

# Multichannel EEG power reflects information processing and attentional demands during visual orienting

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**Abstract** The effects of stimulus complexity and instructions on the EEG orienting response were studied. Temporal and topographical EEG spectral changes from O1, O2, P3, P4, F3, F4, Fz, and Cz were recorded during orienting to, and appraisal of, visual stimuli of varying complexity. Only half the sample of 40 subjects was instructed to attend to the stimuli. Higher stimulus complexity reduced EEG power within  $\beta$ , mid and high  $\alpha$  rhythms, whereas the low  $\alpha$  range was most sensitive to the interaction between stimulus complexity and instructions. Temporal changes in power suggested that the effect of stimulus complexity may be due to late appraisal rather than to early orienting. No single EEG index differentiated between groups. However, when factor scores of relative  $\alpha$ ,  $\beta$ , and  $\theta$  power were subjected to discriminant analysis, clear differences appeared between groups. Active-attention during visual orienting was associated with  $\alpha$  blockade and  $\theta$  enhancement in posterior leads, which might reflect two different mechanisms of orienting. Finally, EEG power changes during stimulus exposure predicted performance in a subsequent recognition task. It is argued that the analysis of short-lasting EEG power changes can offer valuable information about the mechanisms of visual orienting, and that a multivariate approach is required in EEG research on attention.

## Introduction

Orienting Response (OR) theory has provided a rich conceptual and empirical background for the understanding of elementary neural mechanisms of attention (Sokolov, 1963), and the EEG has been linked to orienting phenomena from the outset (Berlyne, 1960). Surprisingly, though, there has been little systematic use of EEG power measures in modern OR research. The OR literature predicts longer-lasting and larger EEG  $\alpha$  and  $\beta$  blocking in response to more complex stimuli, since their neural model would take longer to form than that of simple stimuli. Several laboratories have obtained data to support this claim using a simple OR visual task (Berlyne & McDonnell, 1965; Gale, Christie, & Penfold, 1971; Gale, Spratt, Christie, & Smallbone, 1975).

However, a number of methodological deficiencies have brought into question both the nature of the reported EEG responses to stim-

ulus complexity and the capacity of EEG power to index attention (Becker & Shapiro, 1980; Christie, Delafield, Lucas, Winwood, & Gale, 1972). Two of those deficiencies will be dealt with here:

- 1) Previous EEG studies collapsed EEG data over 30 or more seconds to yield one single average score for each condition of complexity (e.g., Gale et al., 1975). Although results from these studies have been accounted for in terms of orienting (Spinks & Siddle, 1983), such gross EEG averages are likely to have confounded EEG responding to initial involuntary orienting with that elicited by later voluntary forms of processing (Kahneman, 1973; Maltzman, 1979). We have tested this hypothesis by comparing EEG responses to stimulus complexity across a temporal factor (epochs). If complexity effects take place during the first 3 to 6 seconds of visual stimulation, then they could be attributed to early orientation.

Otherwise EEG effects would be better described in terms of later voluntary forms of processing.

- 2) There is little evidence on the differential effects of signal and nonsignal orienting upon EEG power, and those who have compared active and passive attention groups have typically obtained negative results (Becker & Shapiro, 1980; Berlyne & McDonnell, 1965). These failures were attributed to early hand-scoring methods, the use of coarse EEG measures, or the lack of sensitivity of EEG power indexes. However, in contrast with results from group designs, recent data have shown that  $\alpha$  power is a sensitive index of intra-task variations in attentional demands (e.g., Bösel, Mecklinger, & Stolpe, 1990; Klimesch, Pfurtscheller, & Schimke, 1992). These authors found that various sub- $\alpha$  bands respond differently to task-related cognitive processing. Also, the lack of attentional effects might have been caused by a too narrow sampling of brain topography. Thus, if attention is best understood in terms of distributed and parallel processing from multifocal neural systems (Gevins et al., 1985), the use of just one single EEG index and/or location seems a rather inadequate approximation to its nature. To explore this hypothesis several EEG bandwidths were obtained from eight head sites and submitted to principal components and discriminant analyses in an attempt to describe more efficiently the distinctive pattern of overall EEG activation of instructed and non-instructed groups.

From an OR perspective, the examination of the effects of task demands (e.g., signal value) and stimulus complexity combined upon the EEG-OR has an intrinsic theoretical value, and a number of predictions about topographical brain distribution of EEG spectral changes may be derived. Thus, the local and generalized ORs can be distinguished on the basis of the scalp distribution of  $\alpha$  blocking (Barry, 1984), and signal EEG-ORs have been associated with frontal activation (Luria & Homskaya, 1970). Right frontal and parietal cortices are known to play an important role in attentive behavior (Posner & Petersen, 1990). Of interest also is the simultaneous response of various EEG rhythms to stimulus and task pa-

rameters. Prior studies have often found enhancements in  $\theta$  rhythm accompanying occipital  $\alpha$  blockade in arousing conditions (e.g., Gale et al., 1975; Lindsley, 1982), and  $\theta$  has been linked to processes of focused attention and signal detection (Basar-Eroglu, Basar, Demiralp, & Schürmann, 1992).

Finally, this study also examined the functional value of EEG power activation during visual orienting. Following previous positive results in our laboratory (Gale et al., 1975), an index of EEG differential activation during visual orienting was used to predict performance in a subsequent recognition task. This was designed to add an operational definition of attention based on performance measures as well as physiological indices. Differential relationships between EEG and performance can provide information on the significance of particular EEG changes. Performance measures also offer an external validation of subject compliance with instructions.

In summary, two dimensions of stimulus complexity (*number* and *variety*) were manipulated together with the instructions to attend to the stimuli in an attempt to shed light on the nature of the reported EEG-ORs to stimulus complexity and the capacity of EEG power to index attention. The EEG-complexity hypothesis was tested independently at each of eight head locations to allow a direct comparison with the univariate approach of previous studies. The EEG-attention hypothesis was also tested at each electrode independently, and then a higher order multivariate approach was adopted to try and separate out the instructed and non-instructed groups in terms of the principal component structure of their overall EEG activation. A post-task recognition test also enabled us to examine the relationships between instruction, EEG activation, and performance.

## Method

### Subjects

Forty-four students took part in the study (22 males), aged 18–30 years (mean: 20.5, S. D.: 2.8 years). All subjects were right-handed and had normal or corrected to normal vision. Participants received an allowance of £3 for their collaboration. Because of excessive EEG ar-

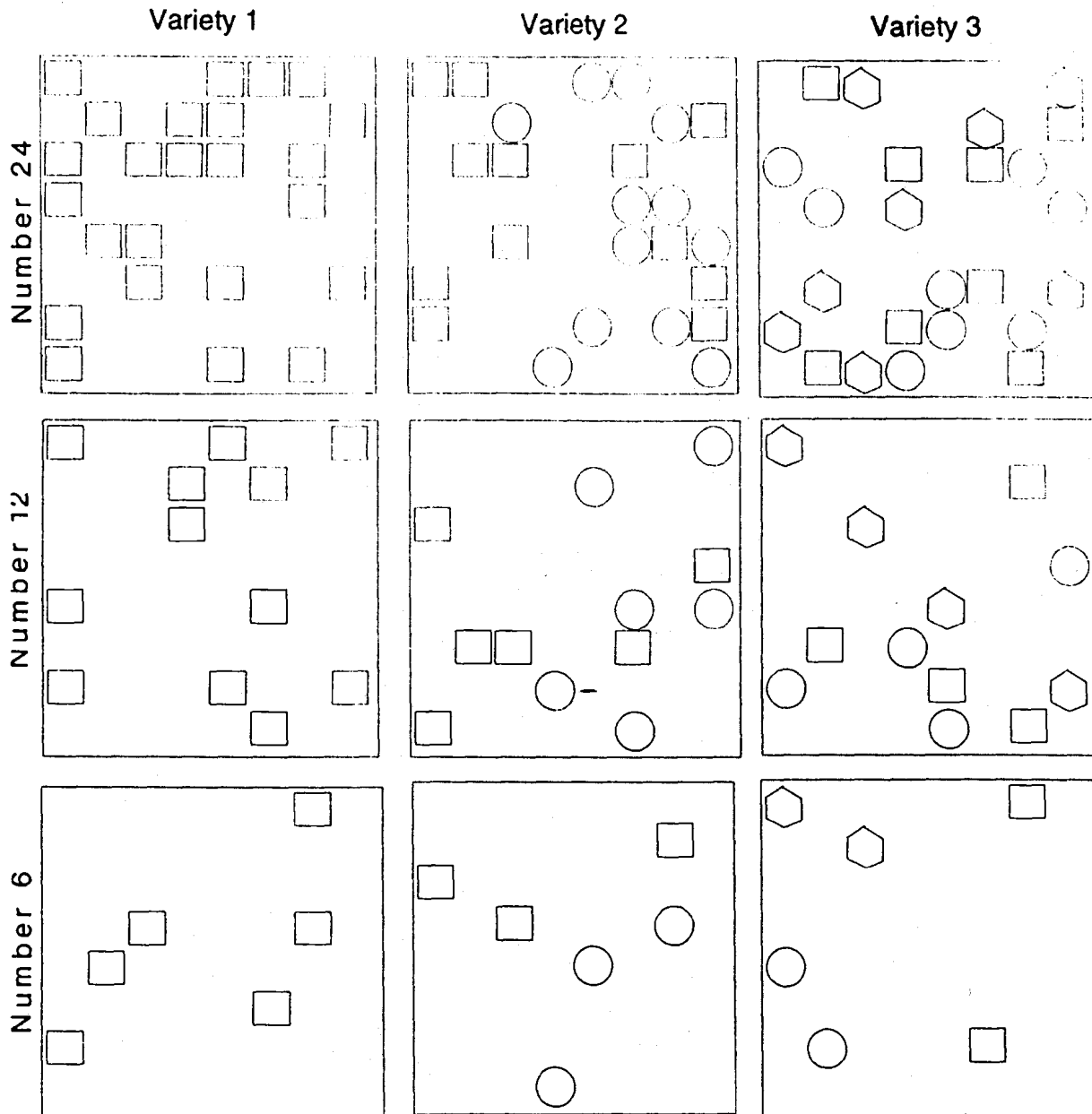


Figure 1 One of the three experimental sets of stimuli used in the study.

tifacts, the data of four subjects were not included in the present analyses.

#### *Experimental procedure*

A total of 27 stimuli were constructed after those of Gale et al. (1975), and presented on a 25.5 × 19.5 cm Philips computer screen. One set of nine stimuli resulted from combining the *number* and *variety* of geometrical elements in a visual display as demonstrated by Figure 1. Thus, each stimulus consisted of either 6, 12, or 24 geometrical elements, which could contain

either one, two, or three types of elements. The elements were 1.5 cm in diameter, and appeared randomly placed on the cells of an 8 × 8 invisible matrix 16.5 cm square. The stimulus thus formed subtended a visual angle of 15° within the gaze of the observer. Two more sets of nine stimuli with different spatial arrangements were constructed to provide control for spatial configuration effects.

Testing took place in a sound-attenuated chamber next to the recording room. Electrodes were attached while the subject read the instructions on a computer screen. Two groups

were formed on the basis of the instructions read on the computer. The instructed group was asked to "work out the rules by which the stimuli had been constructed," in order to remember the stimuli in a subsequent recognition task. The purpose was to confer signal value to the visual stimulation in this group only (Kenemans, Verbaten, Roelofs, & Slanzen, 1989). The non-instructed group was simply asked to look at the stimuli passively, and were told nothing about the recognition task. Groups were formed randomly with the only constraint that there were equal numbers of both sexes in each group.

The instructions emphasized the importance of keeping as still as possible during the recording session, avoiding head or body movements, and not blinking. After a 5-min rest period, the experimental run consisted of 27 visual displays with a duration of 24 s each (ISIs 6 s). Stimuli were presented in sets of nine, and were randomized within sets so as to keep constant uncertainty and other temporal effects.

A recognition task immediately followed the observation task. All subjects were asked to try and recognize which stimuli had appeared during the observation task and which ones had not, by pressing one of two buttons on a response box. One set of nine stimuli from the visual task served as true stimuli. Four "false" stimuli were constructed from each true stimulus by adding or dropping elements from the true stimulus to give the four ratios of 4/6, 5/6, 7/6, and 8/6 elements with respect to each true stimulus. Thus, for a 24-element true stimulus, false stimuli were 16, 20, 28, and 32 in number. Only the number dimension was varied since it was assumed that false stimuli with a new geometrical form in them would be easily recognized.

#### *Data recording and analysis*

Grass gold electrodes were attached according to the 10-20 system with Grass EC2 paste at O1, O2, P3, P4, F3, F4, Fz, and Cz, with linked mastoids as reference. An electrode fixed to the left forearm served as ground. Electrode impedances were kept below 5 kOhms. EEG signals were amplified with a Grass Model 7 system consisting of 7P5B A.C. preamplifiers and 7DA driver amplifiers set at a gain of 50  $\mu$ V/cm. A time constant of 0.1 s was used to reduce the effect of drift and slow artifacts. A

low-pass filter with a turnover set at 27 Hz (48 dB/octave roll-off) was used in combination with a 50 Hz notch filter. The EEG signal was digitized at a rate of 512 values per 3 seconds (170 Hz per channel) and stored for offline analysis. Signal sampling and overall timing were controlled by a Cambridge Electronic Development (CED) 1401 unit, which also provided the windowing and FFT functions used in the analyses. EEG ink-records were obtained on an eight channel Grass 7B polygraph at a gain of 50  $\mu$ V/cm.

Recording and digitizing of the EEG signal began 3 s prior to stimulus onset (the prestimulus value employed as a baseline against which stimulus induced change could be measured) and continued for another 24 s to encompass the whole duration of the stimulus. The time of task-effective recording was 729 seconds (12 min 9 s). Chunks of 3-s EEG recording were treated with a Hanning window and then Fast Fourier Transformed (FFT) to yield the power spectrum between 0 and 27.06 Hz in discrete bins of .33 Hz. Power spectra from adjacent bins were aggregated into 6 bands:  $\theta$  (4.5-7.5 Hz), gross  $\alpha$  (8.0-13.5 Hz), low  $\alpha$  (7.5-9.5 Hz), mid  $\alpha$  (9.5-11.5 Hz), high  $\alpha$  (11.5-13.5 Hz), and  $\beta$  (13.5-19.5 Hz).

#### *Artifact editing*

Power values were initially obtained from all EEG records, and then ink-tracings were visually inspected for artifacts. All epochs with eye movement or muscle artifacts were rescored as missing values, which amounted to 4.6% of epochs in the final dataset. Epochs containing artifacts were equally distributed in both experimental groups. Four participants showed gross movement artifacts during more than 15% of the recording time and were excluded from the analyses.

#### *Statistical methods*

A total of 40 cases entered the analyses (20 instructed). Data from the three sets of displays were collapsed in one single block of data, to yield 81 summed scores per subject: 3 number levels, times 3 variety levels, times 9 epochs. Original absolute power values were obtained in arbitrary units (range 0-99) and then transformed to percent of change from prestimulus power: Change score =  $((x_i - x_0)/x_0) \cdot 100$ ; where

$i = 1, 2 \dots 8$  epochs; and  $x_0$  = prestimulus power. The groups did not differ in their absolute levels of prestimulus EEG power, and this operation considerably improved the signal-to-noise ratio in the data.

To ensure both consistency with earlier studies and a more rigorous statistical approach, traditional univariate analyses were compared with those derived from a higher order multivariate approach. Thus, statistical analyses of EEG data proceeded in two stages. First, the experimental factors were tested in each of the six bands and eight electrodes separately in order to provide a direct comparison with previous univariate research. Forty-eight ANOVAs were carried out, one for each band-electrode combination, with INSTRUCTIONS (2 groups) as the between subject factor and VARIETY, NUMBER (3 levels each), and EPOCHS (1 to 8) as the repeated measures factors. A family-wise level of significance of 0.02 was adopted for all main contrasts as a special precaution against an increased per experiment type I error rate. All within subject main effects and interactions with two or more degrees of freedom in the numerator were adjusted with the Greenhouse-Geisser procedure. The original degrees of freedom and the corrected  $P$ -values are reported in all analyses.

Second, for the multivariate test of the EEG-attention hypothesis, one task average was computed for each of the three main bands and eight electrodes. These 24 variables were subjected to one principal components analysis to extract their orthogonal structure, and then one discriminant analysis was applied to describe group differences in overall brain activation. Finally, a series of multiple regression analyses examined the association between an *ad hoc* index of EEG differential activation to simple minus complex stimuli and subsequent recognition performance. The analyses were conducted with the SPSS-X 3.0 program on the University's IBM-3090 mainframe computer.

## Results

### *Performance data*

Correct and incorrect responses were automatically stored during the recognition task. The hit and false alarm rates were computed by hand and  $d'$  scores then derived ac-

cording to McNicol (1972). Four subjects showed  $d'$  scores more than 2 SDs above (2 instructed outliers) or below (2 noninstructed outliers) their group's mean. Even without considering these outliers, a  $t$ -test showed that the instructed group performed significantly better than the non-instructed group in the recognition task ( $t(34) = 5.54$ ,  $P < .001$ ; with means  $\pm$  SDs of  $1.15 \pm .5$  and  $0.36 \pm .3$ , respectively). Therefore, instructions had the expected signal value effect of drawing attention to the stimuli with the result of a better memorization for the instructed group.

### *EEG power data*

Significant results for the 48 ANOVAs are listed in Table 1. It can be seen that only the NUMBER and the EPOCH main factors reached significance. There were also many reliable INSTRUCTIONS  $\times$  NUMBER interactions. No other effects reached the significance level adopted, and therefore, will not be commented upon further unless they have direct implications for our two hypotheses.

### *EEG-ORs to stimulus presentation*

Changes in EEG power across epochs were significant in all bands, sub-bands and electrodes ( $F_s(7,266) > 6.0$ ,  $P_s < .001$ ). EEG power changes to stimulus onset were universal and mostly confined to the six first seconds of display, after which all data sets showed a progressive recovery to baseline. Thus, *post hoc* comparisons between EEG power from epochs 1-2 versus epochs 3-8 were always significant ( $F_s(1,266) > 7.1$ ,  $P_s < .001$ ), which confirms the distinction between early and late orienting. Figure 2 is an example of the overall effects at F3 and O2, and demonstrates the marked differences between frontal and occipital EEG-ORs. One outstanding feature is the sharp increase in occipital  $\theta$  power during the first 3 s of display, which is concurrent in time with a steep decrease in occipital  $\alpha$  power. At frontal sites, the change in EEG  $\alpha$  from prestimulus values to epoch 1 did not reach significance ( $F_s(1,266) < 1.7$ ,  $P_s > .05$ ). The fact that occipital  $\theta$  power returned to baseline faster than  $\alpha$  and  $\beta$  rhythms, hints at the possibility of simultaneous but different processing mechanisms underlying both types of EEG change.

**Table 1** Summary of significant ANOVA results across six bands and eight electrode locations. Only the main effects for NUMBER(N) and EPOCH(E), and the interaction INSTRUCTIONS  $\times$  NUMBER (I $\times$ N) were statistically significant.

	Theta ( $\theta$ )			Alpha ( $\alpha$ )			Beta ( $\beta$ )			Low- $\alpha$			Mid- $\alpha$			High- $\alpha$		
	4.5-7.5 Hz			8.0-13.5 Hz			13.5-19.5 Hz			7.5-9.5 Hz			9.5-11.5 Hz			11.5-13.5 Hz		
	N	E	I $\times$ N	N	E	I $\times$ N	N	E	I $\times$ N	N	E	I $\times$ N	N	E	I $\times$ N	N	E	I $\times$ N
O1	■			□	■	○	○	■	○	○	■		□	■	○	□	■	□
O2	■			□	■		○	■		○	■		□	■		□	■	○
P3	■			□	■			■		○	■			■			■	
P4	■			□	■			■			■	□		■			■	
Cz	■			□	■	○		■			■	□		■			■	
Fz	■			□	■	○		■			■	○	□	■		○	■	
F3	■			□	■	□		■			■		□	■			■	
F4	■			□	■	□		■			■	□	○	■			■	

■  $P < 0.001$ , □  $P < 0.005$ , ○  $P < 0.02$

### Stimulus driven EEG activation

EEG power reductions with increasing number were significant in all leads within the gross  $\alpha$  band ( $F_s(2,76) > 6$ ,  $P_s < .005$ ) and in occipital sites within the  $\beta$  band ( $F_s > 4$ ,  $P_s < .02$ ). The distribution of this effect within sub- $\alpha$  bands was strongest within the 9.5–11.5 Hz range. In almost all cases the effect resulted from power differences between extreme NUMBER levels, the exception being gross  $\alpha$  at O2 and P4, where differences also appeared between adjacent NUMBER levels. Theta did not show any reliable association with NUMBER. A sample of these effects is presented in Figure 3.

The nature of this inverse EEG association with NUMBER should be qualified by the lack of any reliable EPOCHS  $\times$  NUMBER interactions at the level of significance adopted. Six EPOCHS  $\times$  NUMBER interactions approached significance for O1  $\beta$ , F3, Fz, P4 mid  $\alpha$ , and Fz low  $\alpha$  ( $F_s(14,532) > 1.8$ ,  $P_s < .05$ ). However, these effects were caused by the predicted difference between NUMBER levels appearing *after* the third epoch of display. This result suggests that the above reported NUMBER effects could be due to late appraisal rather than to early EEG-OR phenomena.

In line with the inconsistent results obtained in previous research, the VARIETY factor failed to yield either a main effect or a reliable pattern of interactions with the other factors.

### Effects of instructions on EEG activation

The main effect for INSTRUCTIONS was never significant ( $F_s(1,38) < 2.0$ ,  $P_s > .05$ ). However, INSTRUCTIONS reliably interacted with NUMBER mainly within the  $\alpha$  band ( $F_s(2,76) > 4.5$ ,  $P_s < .02$ ). In all cases, the 24-element condition significantly reduced  $\alpha$  power in the instructed

group, but not in the noninstructed group, compared with the 6-element condition. Figure 4 shows two examples of the direction of this effect within the sub- $\alpha$  band, where the effect of instructions was irregularly distributed across leads. Thus, whereas low  $\alpha$  responded to within the NUMBER  $\times$  INSTRUCTION interaction in Cz, Fz, P4, and F4 ( $F_s(2,76) > 4.5$ ,  $P_s < .02$ ), for mid and high  $\alpha$  the effect was apparent just in occipital leads (see Table 1). This effect was most robust in the gross and low  $\alpha$  bands at centroparietal and frontal leads.

### Principal components and discriminant analyses of EEG power change, with instructions as the criterion

In order to test the hypothesis that differences between the EEG pattern of activation of instructed and non-instructed groups would be better captured from a multivariate statistical approach, task average scores from the three main bands and eight electrodes were subjected to a principal components (PC) analysis with Varimax rotation in the whole sample of 40 subjects. Evaluation of multivariate outliers, normality, and linearity revealed no threat to multivariate analysis (Kaiser's measure of sampling adequacy = .77; Bartlett test of sphericity = 1176,  $P < .0001$ ). Loadings of variables on factors, communalities, and percent of variance explained by the factors are shown in Table 2. Variables are ordered and grouped by size of loadings to facilitate interpretation. Loadings above .40 are printed in bold typeface.

Five PCs were extracted which revealed internal consistency and were well defined by the variables, as reflected in the good proportion of variance explained by each factor. This solu-

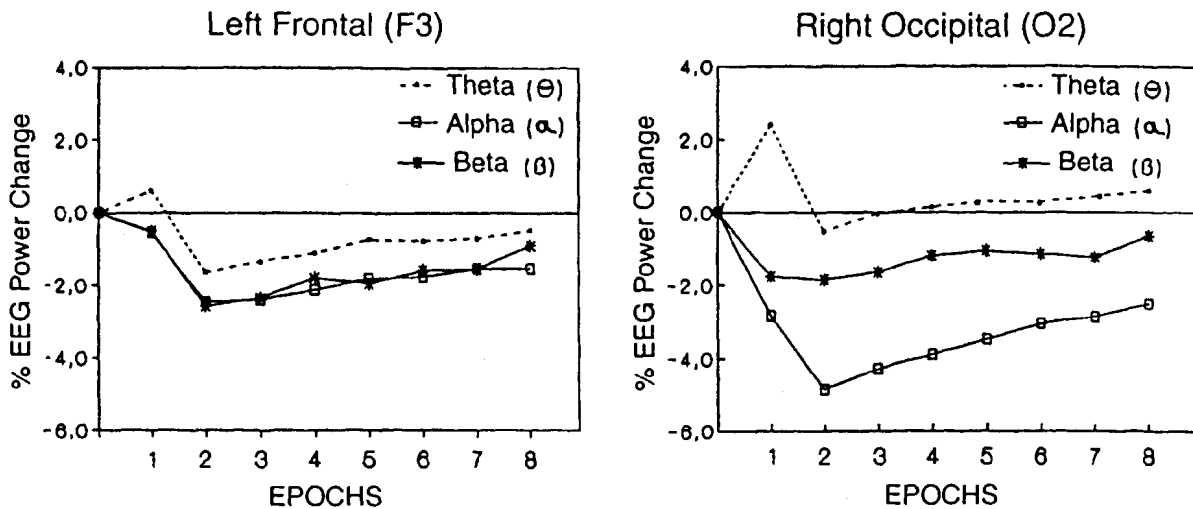


Figure 2 Percent of  $\alpha$ ,  $\beta$ , and  $\theta$  EEG change from prestimulus values after visual stimulation at F3 and O2 leads. Data points represent averages of 40 subjects and 27 trials (1 epoch = 3 seconds).

Main Effects for Number

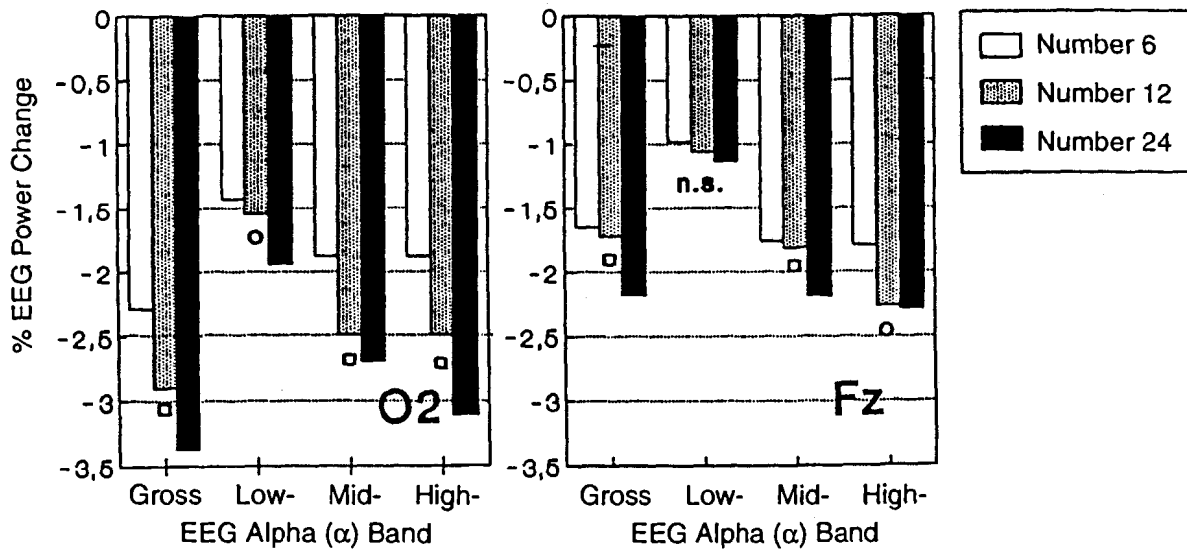


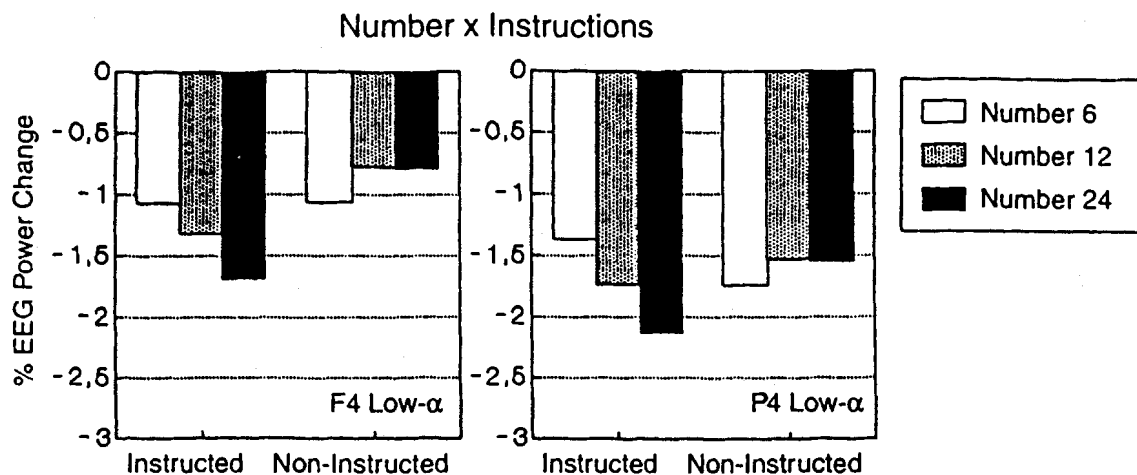
Figure 3 Overall task averages of percent EEG  $\alpha$  change at O2 and Fz for the three levels of NUMBER. Significant NUMBER effects appeared at all sites within the  $\alpha$  band range, and at occipital sites within the  $\beta$  range. Significant differences always appeared between extreme NUMBER levels. ■ =  $P < .001$ , □ =  $P < .005$ , O =  $P < .02$ .

tion organizes the traditional EEG bands along a caudal-rostral continuum rather than across an inter-hemispheric dimension of activation. PC scores were estimated for each subject and then subjected to a stepwise descriptive discriminant analysis (Tabachnick & Fidell, 1989).

Four components showed a reliable association with INSTRUCTIONS ( $\chi^2(4) = 12.13, P < .016$ ). Components are listed in Table 3 ordered ac-

cording to the size of their coefficients. Correct classification rates actually improved from 75% to 80% when individual covariance matrices were employed to estimate the function, which indicates that the discriminant function was robust.

This solution indicates that it would be mistaken to regard desynchronization of the occipital  $\alpha$  rhythm alone as the defining feature of visual attention. In turn, the present multi-



**Figure 4** Task averages of low  $\alpha$  power change for both the instructed and non-instructed groups across the three levels of NUMBER ( $P_s < .001$ ). Only the instructed group showed significant differences between NUMBER levels. Other similar interactions are listed in Table 1.

**Table 2** Principal component loadings (ordered by size), communalities ( $h^2$ ), Eigenvalues, and percent of variance explained after Varimax rotation of 24 variables of relative EEG power.

Variables	Factors					$h^2$
	1 $\beta$	2 <i>Ant-<math>\alpha</math></i>	3 <i>Post-<math>\theta</math></i>	4 <i>Ant-<math>\theta</math></i>	5 <i>Post-<math>\alpha</math></i>	
Cz $\beta$	<b>0.89</b>	0.16	0.13	0.09	0.24	0.90
Fz $\beta$	<b>0.88</b>	0.23	0.15	-0.03	0.03	0.86
F8 $\beta$	<b>0.88</b>	0.14	0.05	0.15	0.16	0.84
F7 $\beta$	<b>0.83</b>	0.28	0.21	-0.09	0.14	0.83
P6 $\beta$	<b>0.72</b>	0.23	-0.05	0.26	0.22	0.69
P5 $\beta$	<b>0.59</b>	0.11	0.14	<b>0.55</b>	0.19	0.71
O2 $\beta$	<b>0.51</b>	-0.06	-0.01	0.39	<b>0.57</b>	0.74
O1 $\beta$	<b>0.45</b>	0.01	0.30	0.34	0.40	0.57
Fz $\alpha$	0.19	<b>0.91</b>	0.29	0.04	0.16	0.97
F8 $\alpha$	0.21	<b>0.89</b>	0.25	0.07	0.19	0.94
F7 $\alpha$	0.19	<b>0.88</b>	0.31	-0.03	0.15	0.93
Cz $\alpha$	0.33	<b>0.80</b>	0.21	0.16	0.28	0.91
P6 $\theta$	0.08	0.18	<b>0.85</b>	0.28	0.20	0.88
P5 $\theta$	0.18	0.18	<b>0.85</b>	0.34	0.12	0.91
O2 $\theta$	0.04	0.35	<b>0.83</b>	0.11	0.26	0.90
O1 $\theta$	0.16	0.33	<b>0.78</b>	0.17	0.07	0.78
Cz $\theta$	0.11	0.20	<b>0.78</b>	<b>0.46</b>	0.07	0.87
F8 $\theta$	0.07	0.06	0.29	<b>0.92</b>	0.08	0.94
Fz $\theta$	0.08	0.01	0.27	<b>0.90</b>	0.12	0.90
F7 $\theta$	0.13	0.13	0.32	<b>0.87</b>	0.14	0.91
O2 $\alpha$	0.26	0.33	0.19	0.05	<b>0.79</b>	0.85
O1 $\alpha$	0.15	<b>0.42</b>	<b>0.42</b>	0.11	<b>0.73</b>	0.93
P5 $\alpha$	0.36	<b>0.50</b>	0.24	0.22	<b>0.64</b>	0.90
P6 $\alpha$	0.33	<b>0.54</b>	0.13	0.24	<b>0.62</b>	0.87
Eigenvalues	12.00	3.33	2.83	1.36	1.01	
% Variance	20.92	18.66	18.29	15.29	12.38	85.54

Note. Proposed labels are in italics: Ant-, Anterior; Post-, Posterior. Loadings larger than .40 have been highlighted.



variate analysis shows that depression of posterior  $\alpha$  and enhancement of posterior  $\theta$  both contribute to active attention. Moreover, clear differences have been demonstrated between  $\theta$  changes recorded caudally and  $\theta$  recorded rostrally, in that they react in opposite directions to increased attentional demands. The global contribution of  $\beta$  activation to this solution is in agreement with the construct of generalized orienting (Sokolov, 1963) or with the unspecific action of an alerting system (Posner & Petersen, 1990).

*Association between EEG differential activation (N6-N24) and recognition performance*

An index of EEG activation to stimulus complexity was computed as the difference between the task averages of absolute power between the two extreme number conditions (N6-N24) (e.g., Gale et al., 1975). Rather than a global index of activation for each subject, nine individual scores were derived, one for each epoch of display. These values served as the nine predictors in the regression equations and recognition performance ( $d'$ ) served as the criterion. The data from four subjects with very deviant  $d'$  scores were dropped from these analyses (see above); their inclusion would have exaggerated the expected association. Twenty-four multiple regression analyses were performed in each group (instructed and non-instructed) across all three main bands and eight electrode sites. A stepwise selection of predictors was adopted, with  $P < .05$  for inclusion and a maximum correlation between predictors of  $R_{\max} = .10$ . More conservative adjusted  $R^2$  coefficients were calculated to compensate for the poor ratio between the number of predictors in relation to sample size.

Results from these analyses are shown in Table 4. Differential  $\alpha$  power during exposure to 6- and 24-element displays showed the most consistent pattern of association and explained the greatest proportion of variance of the  $d'$  scores. For the instructed group, differences in posterior  $\alpha$  power between N6 and N24 during the second epoch of display alone predicted up to 37% of variance in performance (O1). The pattern of significant correlations for this group extended to later epochs at frontal leads, with a maximum contribution from epoch 6, although activity from earlier epochs also ex-

plained part of this association. The non-instructed group presented a much weaker and disorganized pattern of correlations. Thus, if a more stringent level of significance was adopted given the number of analyses performed (i.e.,  $P < .01$ ), the majority of  $R^2$  coefficients in the non-instructed group would not be statistically reliable. Prestimulus differential EEG values were never associated with  $d'$ .

Unexpectedly,  $\theta$  did not show any reliable association with  $d'$  scores, which confirms that the strong increase observed in occipital  $\theta$  during the three first seconds of visual stimulation does not have the same functional significance as appears to be associated with the blockade of occipital  $\alpha$  during the second epoch of stimulus display.

## Discussion

### *Nature of the stimulus driven EEG activation*

The data confirm the prediction that high content information stimulation evokes greater EEG activation within the  $\alpha$  and  $\beta$  EEG bands. This result is in agreement with previous findings (Berlyne & McDonnell, 1965; Gale et al., 1971, 1975).

The number of elements within stimuli was maximally discriminated at occipital sites, particularly in the mid and high  $\alpha$ , and  $\beta$  ranges, which confirms prior evidence that stimulus features are maximally responded to within the upper end of the spectrum (Gale et al., 1975). VARIETY was not discriminated by our EEG indexes. This and earlier inconsistencies bring into question the validity of quasi-vernacular definitions of stimulus parameters (Christie et al., 1972). At the same time, while the inclusion of VARIETY as an element within the stimuli might have enhanced their aesthetic appeal, it does not present a taxing challenge in terms of attentional demands or storage and retrieval processes.

The temporal nature of the association between stimulus complexity and EEG activation was examined with an EPOCH factor. Since reliable interactions between the NUMBER and EPOCH factors were lacking, NUMBER EEG effects cannot be uncritically attributed to early orienting mechanisms. On the contrary, six marginally significant interactions suggested that the reported NUMBER effects might be

**Table 3** Results of the discriminant analysis of EEG power PC scores, with instructions as the criterion

Principal Components	Standardized Coefficients	Correlations with DA Function	
Posterior $\alpha$	.61	.48	(*)
Anterior $\theta$	.59	.46	(*)
$\beta$	.54	.42	(*)
Posterior $\theta$	-.53	-.40	(*)
Anterior $\alpha$	.01		
Eigenvalue	.40		
Canonical Correlation	.54		

(\*) Components significantly associated with INSTRUCTIONS,  $P < .016$

caused by later sustained attention rather than by early, automatic orienting to stimulus onset. Thus, the present results cast doubt as to whether the EEG complexity effects reported in earlier studies reflected automatic orienting to stimulus onset, or whether they encompassed some other form of sustained attention. Future research should aim to solve this confounding, preferably by introducing a finer temporal analysis.

#### *Temporal EEG power changes reflect visual processing*

The EEG power changes elicited during stimulus onset and appraisal suggest that qualitatively distinct stages of visual processing were encoded differentially by various brain rhythms. Important variations between bandwidths were focused during the first six seconds of stimulus display, which supports an interpretation in terms of orienting processes (Berlyne & McDonnell, 1965). Moreover, differen-

ces between early (1-2) and late epochs of display were ubiquitous and confirm the theoretical distinction between early and late processing during visual orienting. Depression of occipital  $\alpha$  rhythm to visual stimulation has traditionally been regarded as an indicator of the localized OR (Barry, 1984) and been attributed to a blockade of specific thalamo-cortical sensory circuitry (Klimesch et al., 1992). The absence of  $\alpha$  blocking during epoch 1 at frontal leads lends further support to this interpretation.

Most remarkable was the association of localized orienting with a sharp increase in posterior  $\theta$  power. Previous studies have reported  $\theta$  power increments accompanying  $\alpha$  desynchronization in visual processing tasks (Gale et al., 1971, 1975). However, the temporal dynamics of this effect had not been investigated before. Increases in  $\theta$  power were originally linked to focused attention and orientation behavior in cats (Schacter, 1977), but the experimental procedure did not clearly replicate the classical OR paradigm. Increases in  $\theta$  power have been related to selective attention (Schacter, 1977) and detection of visual targets in a vigilance task (Basar-Eroglu et al., 1992) or memory search (Mecklinger, Kramer, & Strayer, 1992). Schacter also mentioned the existence of a variety of topographically distinct  $\theta$  rhythms. The present study suggests at least two topographically distinct  $\theta$  rhythms involved in orienting and attention, one of parieto-occipital origin and another one centered in frontal areas.

A close comparison of the posterior increment in  $\theta$  with the early depression of  $\alpha$  power (see Figure 2) suggests that both reactions are

**Table 4** Proportion of variance in performance (Signal Detection Theory measure of sensitivity  $d'$ ) explained by gross  $\alpha$  and  $\beta$  EEG differential (N6-N24) activation in each of the eight electrode sites and two groups of subjects

	Instructed group (n = 18)								Non-instructed group (n = 18)									
	O <sub>1</sub>	O <sub>2</sub>	P <sub>5</sub>	P <sub>6</sub>	Cz	F <sub>3</sub>	F <sub>4</sub>	Fz	Gross $\alpha$									
Gross $\alpha$																		
Adj R <sup>2</sup>	.37	.40	.32	.27	.30	.62	.66	.61	Adj R <sup>2</sup>	.47	.18	.16	.18	.18	.16			
Epochs	<i>2nd</i>	<i>2nd</i>	<i>2nd</i>	<i>2nd</i>	<i>2nd</i>	<i>6th</i>	<i>6th</i>	<i>6th</i>	Epochs	<i>7th</i>	<i>7th</i>	<i>7th</i>	<i>6th</i>	<i>6th</i>	<i>6th</i>			
$\beta$									$\beta$									
Adj R <sup>2</sup>		.21	.56	.24	.48			.12	Adj R <sup>2</sup>		.16							
Epochs		<i>3rd</i>	<i>3rd</i>	<i>2nd</i>	<i>3rd</i>			<i>7th</i>	Epochs	<i>7th</i>								

Note. Nine predictors (pre-stimulus, epochs 1 to 8) were entered in each regression equation. Adj R<sup>2</sup>: Adjusted squared multiple regression coefficients. Epochs: Epochs with maximum contribution to each regression equation. Unique significant predictors are printed in *italics*. All regression coefficients displayed are significant at  $P < .05$ . Coefficients above .30 are significant at  $P < .01$ .

tapping different subjacent mechanisms. It seems that the mechanisms involved in  $\theta$  arising during the first epoch cease to be active during the second epoch of display, when  $\alpha$  depression reaches its minimum. The reciprocal relationship between  $\alpha$  and  $\theta$  rhythms has been associated with the activation of two antagonistic neuronal systems (Lindsley, 1982). Lindsley observed that the activation of a thalamo-cortical system desynchronized  $\alpha$  and synchronized  $\theta$  waves, whereas the activation of a hypothalamic-hippocampal system reversed the pattern of activation. The results of our temporal analysis indicate that EEG power indexes may be useful for extricating the contribution of these two neural systems, and are consistent with current views of orienting as a compound of both selective attention and arousal (Näätänen, 1986). A design with the appropriate manipulations and a finer temporal resolution should differentiate and determine the functional role of both responses.

*EEG power changes differentiate instructed from non-instructed groups*

In the initial series of univariate analyses, the main effect for INSTRUCTIONS never reached significance. However, there were several significant interactions with NUMBER, all of which were caused by the reported inverse relationship between EEG power and stimulus number for the instructed group only. This result supports the use of within-subject designs in the test of EEG spectral differences in attention. Within sub- $\alpha$  bands, the 7.5–8.5 Hz range was the most clearly affected by instructions at right parietal and frontal leads, whereas mid and high  $\alpha$  ranges were affected by instructions in occipital leads only. This result lends support to the existence of a multiplicity of topographically distinct sub- $\alpha$  rhythms which respond differentially to task and stimulus parameters (Bösel et al., 1990; Klimesch et al., 1992; Pfurtscheller & Klimesch, 1990).

The multivariate analysis of the pattern of global EEG activation induced by our instructions was highly successful, and confirms the importance of a multivariate approach in the study of EEG-attention relationships. The principal components and discriminant analyses produced a new and interesting pattern of results, whereby the antagonistic activation of posterior  $\alpha$  and  $\theta$  power significantly separate

out passive from active attention conditions. The contribution of parietal  $\alpha$  and frontal  $\theta$  to the discriminant function is in harmony with claims of the role of these areas to attentional processing (Luria & Homskaya, 1970; Posner & Petersen, 1990). Despite a relatively small sample size, and a very coarse manipulation of attention, the present findings support the views that higher cognitive functions are unlikely to be localized in separate brain areas (Gevins et al., 1985), and that a "system level analysis" is mandatory in the study of attention (Posner & Petersen, 1990).

*EEG differential activation predicts recognition performance*

The final part of this study addressed the issue of the functional role of EEG activation. Recognition performance was reliably associated with differences in EEG power between the two extreme *number* conditions, mainly in the  $\alpha$  band. The association was strongest precisely when  $\alpha$  depression reached a minimum during the second epoch of display. The pattern of correlations extended in later epochs towards more frontal leads. Only the instructed group showed such consistencies, whereas the non-instructed group presented a much weaker and unsystematic pattern of correlations. Former studies had already reported such correlations within the  $\alpha$  range of frequencies (Gale et al., 1975; Bösel et al., 1990). The evidence presented here extends those findings and shows a meaningful temporal and topographical pattern of association between  $\alpha$  differential reactivity to stimulation.

Any interpretation of these correlations should be qualified by the fact that subjects did not generally find out the rules of construction of the displays (e.g., "equal ratios of 1, 2, or 3 geometrical elements totalling 6, 12, or 24 in number"). Two instructed subjects who did find out the rules were dropped from the analyses because of their extremely good  $d'$  scores (4 SDs), which would have distorted their group's means. Their inclusion, though, would have meant an even stronger association between the EEG predictors and performance. This suggests that the reported association hinged on the more intense attentive state induced by the instructions (signal value), regardless of whether the subjects succeeded or not in finding out the rules (e.g., abstract reasoning or intel-

ligence were not decisive). A tentative explanation of these effects would be that enhanced attention facilitated the creation of a memory trace, which was reflected at occipital and parietal leads during the first stages of information processing, shifting to frontal locations as the processing of the stimulus continued.

Although expected, a negative association between occipital  $\theta$  power (epoch 1) and performance was lacking. If somewhat disappointing, this fact may be taken to reinforce the suggestion that the mechanisms which underlie posterior  $\theta$  enhancement during orienting are different from those responsible for  $\alpha$  blocking. Also, the purported link between  $\theta$  and processes of selective attention still needs clarification. A larger sample size, a tighter controlled task, and the use of a psychometrically more valid test of performance will guarantee more solid inferences about the relationships between EEG activation and the cognitive processes partly disclosed in this study.

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