complex 5-factorial interaction CONVAR X NITEM X HEMI X LOC X MEMORY (F(4,56) = 3.19; p' < 0.04). We thus focus on the explanation of this complex interaction which is depicted in figures 6, 7, 8 and 9.

Because of the complexity of the interaction, we focus only on the following three basic results, which are of primary interest for our hypotheses. First, memory load leads to a consistent drop in IAF at all recording sites and in both hemispheres (the first and second row of bars reflecting the results of the left hemisphere and the third and fourth row, reflecting the right hemisphere). Second, this effect holds true for good and bad performers (compare figure 6 with figure 7 and figure 8 with figure 9) as well as for both levels of attentional load (compare figure 6 with figure 8 and figure 7 with figure 9). Third, primarily at parietal sites, the left hemisphere of bad performers (compare the bars in the first and second row with the third and fourth row in figure 6 and 8) - but not the left hemisphere of good performers (compare the respective bars in figure 7 and 9) - shows a reduced IAF.

ANOVA-E uses ERD- instead of frequency-values. Because t1 serves as reference interval for the calculation of ERD, only two intervals, the encoding (t2) and the retrieval interval (t3) remain for statistical analyses. ANOVA-E comprises 7 factors, the grouping factor MEMORY and the 6 treatment factors, HEMI, LOC, CONVAR, NITEM, FREQ and TIME. Out of the 7 main

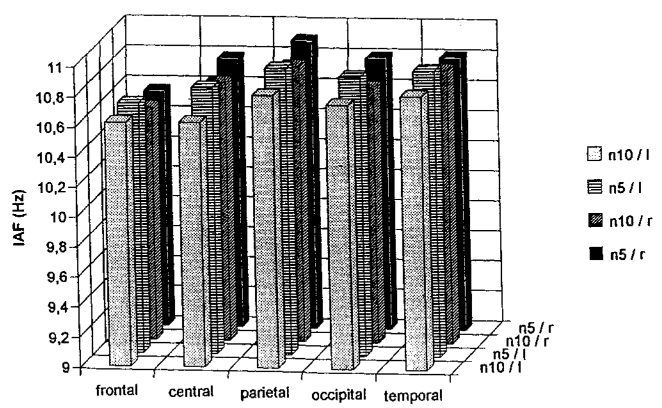

Figure 7. IAF, retrieval interval (t3): Interaction between the factors CONVAR, NITEM, HEMISPHERE, LOCATION and MEMORY; displayed for good memory performers (M+) under the varied mapping condition (var).

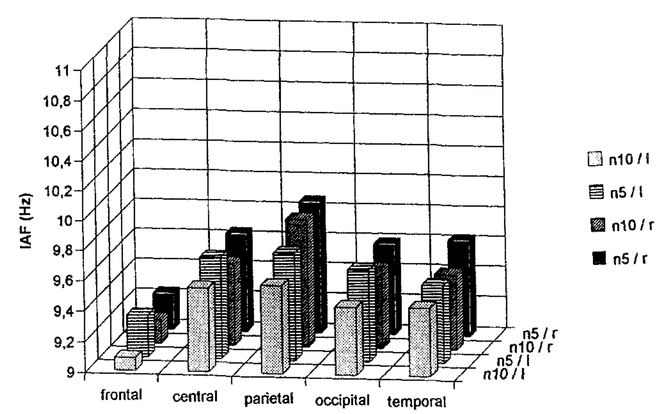

Figure 8. IAF, retrieval interval (t3): Interaction between the factors CONVAR, NITEM, HEMISPHERE, LOCATION and MEMORY; displayed for bad memory performers (M-) under the consistent mapping condition (con).

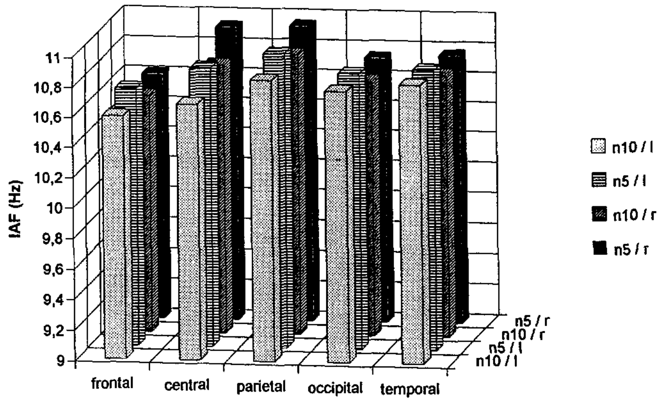

Figure 9. IAF, retrieval interval (t3): Interaction between the factors CONVAR, NITEM, HEMISPHERE, LOCATION and MEMORY; displayed for good memory performers (M+) under the consistent mapping condition (con).

effects only the following two exceeded the 5%-level of significance, HEMI (F(1,14) = 4.69; p < 0.048) and LOC (F(4,56) = 3.5; p' < 0.039). Inspection of the means reveals a left hemisphere advantage (higher ERD-values over the left side of the scalp) and a tendency for larger ERD-values at posterior as compared to anterior recording sites.

A total of eight significant higher order interactions point to a complex pattern of results. When relying on conventional graphic representations we would have to use between 10 - 16 figures in order to interpret these results. In an attempt to make the interpretation of our results easier, we will rely on maps (depicted in figure 10). Because maps provide a simple means of interpretation we have included the entire epoch in figure 10 (excluding the reference interval). The two intervals t2 and t3 are represented by columns 1 and 5. Each map represents an interval of 1000 msec. Hot colors indicate positive ERD-values (i.e., a decrease in band power as compared to the reference interval), whereas cool colors indicate negative ERD-values (i.e., an increase in band power as compared to the reference interval). We interpret recording sites showing positive ERD-values in terms of "activated" cortical regions.

There are two highly significant two factorial interactions TIME X LOC (F(4,56) = 13.44; p' < 0.001) and FREQ X LOC (F(4,56) = 11.37; p' < 0.001) which are included in the interactions FREQ X LOC X TIME (F(4,56) = 13.49; p' < 0.001) and NITEM X FREQ X LOC X TIME (F(4,56) = 3.79; p' < 0.034). Inspection of figure 10 reveals that factor LOC varies as a function of TIME and FREQ: the lower band shows a flat topographical distribution of

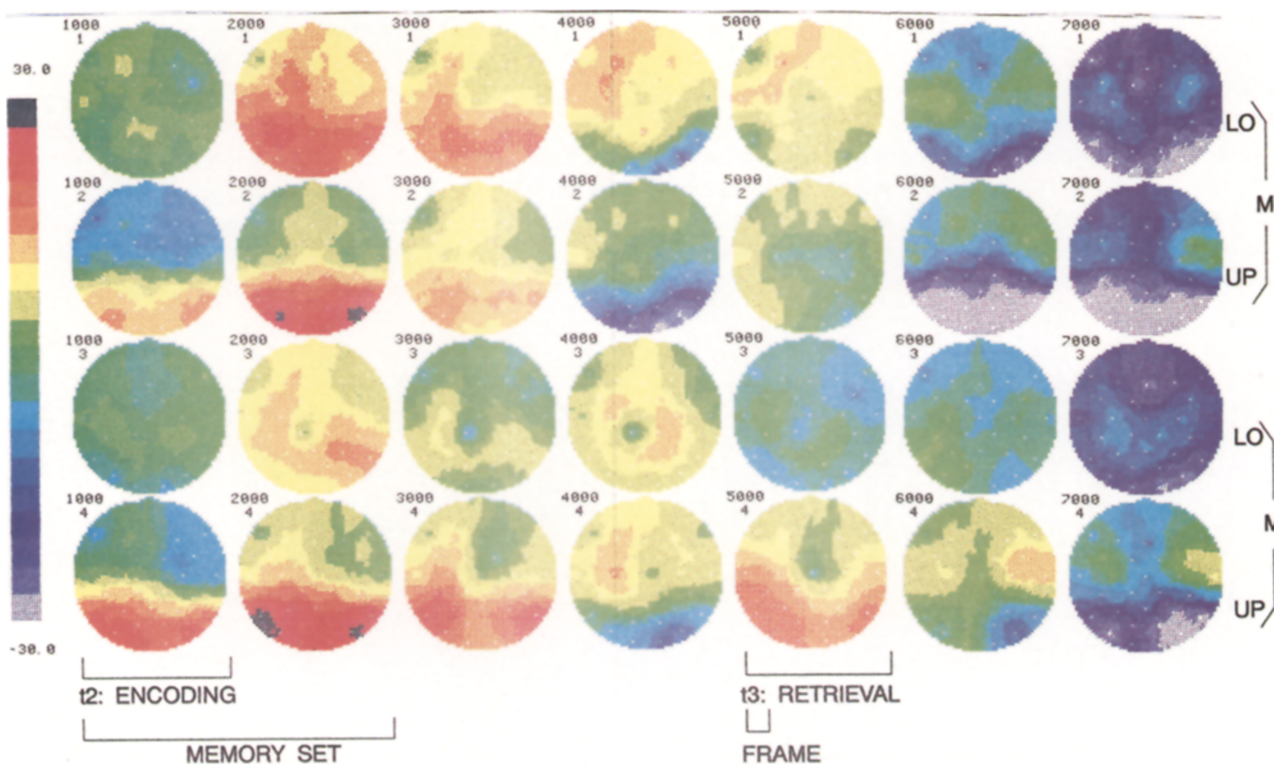

Figure 10. ERD-maps showing the percentage with which an alpha power decrease (hot colors) or increase (cool colors) occurs. First two rows: lower and upper alpha band, good memory performers. Second two rows: lower and upper alpha band, bad memory performers.

ERD during encoding (maps 1 and 3 in column 1) and retrieval (map 3 in column 5 but notice the left hemispheric activation at frontal sites in map 1). In contrast to the lower band, the upper band shows a completely different topographical pattern of activation which in both intervals, the encoding and retrieval interval, is restricted to posterior recording sites (maps 2 and 4 in column 1 and map 4 in column 5).

Factor NITEM in the 4-way interaction with FREQ, LOC and TIME reveals an interesting effect. Inspection of the respective means show that high memory load leads to a more pronounced ERD but only during retrieval and only in the upper band. The lower band shows a strikingly different pattern of results. Here, memory load does not differentiate during retrieval but instead during encoding and at posterior recording sites only. Furthermore, in contrast to the upper band, high memory load during encoding is associated with a decrease in ERD whereas the opposite is true for low memory load.

The marginally significant interaction HEMI X NITEM X TIME ($F(1,14) = 4{,}78$; $p < 0.046$) indicates a small tendency that the degree of a left hemispheric advantage varies as a function of memory load and time interval. Inspecting the respective means reveals that during encoding the left hemispheric advantage for low and high memory load is of comparable size. But during retrieval high memory load is associated with a left hemispheric advantage which is larger in size than that for low memory load. Factor NITEM is also involved in the interaction FREQ X NITEM X TIME ($F(1,14) = 8.32$; $p < 0.012$) which is embedded in the 4-way interaction with LOC and which replicates the findings we already have discussed above (excluding the effects of LOC).

With respect to our hypothesis of a relationship between alpha activity and memory performance the interactions MEMORY X FREQ X TIME ($F(1,14) = 6.43$; $p < 0.024$) and MEMORY X FREQ X NITEM X TIME ($F(1,14) = 8.01$; $p < 0.013$) are of importance. Comparison of maps 1 and 3 in columns 1 and 5 in figure 10 shows that good performers show larger ERD-values in the lower band during retrieval. However, the opposite result holds true for the upper band. Here bad performers show a more pronounced ERD than good performers. Inspection of the respective means for the complex interaction with NITEM documents that for good as well as for bad performers, ERD-values in the upper band increase with increasing memory load during retrieval. During encoding, good and bad performers differ. Whereas for good performers ERD-values increase as memory load increases, the converse is true for bad performers. Furthermore, as compared to the upper band, the lower band shows a completely differnt pattern of results. For good performers, lower band ERD's decrease with memory load, for bad performers, lower band ERD's increase with memory load. This latter effect holds true for encoding and retrieval as well.

Discussion

The results of the present study provide evidence for a close relationship between EEG-correlates of the (extended) alpha band and memory performance. The results of frequency analyses have shown that the IAF of good performers is generally higher than the IAF of age matched bad performers. As compared to a resting state, the IAF of good performers remains at a comparatively constant level when memory related task demands increase (figure 5). But for bad performers IAF decreases as memory related task demands increase. The largest difference between good and bad performers was found during retrieval, the second largest during encoding, the third largest during a reference interval and the smallest in a resting state with eyes closed. This result thus provides evidence for the hypothesis that IAF is more closely related to retrieval as compared to encoding and to the non-task specific demands of the resting state and the reference interval. Furthermore, the fact that memory load influences IAF only during retrieval but not during encoding (results of ANOVA-t2 and ANOVA-t3) is also in line with the suggestion that IAF plays a specific role for retrieval.

The specific role of IAF for memory performance and retrieval in particular is not questioned by the fact that IAF varies also as a function of attentional demands. This result simply shows that memory performance is not the only factor influencing IAF and that attentional demands are also capable of influencing IAF. It is important to note that no direct interaction was found between attentional demands (factor CONVAR) and memory load (factor NITEM). Both factors exert comparable effects: with increasing attentional demands and memory load IAF decreases. This effect is of comparable magnitude for good and bad performers (figures 6, 7, 8 and 9).

A decrease in IAF always seems to be related with bad performance. This not only holds true for the distinction between good and bad memory performers but also for increasing memory load and increasing attentional demands. The latter two factors lead to a capacity overload and hence to a decrease in IAF. In good agreement with these results, topographical differences in IAF indicate further that those regions of the brain which are involved in the performance of a task show a drop in IAF. As an example, let us consider figures 2, 3 and 4. As compared to the resting period (figure 2) and to the reference interval (figure 3), IAF drops in the left hemisphere at parietal and central regions (figure 4) when subjects are actually encoding letters and numbers, which is a typical left hemispheric task. Another example is the frequency drop at parietal recording sites of the left hemisphere which was found for bad performers (figures 6 and 8). In contrast to bad performers, good performers do not show hemispheric differences with respect to the frequency drop at parietal recording sites. These results might indicate that bad performers use only (or primarily) their left hemisphere, whereas good performers rely on both hemispheres when performing a memory task.

The results of the amplitude analysis also confirm that alpha activity correlates with memory performance. However, good and bad performers show opposite results in the lower and upper alpha band (the maps in columns 1 and 5 in figure 10). When trying to interpret this result we proceed from two different hypotheses. The first hypothesis refers to the assumption that the lower alpha band reflects attentional processes whereas the upper alpha band reflects stimulus related cognitive processes. This hypothesis was confirmed by the results of recently performed experiments (Klimesch et al. 1988, 1990). The second hypothesis refers to the more general idea that mental performance is based on attentional as well as cognitive processes. By attention we mean the control of information processing and by cognitive processes the ability to perform a particular type of task. As an example, let us consider the memory scanning task of our experiment. The way in which a subject controls the encoding and retrieval of different items reflects attentional processes. The ability to encode and retrieve reflects cognitive processes. Let us further assume that these two types of processes operate in an interactive way: the better attentional processes operate, the faster and easier the cognitive task can be performed.

Now, let us put the two hypotheses together and let us consider the results in figure 10. When comparing the lower alpha band for good and bad performers we see that the lower alpha ERD's (reflecting attentional processes) are generally much larger for good performers (1st row of maps) than for bad performers (3rd row of maps). This result might indicate that in contrast to bad performers, good performers are well capable of increasing their attention after the memory set is presented (the 1st and 2nd columns in the 1st and 3rd column in figure 10). During retrieval (5th column) good performers are still highly attentive, whereas this is not true for bad performers. Because of their superior attentional performance (reflected by large lower alpha ERD values), the retrieval task is easy (reflected by small upper alpha ERD values) for good performers. For bad performers their inferior attentional performance (reflected by small lower alpha ERD values) makes the retrieval task difficult (reflected by large upper alpha ERD values).

The large difference between the lower and upper alpha band, found in this as well as in an earlier performed experiment (Klimesch et al. 1990a), most likely is the reason why other studies have failed to find a relationship between alpha correlates and memory performance. To our knowledge, the only other study, which also has found a positive relationship between alpha frequency and memory performance is Saletu and Grünberger (1985). Although they emphasize that this relationship was confounded with the level of vigilance which was higher for good than for bad performers, we believe that their results are due to the following two facts. First of all, they also have distinguished between an upper and lower alpha band. Second, their large sample of age matched subjects may well have helped to reduce interindividual differences in alpha frequency.

We are aware that the interpretation of the upper and lower alpha band which we have suggested above is still rather speculative. Further experiments are needed to test the hypotheses proposed here. But whatever the correct interpretation, the striking difference between the lower and upper band provides a challenging fact.

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