NsG-505

NAS 9-1970

COMPREHENSIVE SPECTRAL ANALYSIS OF HUMAN EEG GENERATORS IN POSTERIOR CEREBRAL REGIONS

by

D. O. Walter, Ph.D., J. M. Rhodes, Ph.D,
D. Brown, B.S., and W. R. Adey, M.D

UNPUBLISHED PRELIMINARY DATA

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

Departments of Physiology and Anatomy
and the Brain Research Institute
University of California at Los Angeles
Los Angeles, California

FACILITY FORM 602

N66-18389 (ACCESSION NUMBER) — (THRU) 1

48 (PAGES) — (CODE)

CR 57050 (NASA CR OR TMX OR AD NUMBER) — 04 (CATEGORY)

[redacted]

Running Title: Spectra of Posterior EEG Generators

If accepted, please send proofs to:

Dr. D. O. Walter
Space Biology Laboratory, Brain Research Institute
Center for the Health Sciences
U.C.L.A.
Los Angeles, California 90024

[redacted]

INTRODUCTION

The complexity of human cerebral electrical activity has long frustrated its finer analysis, but recently developed mathematical models and computer technology have begun to remedy this situation. We report here on some aspects of intracerebral electric generation illuminated by a novel extension of spectral anaylsis (Walter 1963; Walter and Adey 1963). The extension consists of performing many sequential spectral analyses, and producing suggestive visual transformations of spectral intensity and strength of spectral relationship, as a function of both time and frequency. These contour maps and density plots give a broad overview of the stability, fluctuation, and evolution of patterns of wave generation and propagation in the EEG, which lead to a broadened conception of the familiar alpha wave, as well as to clear delineation of linear and non-linear transmission.

METHODS

Data Acquisition

An extensive library of normal scalp electroencephalograms and other physiological parameters has been collected[1] under the direction of Dr. Peter Kellaway. Data are being recorded from approximately 200 U.S. Air Force pilots by Dr. R.L. Maulsby and others; Dr. Martin Grahame has been responsible for development and operation of the electronic equipment. A full description of the techniques of collection will be published elsewhere; data for the present paper relate to subjects early in this series.

Data were recorded by an EEG, Model 709, (Offner Div., Beckman Instruments) and on two 14-channel magnetic tape recorders (Model 400A, Precision Instruments Corp.). Standard clinical electrodes were placed with molten paraffin, after cleaning and scraping the scalp. The electrode placements conformed to the International 10-20 System, and were recorded in bipolar chaining. Linkages to be discussed, and their coded designations, are: bilateral mid-temporo-parietal (LCP and RCP); parieto-occipital (LCPO and RCPO); and left to right occipital (BIOCC). In order to assure near-identity in the stimulation of each subject, stimuli were presented by an automatic device developed in this laboratory (Kado, 1964). Briefly, a two-channel magnetic tape contained spoken instructions for the subject on one channel, and pulses which identified the successive situations and controlled stimulus-presentation equipment on the other. The latter channel was re-recorded onto both data tapes, to allow later positioning.

After 20 minutes of flashes, clicks, and other simple physiological stimuli, the following taped instructions were given: "You will now hear groups of three tones like this:", (3 tones presented). 'When you hear the third tone, you are to push the button under your first finger, on the right side of your chair. Remember to wait for the third tone of each group before pushing the button. Now close your eyes." Eighty sets of 3 clearly audible tones at 500 c/sec were presented, each tone lasting 0.08 sec. Three seconds elapsed between sets; within a set the tones were one second apart, except in the 40th and 80th sets. The 40th set had its third tone delayed an extra second, the 80th, two extra seconds.

Each data tape was copied at the recording laboratory and the copies sent to UCLA. A recorder of the same model reproduced each tape in our laboratory; the resulting voltages were converted to digital form by equipment made by Airborne Instrument Laboratories, Inc. The nominal accuracy of conversion was one part in 512; the rate of conversion was 3000 samples per second. Voltage calibrations were not incorporated into these analyses, so that reported microvolts are approximate; calibrations vary about 10% between channels.

Data Analysis

The output of the analog-digital converter was recorded on magnetic tape by a Control Data Corporation Model 160A computer. These digital tapes were processed by larger computers (IBM Models 1410 and 7094) at the UCLA Health Sciences Computing Facility, for which we are most grateful. There, programs written by us positioned the data tape to the requested segment, performed digital filtering to a requested resolution, computed auto- and cross-spectrograms, phase angles and coherence functions, and finally produced both printed tabulations and digital tapes for further processing. Spectra and cross-spectra were produced directly by filtering the data, rather than by transforming auto- and cross- correlation functions. Further computations provided tapes to be plotted as contour maps by the digital plotted of the 160A computer. These maps are directly analogous to topographic maps containing altitude contours. Maps of two functions will be employed here: intensity (such as Figs. 1 & 2), and coherence (Fig. 3). For contours of intensity, spectral analyses had been performed over a succession of adjacent 12-second epochs, extending over several minutes. The numbers representing estimated spectral intensity in a single channel at each frequency, for each epoch, were considered as heights defining a topographic surface. In order to visualize this mountainous surface, its contour curves, of equal intensity, were drawn by the computer. As a guide in reading the maps, the computer was programmed to draw "H" at those frequency-time points which were highest among their immediate neighbors, "L" at lower ones.

Alternatively, instead of spectral intensity, coherence (Walter, 1963) could be represented. The coherences relating a chosen pair of channels were thought of as defining another surface over the same frequency-time plane, and contours of equal coherence were produced. As a guide to interpretation of coherence peaks, the computer was programmed to include an extract of the two relevant autospectral maps along with the coherence map: after the contours defining the coherence surface relating LCPO to RCPO, for example, had been drawn, the computer superimposed, over the same frequency-time grid, the H's and L's extracted from the LCPO autospectral map. Then the computer superimposed an exactly analogous extract from RCPO, labeling highs and lows with other letters (Fig.3). A few inelegancies may be detected in the contour maps, in that some contours fail to close, and some cross themselves. More elaborate programming could have avoided this, but it was not felt to be justified.

The precise locations of spectral maxima and minima may be anywhere within the band associated with a filter. That is, a narrow peak associated with the 9.0 c/sec band might have its proper maximum anywhere from 8.75 to 9.25 c/sec. In one sense, no closer determination is conceivable, on the basis of the uncertainty principle governing time and frequency; but interpolation can yield a most probable location, and was used in later maps such as Fig. 4. Besides taxing the eye less, such rounded maps actually give a more proper representation of the spectra and their evolution, for our filters are designed to overlap slightly between frequencies during one epoch, and between epochs at the same frequency. These maps still require much experience and comparison for their interpretation. Because density modulation is often easier to comprehend than line graphs, we developed computer programs for simultaneously presenting two intensity functions and the coherence function relating them, by modulation of both the width and density of tracing (Fig. 6). The width and the density of each outer tracing of a tripartite trace are both made proportional to the spectral intensity function of one lead. The middle trace is similarly modulated, but in proportion to the coherence function between the two leads, during the same epoch. Each swath is labeled with the starting time of its epoch.

Other summarizing parameters were computed for each epoch and channel; in particular, the equivalent noise bandwidth, and the equivalent filter duration (Rhodes and Brown, in preparation). These have been found to provide a state description more compact, if more approximate, than that offered by spectral analysis. Bandwidths reported here relate to the range above 1.5 c/sec only.

Statistical Treatment

All calculated parameters of this study are statistical in nature, and subject to sampling fluctuation. Sampling errors in spectra and phase angles were covered in earlier papers (Walter, 1963; Walter & Adey 1963, 1964). The sampling distribution of coherence was derived by Goodman (1963), and tabulated by Alexander & Vok (1964). As an alternative to the hypothesis that records are coherent to a worthwhile extent, we have taken, not the null hypothesis that they had a true coherence of zero, but instead, "these records are coherent less than 0.05". If sample coherence exceeds the critical value for this hypothesis (found in the table), we are justified in saying that such a coherence could have arisen by chance from jointly Gaussian-distributed records actually coherent 0.05 or less, with a probability of only about 5%. We call such sample coherences simply "significant coherences". Because brain waves are often not close to jointly Gaussian distributed (D.O. Walter, unpublished data), we have proceeded with some conservatism, and give physiological interpretations only when the same pattern is observed in several epochs.

Flutter Compensation

In processing analog data on magnetic tape there is inevitably some irregularity in the speed of tape motion, that is, flutter.[3] This produces artifactual amplitude modulation of the reproduced signal in all channels, cumulatively in the steps of recording, reproduction, re-recording, and final reproduction for digitization. Partly to allow compensation for these artifacts, a 10 Kcs/sec sine wave had been superimposed on the voice channel of both of a subject's data tapes during the original recording process. We could have used flutter-compensation networks, but as the measured amount of flutter in the recorders used was less than 0.25 percent, and such correction networks may contribute new errors, no such compensation was used. Since some unexpectedly high coherences were observed, however, we performed digital flutter compensation *a posteriori* in some representative situations.

The 10 Kc signal was detected, digitized, and spectrally analyzed along with several EEG channels. The spectra of flutter varied somewhat from time to time in the relative intensities of peaks, but the strongest of the peaks were always at 5.0 and 7.5 c/sec, with progressively weaker peaks at 10.0, 12,5, and 15.0 c/sec.

The coherences between flutter and reproduced EEG channels were insignificant in all but a few instances; these were all at 7.5 c/sec, at times when the EEG channels were relatively weak in that band. The worst such case was chosen, and the spectral matrix representing two EEG channels and the flutter channel at this frequency was inverted to calculate the conditional coherence (Goodman, 1963). Before compensation for the flutter, the calculated coherence between the EEG channels was 0.69; after compensation it was 0.58. Since this was the worst case observed, and occurred in a frequency band which had not come to our notice as yielding unexpected results, it was concluded that routine flutter compensation was not necessary.

RESULTS

Subject 207

Contours of spectral intensity for Subject 207 during the major part of the auditory vigilance task are shown in Fig. 1. For explanatory purposes, the contours for the left central parieto-occipital lead (LCPO: P3-O1) are shown at a larger scale in Fig. 2A, together with the ordinary spectrum for the first epoch. Fig. 2A can be understood by considering its left edge; the elevation from this view would be precisely Fig. 2B, wherein heights for which contours are plotted are shown intersecting the autospectral graph for the first epoch. The high-intensity zones in Figs. 1 and 2 are seen largely in two frequency ranges: below 1 c/sec; and from about 9.5 to 11.0 c/sec.

9.5-11 c/sec Band: the Longitudinal Waves

The most representative map is that for LCPO. Here the wave is initially a rather narrow-band (that is, regular) process, centered at 11.0 c/sec; it clearly represents this subject's alpha wave.

In the first minutes, it decreases in intensity (from about 50 to less than $10 \mu V^2/(c/sec)$) and frequency (from 11.0 to 10.5 c/sec); and increases in bandwidth (from about 1.5 c/sec to 2.8 c/sec). This is in relation to the subject's gradually increasing tendency to respond within, or even before, the third tone. After the unusual stimulus group at 4 minutes, the subject's alpha wave returned with very high amplitude ($>100 \mu V^2/(c/sec)$) and regularity, and at 11.0 c/sec. It seems probable that his attention had wandered or waned, concomitantly with the attenuation of his alpha wave; when the unusual stimulus group occurred, the subject's conscious responses, as well as his longitudinal EEG waves; returned to their initial conditions. In the period just preceding the unusual stimulus, in which the subject was responding prior to the third tone, local spectral maxima occurred at low intensity at 2.0, 3.5, and 7.0 c/sec, recalling the findings of Williams et al. (1962) and of Haider, (pers. comm.) of theta- and delta- band activity associated with errors of omission, in somewhat similar vigilance tasks.

The pattern was similar, though more fragmented, in the other longitudinal leads. What is more significant in binding them together is the pattern of relationship shown by their contours of coherence, Fig. 3. Consider the second map in the second row, which delineates the coherence surface relating LCPO and RCPO, which have the strongest and most consistent relationship found. While there were many time-frequency combinations having moderate coherences, the bands of greatest consistency were the alpha bands, and their closest relationship occurs during the epochs of intense activity following the first unusual stimulus group. The high coherences extend lower in frequency than the spectral peaks, but not higher. Similar results were also clearly found in another subject. The same description applies to the maps for the pairings RCP/RCPO and RCP/LCPO. It is a general rule that such co-occurrences of high intensity with high coherence, and low intensity with low coherence, can be interpreted as indicating a generating process which is waxing and waning in intensity; when active, it dominates these leads, and binds them together; when inactive, it allows each lead's local activity to be seen. Reference to the phase angle calculations (not reproduced) showed that LCPO and RCPO have their alpha waves essentially in phase, while there is an angular lead of approximately 30^{o} (equivalent to approximately 15 msec.) between either of them and either LCP or RCP, thus suggesting forward transmission of these waves.

9.5 c/sec Band: the Lateral Waves

The BIOCC lead also had much of its activity concentrated into the alpha range, though it was spectrally wider (i.e., less regular) and was more stably centered at 10.5 c/sec. It continued with unabated intensity, frequency and width, throughout the task. Its second-by-second independence from the longitudinally oriented waves is domonstrated by the coherence maps in the bottom row of Fig. 3. Each of these maps relates BIOCC to one of the other traces: the bareness of all three at all frequencies is in strong contrast to the other maps. In short, BIOCC's activity is not shared; essentially none of its power could be accounted for by any power in the other leads. Bioelectrically it is easy to interpret this independence: throughout this task, the bioccipital generator or generation process is laterally oriented; that producing the alpha waves is, in effect, longitudinally oriented. It may be that the lateral generator represents that activity sometimes called Kappa (Liberson, 1937; Chapman, Armington, and Bragdon, 1962).

This tentative identification is consistent with the facts that peak activity was at a frequency slightly below that of the alpha; that it was recorded from a laterally disposed recording dipole (the usual linkage is bitemporal): and that it was relatively unaffected by widely varying levels of attention.

Low-frequency Band

BIOCC and VERTEX (not reproduced) show considerable activity between 0 and 1.0 c/sec. But Fig. 3 showed almost no significant coherences between any pair of leads in this band, and it is a direct implication of the mathematical model being employed that EEG activity not coherent with other EEG channels is either local or, at most, can depend on other physiological parameters.

Since this is a frequency band occupied by heart activity, an additional spectral analysis was performed to determine the relation between the plethysmographic lead and BIOCC, VERTEX, and LCP (included as a control example). In order to increase the statistical reliability of the spectral estimators, epochs of 24 sec. were analyzed. With the bioccipital lead, the plethysmograph showed marginally significant coherences of about .5 in the 1.0 c/sec band, and a usually smaller coherence near 0.5 c/sec. With the VERTEX lead, the plethysmograph less often showed significant coherences; coherences with LCP were all insignificant. Thus a limited but non-negligible proportion of activity in two leads can be attributed to pulsation. But it is necessary to seek further, perhaps by extensions of spectral analysis, for explanation of the other half of the 1.0 c/sec wave activity, and of almost all of the activity at and below 0.5 c/sec, in both the bioccipital and VERTEX leads in this subject.

Subject 212

In addition to stable alpha activity (10-11 c/sec) in LCPO and RCPO, this subject showed (Fig. 4) a broad minimum of activity in the range of approximately 4 to 7 c/sec, in all leads. The spectra were quite similar in the symmetric pairs LCP/RCP, and LCPO/RCPO, but less similar in other pairings. The major modulation of intensity in response to both unusual stimulus groups is in BIOCC, in contrast to the finding in the previous subject; some flattening is also seen in LCP at these times. Fig. 4 also contains a set of time histories extracted from the contour maps, as if each had been sliced along a single-frequency line near the lower border of the band of strong alpha activity, and the slices displayed as the five ordinary graphs shown. The first four leads showed two rather dissimilar waxing and waning processes shared in the symmetric pairs mentioned. BIOCC had a third pattern of modulation. This subject did not show Subject 207's errors of anticipation, but frequently responded more than once per tone group, as indicated in the lower left of Fig. 5.

Fig. 5 contains a selection of coherence maps for this subject, 4 concerning LCP, 3 RCPO; those not reproduced confirm the indications given by these maps. In consonance with the similarity of their autospectral maps, coherences LCP/RCP and LCPO/RCPO are high, in and near the alpha bands. The ipsilateral pair LCP/LCPO show intermediate strength and consistency of relationship in these bands, while LCP/RCPO relate only weakly. LCP/BIOCC and RCPO/BIOCC indicate the essentially complete independence of BIOCC from the other leads. Fig. 6 presents some of the autospectral and coherence data for LCP/RCP in a new transformation, the coordinated density plot, which allows a new insight on the data. This plot juxtaposes data previously presented in three separate contour maps; unfortunately, it loses in comprehensibility if compressed to the area of a contour map. Even from these selected epochs, two important findings emerge; first, in each epoch, intensity of activity was high in one, or at most two adjacant filter bands, commonly the same bands on both sides. Coherence between them, in contrast, was usually significant over several additional neighboring filter bands, a total band from 2 to 4.5 c/sec in width. This range of agreement is much wider than we anticipate from the narrow bands of high alpha intensity.

The intensity reached its narrow peak between 9.5 and 10.5 c/sec, appearing once at 9.0, but the shared process flanking this peak typically extends from 7.5 to 12 c/sec, a range in which the intensity varies by a factor of ten or more. There was some variation in its location, apparently correlated with the location of the intensity peak; there was relatively little variation in the coherence level in different frequencies in an epoch, and not much more between epochs.

Study of the analogous plot (not reproduced) for LCPO/RCPO shows a similar effect, through the peaks are at different frequencies in most epochs. Other pairings, such as LCP/LCPO, had, as well as lower coherences generally, much variation both in location and in coherence level, during the same time period.

In the epoch following the unusual stimulus group, LCP flattened. RCP continued relatively unflattened, and the coherence between them shows a significant drop, indicating a nearly complete loss of transmission. BIOCC also weakened them, as noted earlier. Also during this period, the subject's GSR showed a rise, then oscillated for 15-20 sec. Similar reaction patterns occurred in a few other subjects and situations. For a finer analysis of this reaction pattern, more studies will be needed.

Subject 213

Contours of intensity for subject 213 are in Fig. 7. Attending first to those for RCP, we see an extremely clear ridge in the 9.5 c/sec band, varying only slightly in the location of its peaks throughout the task. This ridge is bounded above by a surprisingly straight cliff, which reaches the $10uv^2/(c/sec)$ level by 10.0 c/sec. There is a consistent valley from about 5 to 6 c/sec. This pattern persists throughout the task, and disappears only with the beginning of a new one, when an almost opposite picture develops transiently (local peaks at 1, 3.5-5.5, 7,11, and 14 c/sec, and a valley in place of the ridge). LCP, LCPO and RCPO contain very similar ridges in the 9.5 c/sec band, although the last two are of lower intensity. The extracted time histories of intensity at the upper border of this band, also given in Fig. 7, show in what detail the modulation agrees among RCP, LCP, and LCPO, but not RCPO. These last two leads both showed some ridge structure in the range 2-4 c/sec, especially LCPO, though less well formed than the alpha ridges, these low-frequency ridges contrast with the same bands in LCP and RCP. None of these four structures had any clear response to the two unusual stimulus groups. BIOCC showed a generally similar ridge in the alpha band, which has a distinct narrowing in the epoch of the first unusual group. This subject made no errors at this or any other time, but his GSR rose following each unusual stimulus group.

Coherences: the alpha band.

The coherence map for LCP/RCP (see Fig. 8) shows a broad band of significant coherences, bounded above at 9.5-10.0 c/sec, but usually extending considerably further toward low frequencies than do the high-intensity ridges of the autospectra of these leads. The corresponding intensities have a dynamic range of approximately ten, like those illustrated for the previous subject for the same two leads. In the band around 9.5 c/sec, coherence maps LCP/LCPO and RCP/LCPO have a similar, but narrower, zone of high coherence. Thus the major wave process present these three leads is well shared. The phase angles are all close to zero, suggesting centrifugal rather than cortico-cortical transmission: but more powerful analytic techniques would be required to decide between those very interesting alternatives.

In this band, the maps relating to RCPO, both these shown and those not reporduced, show considerably weaker coherences, in spite of RCPO's intensity ridge like the others'. These weaker coherences confirm the implication from the time histories in Fig. 7, of relative independence in RCPO's alpha wave.

Coherences: Delta Bands

The coherence map LCPO/RCPO has a broad zone of intermettent high coherence in the range from 2.5 to 4.5 c/sec, whose pattern follows the ridges of LCPO to a noticeable extent. Other pairs share these waves. These may be weak, fluctuating delta waves, generated independently of the alpha waves, Another possibility, which recommends itself for further study, is that they represent a quadratic interaction term, either between the disparate alpha generators, or between brain wave and vascular pulsation wave. This possibility can be studied by bispectral estimation (Hasselman, Munk, Mac Donald, 1963).

Other Situations and Subjects

Comparison of the vigilance situation with their subjects' earlier periods of rest (with eyes closed) showed illuminating similarities and differences. These three subjects also displayed in the rest epochs, bioccipital waves in the alpha band totally incoherent with the longitudinal waves. So far, rest periods have been analyzed in ten other subjects. Six of them showed an analogous pattern of lateral independence; the four others displayed four different patterns. Thus a clear lateral alpha is the most common pattern, and we do not yet have an indication of any other pattern.

In pairings which showed wide coherence superimposed on narrow peaks of alpha intensity, the bands of coherence were narrower in the rest periods: for subjects 207 and 213 the band of significant coherences covered 1.5 to 2 c/sec, with a dynamic range of only about 3, against 10 in the former; for 212, the width was 2 to 3 c/sec and the dynamic range approximately 5. Thus the striking sharing is better expressed during auditory attention than during rest, the eyes closed in both cases. Unfortunately, other subjects' vigilance records have not been analyzed at this time; rest periods of nine of the ten mentioned above show restricted sharing like 207 and 213, while one agrees with 212 in covering a dynamic range of about 5.

DISCUSSION

Several significant linear and non-linear relationships are implied by these results. In sum, they lead to a broadened conception of the generation and propagation of the alpha wave. Some of these observations could have been made by a trained observer without mechanical assistance; others with an ordinary frequency analyzer. Many, however, are completely imperceptible without the "physiological microscope" provided by these spectral methods.

While it would be most parsimonious to interpret these results in terms of a few dipolar sources, to do so would ignore the body of detailed observations (Walter and Crow, 1964; Chatrian, Bickford and Uihlein, 1960) from surface and depths of the occipital lobe.

Clearly, deep bioelectric generation processes are protean in their variety of size, shape, strength, and orientation. While the present analysis is phrased in terms of a few generation processes; this should be understood as constraining only the average tendencies of the deep generators.

Linear Aspects of the Results

The spectral results allow us to separate two or, in some subjects, three generators or generation processes, oscillating in similar frequency bands within the posterior part of the head. The calculations do not yield a fundamental causal explanation of the processes so elucidated, but they do provide sharp and explicit imits to the range of explanatory models which can be considered acceptable.

BIOCC's low coherences in some subjects imply geometric contraints on the orientation of generators, and the propagation of their waves. Consider a bioelectric model, restricted to LCPO (P3-01), RCPO (P4-02), and BIOCC (01-02). Let A1(t) and A2(t) be two approximately 9.5 c/sec oscillations, whose differing modulations lead them to be statistically independent. Let us suppose that the voltage differnce between electrode 01 and some ideal reference is approximately

$$01(t) - Ref = A1(t) + A2(t) + n1(t)$$

where n1 is a statistically independent noise signal of low intensity. Suppose further that the other electrodes behaved in accord with Fig. 9, so that their monopolar records would be:

$$O2(t) - Ref = A1(t) + (1+g)A2(t+h) + n2(t)$$
$$P3(t) - Ref = (1+a)A1(t+b) + A2(t) + n3(t)$$
$$P4(t) - Ref = (1+a)A1(t+b) + (1+g)A2(t+h) + n4(t)$$

Where a and b are respectively a gain modifier and a time delay on the A1 process, either of which (but not both) may be zero, g and h are analogous operators on A2, similarly restricted, and the n's are so many independent noise sources. Under these assumptions, the bipolar voltage differences actually recorded would obey:

$$P3(t) - O1(t) = (1+a)A1(t+b) - A1(t) + n3(t) - n1(t)$$
$$P4(t) - O2(t) = (1+a)A1(t+b) - A1(t) + n4(t) - n2(t)$$
$$O1(t) - O2(t) = A2(t) - (1+g)A2(t+h) + n1(t) - n2(t)$$

P2-O1 and P4-O2 would be strong and coherent in the 9.5 c/sec band, incoherent outside it. O1-O2 would also be strong in that band, but incoherent with other leads. The A1 process affects the sites of O1 and O2 equally, P3 and P4 equally, and O2 and P4 equally. These constraints on the model seem to be the only simple ones compatible with the observations. On the other hand, there must be either a time delay or a gain difference or both, between the effect of A1 on the posterior vs. the anterior electrodes, and similarly as to the effect of A2 on left vs. right electrodes. In some subjects the gain difference seems to predominate, as there is no phase shift between P3-O1(LCPO) and C3-P3 (LCP); in other subjects, the time difference is significant, since such a phase shift is observed.

The pattern of coherences was a little more complex in subject 212, with strong side-to-side coherences, and moderate coherences between fore-and-aft pairings. This pattern implies additional constraints on the model for his records. According to the method of generator analysis (Walter & Adey, 1964) it could have arisen from either of two geometrically different dispositions of electrical generators. In spite of their geometric differences, these two alternative resolutions of the data are mathematically equivalent, as far as present methods of analysis are able to carry us. Either model requires three generation processes in order to reproduce the pattern observed.

Non-linear aspects of the results

The alpha "process". One non-linearity common to all three subjects in differing degrees is that which produces wide bands of high coherences in the face of narrow bands of high intensity. The high coherences themselves express linear relationships, but their association with the narrow alpha waves implies a non-linear relationship between activity in the strong band and its neighbors.

Bioelectrically, we would have inferred a narrow-band alpha generator from just the autospectrograms, as is implicit in the classical descriptions (Grey Walter, 1959).

The wide coherent band, however, strongly suggests that a single alpha generation process covers this entire width, though at greatly differing intensities. It is well known, for instance in radio transmission theory, that a regular oscillation whose frequency or amplitude is being modulated, is mathematically equal to the sum of the regular oscillation (the "carrier") and weaker "side-bands" in the neighborhood of the carrier, whose frequencies differ from that of the main wave by small-integer multiples of the modulating wave. Perhaps our findings of high coherences between weak waves in bands adjacent to the alpha reflect the transmission between brain areas of the side-bands defining the modulations of the main alpha wave. Such a hypothesis requires some care to properly test it in the present context of statistical communication theory. Such a test is now under development.

Other effects of the alpha process. An additional property of the coherence bands was noted particularly for subject 212, but applies also to the others. It related not to their width, but to their height, to the relative constancy of coherence values within the wide band, flanked by relatively steep drops to negligible coherences.

To interpret these high coherences, recall (Walter, 1963) that a coherence[4] of 0.8 between two leads means that in this frequency band, 80% of the activity in one lead can be inferred (or "predicted") from the activity of the other. In different words, 20% of the activity is not thereby predictable. Since the prediction implied by the coherence includes optimum corrections for gain and phase change, this precludes any linear relation between predicted and unpredicted activity. Two alternative explanations of the unpredicted, local activity remain: either it is merely coincidentally present in the same band as the shared activity, or else it has some non-linear relation to it.

Now, the shared activity varies in intensity over at least the range 50 to $5\mu v^2/(c/sec)$, in the different filter bands which are about 80% coherent. In order to maintain a coherence near 80%, over bands differing so much in intensity, the spectrum of the local activity must follow the shape of the shared spectrum, over the same dynamic range of a factor of ten. But such similarity of spectrum, over such a range, persisting for minutes at a time and moreover, peaking at different frequencies in some epochs, cannot well be coincidental. We conclude that, although they are not linearly related, the shared activity must be causing the local activity, or at the least, that the two are causally related.

This non-linear causation cannot be produced simply by non-proportionality of electrical response, a ubiquitous property of cerebral tissue, unless the input-output curves defining such non-proportionalities differ between different leads; for equal curves would result in equal distortions, hence little reduction in coherences. The analysis thus leads us to a conception of a process which produces the alpha wave and also, non-linearly, evokes some local activity in intensities roughly proportional to its own intensity.

A different non-linearity is indicated in the activity of Subject 213's area RCPO, which peaked in the same band as the shared alpha of the other leads, and dispersed into different bands after the end of the task as they did; but was only weakly coherent with them. This coincidence of peaks and dispersals argues some general tendency for all four areas to prefer about 9.5 c/sec during the task and not after, and this relation too contains a non-linear portion.

Analogous co-occurences of linear and non-linear relationships have been noted previously in spectral studies (Walter, 1963; Walter & Adey, 1963): methods of analyzing non-linear relationships are now being developed by us (Walter & Brown, 1963). Meanwhile, spectral analysis delimits the frequency bands and intensities of some of these effects, though not the intimate details of their production.

Methodological Comment

The close intermingling of linear and non-linear relationships revealed by our analyses was unexpected. These findings have suggested several modifications of the original methods, which are now being developed and tested. Both old and new methods promise additional revelations about cerebral behavior, as our mathematical tools are increasingly adapted to the nature of the physiological function we are investigating.

While these tools are costly to develop and apply in the full generality necessary for their unbiased evaluation as neurophysiological research methods, it is possible, in the light of these general evaluative results, to develop methods for studying more restricted problems in the same spirit, but with restricted means. By joint prosecution of global and specialized analyses, we hope best to advance neurophysiological research.

SUMMARY

Continuous spectral analyses of several minutes of normal human EEGs were prepared by computer, and converted to a compact graphic form. This new presentation of voluminous data in contour maps gives an overview of the evolution of patterns in the EEG. Parameters graphed were spectral intensity ("power spectral density"), and coherence, a quantity expressing strength of relationship between brain areas. The strongest relations were among longitudinally oriented parieto-occipital linkages, representing the subject's alpha wave. Wave activity in a similar frequency band, recorded across the occipital midline, was completely incoherent with the alpha wave. Thus two independent generation processes in the same frequency band are required to account for these records. Low frequency activity in two leads was related only partially to the heart-beat.

Fig. 1. Contours of Spectral intensity for five leads, simultaneously recorded from a narmal subject. Construction of the contours is explained in the text, and by Fig. 2. Time-frequency loci of intensity greater than 10 $uv^2/(c/sec)$ are darkened, but note that high peaks are attained, particularly at 11 c/sec, just after 4 minutes. For lead abbreviations and description of stimulus, see methods section. A summary of the subject's performance is shown below the map for LCPO. Note similarity of evolution of A-P oriented leads, in contrast with laterally oriented BIOCC.

Fig. 2. Construction of Contour Maps

A. The map for LCPO, shown at a larger scale than in Fig. 1. Note clustering of many contour curves (indicating a steep and high peak) at 11 c/sec, just after 4 minutes, when an unusual stimulus group was presented.

B. Autospectrogram for the first 12-second epoch of this situation, from which the left-hand beginnings of the contour curves were derived, as shown by lead lines. Those intensity levels at which it was decided to create contour curves are drawn in part B, as lines parallel to the frequency axis; the frequency at which the autospectrogram crosses such a line (as determined by interpolation) is carried to the map, and initiates a contour curve. Each contour level has a code (given in Fig. 1, lower right) by which its contour curves are distinguished. The chosen contours levels are at approximately constant logarithmic intervals, so that the density of contours is as if the logarithm of the intensity had been plotted.

Fig. 3. Contours of Coherence for Pairs of the Same EEGs Analyzed in Fig. 1. The line and arrows from the location of the lead RCP on the head diagram indicate that each of the three maps in the left-hand column show the relations of RCP with another lead; for instance, the top one relates RCP and LCPO. The bifurcated arrows from LCPO and RCPO direct attention respectively to the three maps for each of these leads' relations. Finally, the line from BIOCC indicates that the three maps in the bottom row show BIOCC's relationships. Loci of significant coherences (see methods) are blackened.

The time period covered extends slightly further than that analyzed in Fig. 1. Note the disappearance of alpha-band coherence just before first unusual stimulus group.

Fig. 4. Contours of intensity for Subject 212. Linkages as in Fig. 1. Note that shading begins at a lower intensity level for this figure than for Fig. 1 (an area near 9 c/sec, 60 sec was erroneously left unshaded in the RCP map). The "Time histories of spectral intensity" represent slices through the topographies represented by each of the contour maps, slices made at the 9.5 c/sec line. Note relative similarity between the time histories of LCP and RCP, and between LCPO and RCPO.

Fig. 5. Selected contours of coherence for the same records analyzed in Fig. 4. Note coherence maxima in range of intensity maxima; but left/right coherences (LCP/RCP and LCPO/RCPO) are higher than anterior/posterior ones (LCP/LCPO). Coherences with BIOCC again very low.

Fig. 6. Density-modulated transformation of portions of preceding two figures. Seconds from beginning of situation marked at left, frequency scale across the bottom. Each numbered swath shows relative intensity in LCP (upward ticks), intensity in RCP (downward ticks), and coherence between them (symmetric ticks). The calibrations at the top are of coherence. Note the wide coherent band surrounding the relatively narrow alpha bands.

Fig. 7. Contours of Intensity for Subject 213.
Note the remarkably stable upper boundary of the alpha-wave ridge in the A-P oriented leads, in contrast to the more modulated BIOCC. Note that the extracted time histories of spectral intensity at 9.5 c/sec are very similar among the first three leads, but different in both others.

Fig. 8. Selected contours of coherence for the same records analyzed in Fig. 7. Note low-frequency coherences in addition to those in alpha range.

Fig. 9. Hypothetical composition of generation processes. See text.

FOOTNOTES

1. This normative library was conceived and created under the sponsorship and encouragement of Dr. J. Henry and Dr. L. F. Dietlein. We are happy to acknowledge support of this work by NASA, under contract NAS 9-1970 and Grant NsG 505, and by USPHS, under Grant NB 2501-04, and USAF under Grant AF-AFOSR 246-63.

2. It is a pleasure to acknowledge here the enthusiastic programming assistance of Mr. A. Parmelee, III.

3. We are indebted to Dr. M. Grahame for pointing out the possible special importance of small amounts of flutter in coherence analyses.

4. Note that the quantity called coherence in this paper is the square of the quantity so called in the reference paper; this accords better with others' usage.

REFERENCES

ALEXANDER, M. J. and VOK, C. A. *Tables of the cumulative distribution of sample multiple coherence.*, Rocketdyne Division, North American Aviation. Research Report, 63-37, 1963. (Limited Distribution).

CHATRIAN, G. E., BICKFORD, R. G. and UIHLEIN, A. Depth electrographic study of a fast rhythm evoked from the human calcarine region by steady illumination. *Electro-enceph. clin. Neurophysiol.*, 1960, *12*: 167-176.

CHAPMAN, R. M., ARMINGTON, J. C. and BRAGDON, H. R. A quantitative survey of kappa and alpha EEG activity. *Electroenceph. clin. Neurophysiol.*, 1962, *14*:858-868.

GOODMAN, N. R. Statistical analysis based on a certain multivariate complex Gaussian distribution. (An Introduction). *Annals Math. Stat.*, 1963, *34*:152-177.

HASSELMAN, K., MUNK, W., and MACDONALD, G. F. Bispectra of ocean waves. In M. Rosenblatt (Ed.), *Proceedings of the Symposium on Time Series Analysis.*, Wiley, New York, 1963, pp. 125-139.

KADO, R. T. Psychophysiological test and control system. Final Report, AF Contract AF 61(052)-203 and NASA Grant NASA 9-1200. 1964.

LAUGIER, H and LIBERSON, W. Contribution à l'étude de l'electroencephalogramme humain. *C.R. Soc. Biol. (Paris)*, 1937, *125*:13-17.

WALTER, D.O. Spectral analysis for electroencephalograms; mathematical determination of neurophysiological relationships from records of limited duration. *Exp. Neurol.*, 1963, *8*:155-181.

WALTER, D. O. and ADEY, W. R. Spectral analysis of electroencephalograms recorded during learning in the cat, before and after subthalamic lesions. *Exp. Neurol.*, 1963, *7*:481-501.

WALTER, D. O. and ADEY, W. R. Analysis of brain waves as multiple statistical time series. IEEE Trans. Bio-med. Eng., (In Press).

WALTER, D. O and BROWN, D. Mutual information between two physiological records. Physiologist, 1963, 6:293.

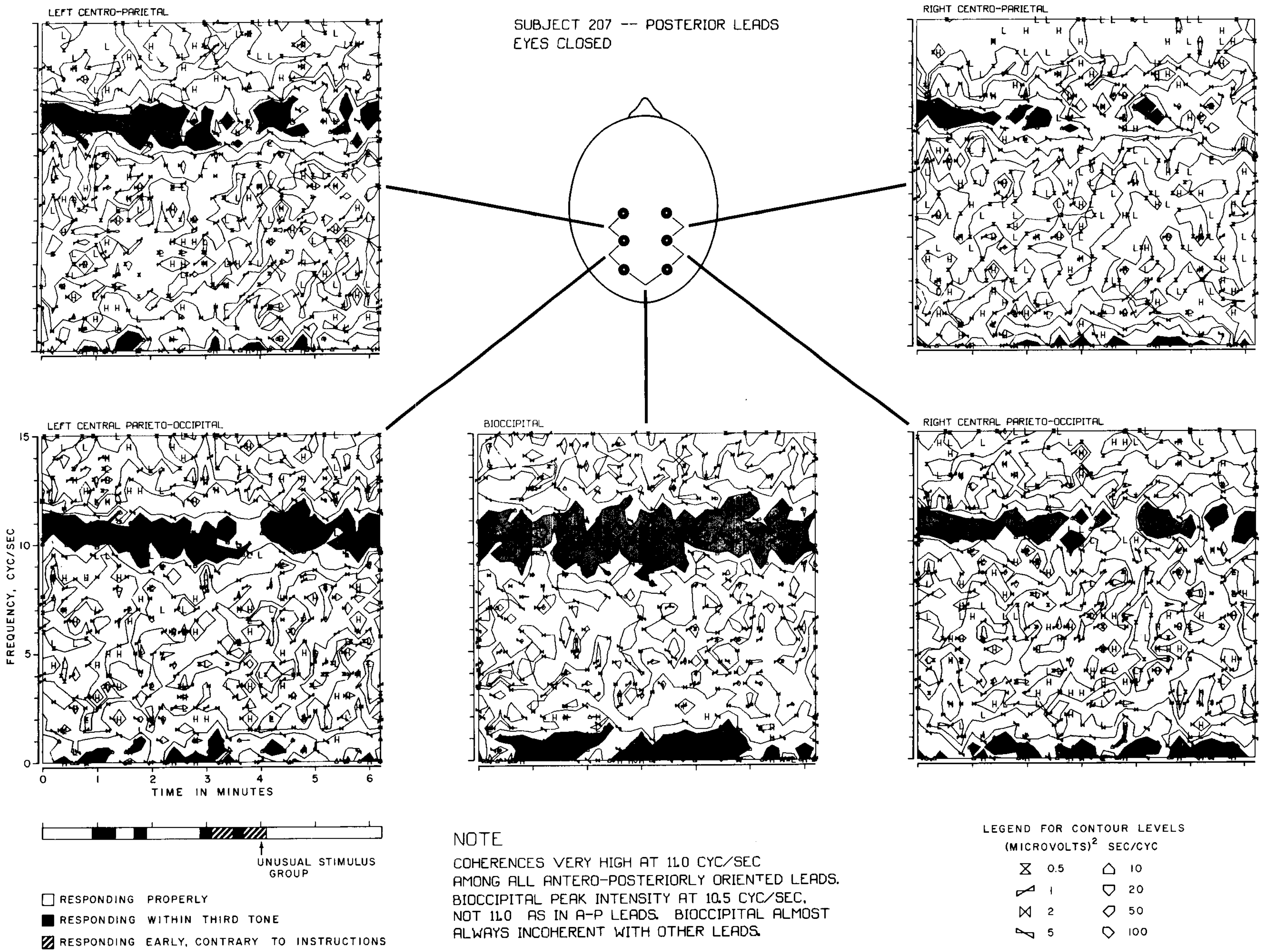
WALTER, W. G. Intrinsic rhythms of the brain. In J. Field (Ed.), Handbook of Physiology, Sect. 1, Amer. Physiol. Soc., Washington, D. C., 1959, 1:279-298.

WALTER, W. G. and CROW, H. J. Depth recording from the human brain. Electroenceph. clin. Neurophysiol., 1964, 16:68-72.

CONTOURS OF SPECTRAL INTENSITY   AUDITORY VIGILANCE TASK

SIMULTANEOUS AUTOSPECTRAL ANALYSES

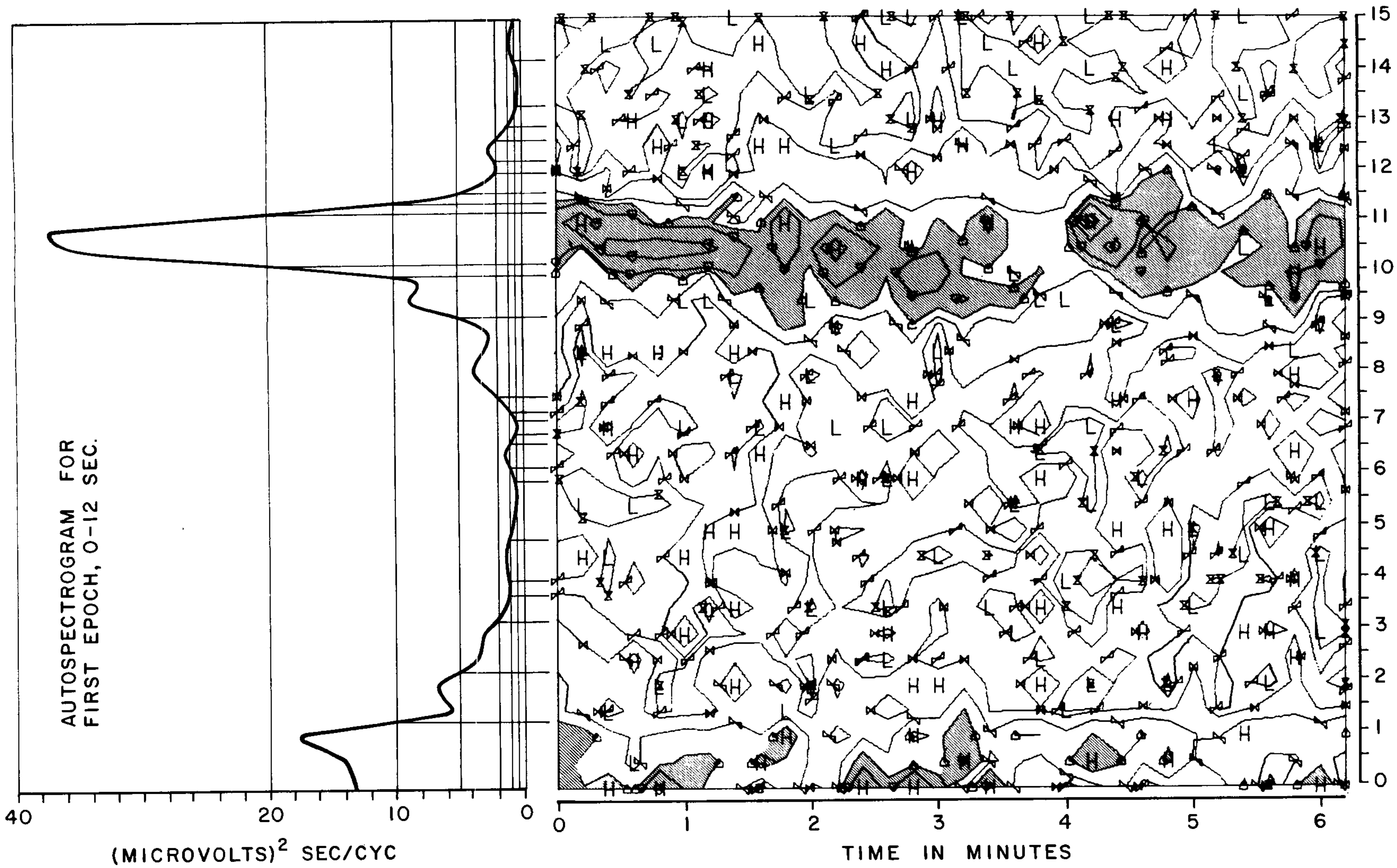
SUBJECT 207 -- POSTERIOR LEADS
EYES CLOSED



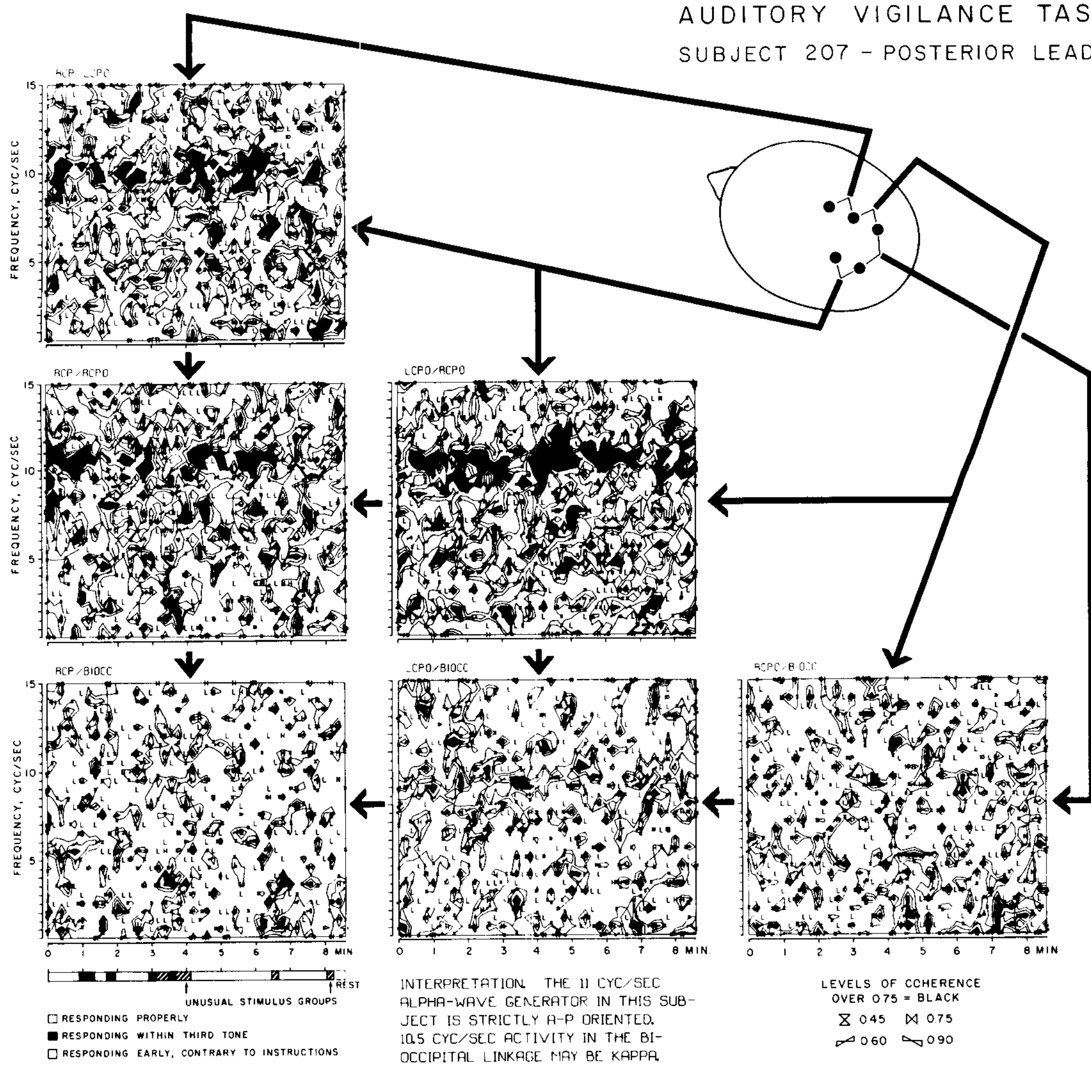
NOTE

COHERENCES VERY HIGH AT 11.0 CYC/SEC AMONG ALL ANTERO-POSTERIORLY ORIENTED LEADS. BIOCCIPITAL PEAK INTENSITY AT 10.5 CYC/SEC, NOT 11.0 AS IN A-P LEADS. BIOCCIPITAL ALMOST ALWAYS INCOHERENT WITH OTHER LEADS.

CONSTRUCTION OF CONTOURS OF INTENSITY

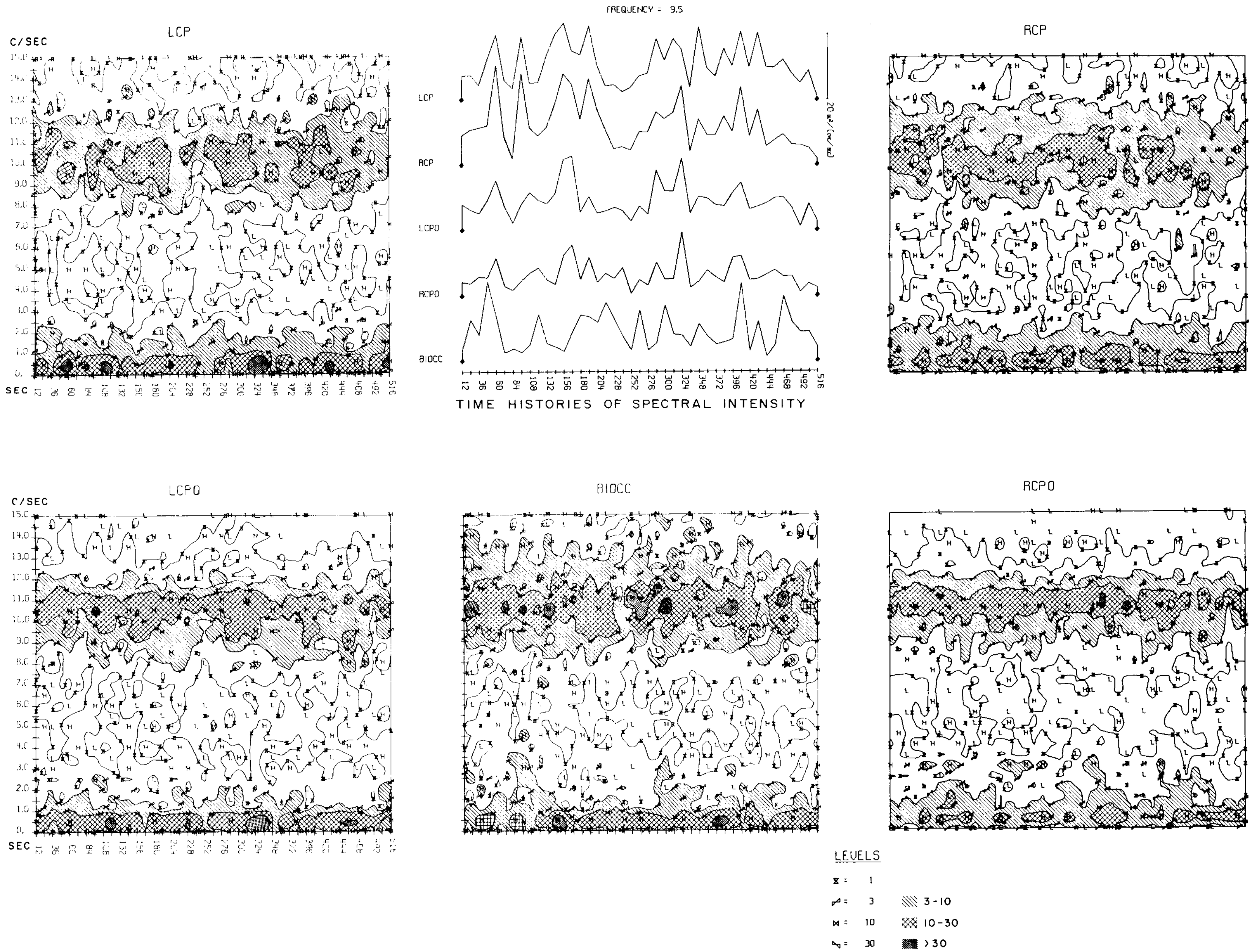


CONTOURS OF COHERENCE (LINEAR PREDICTABILITY)
AUDITORY VIGILANCE TASK
SUBJECT 207 - POSTERIOR LEADS

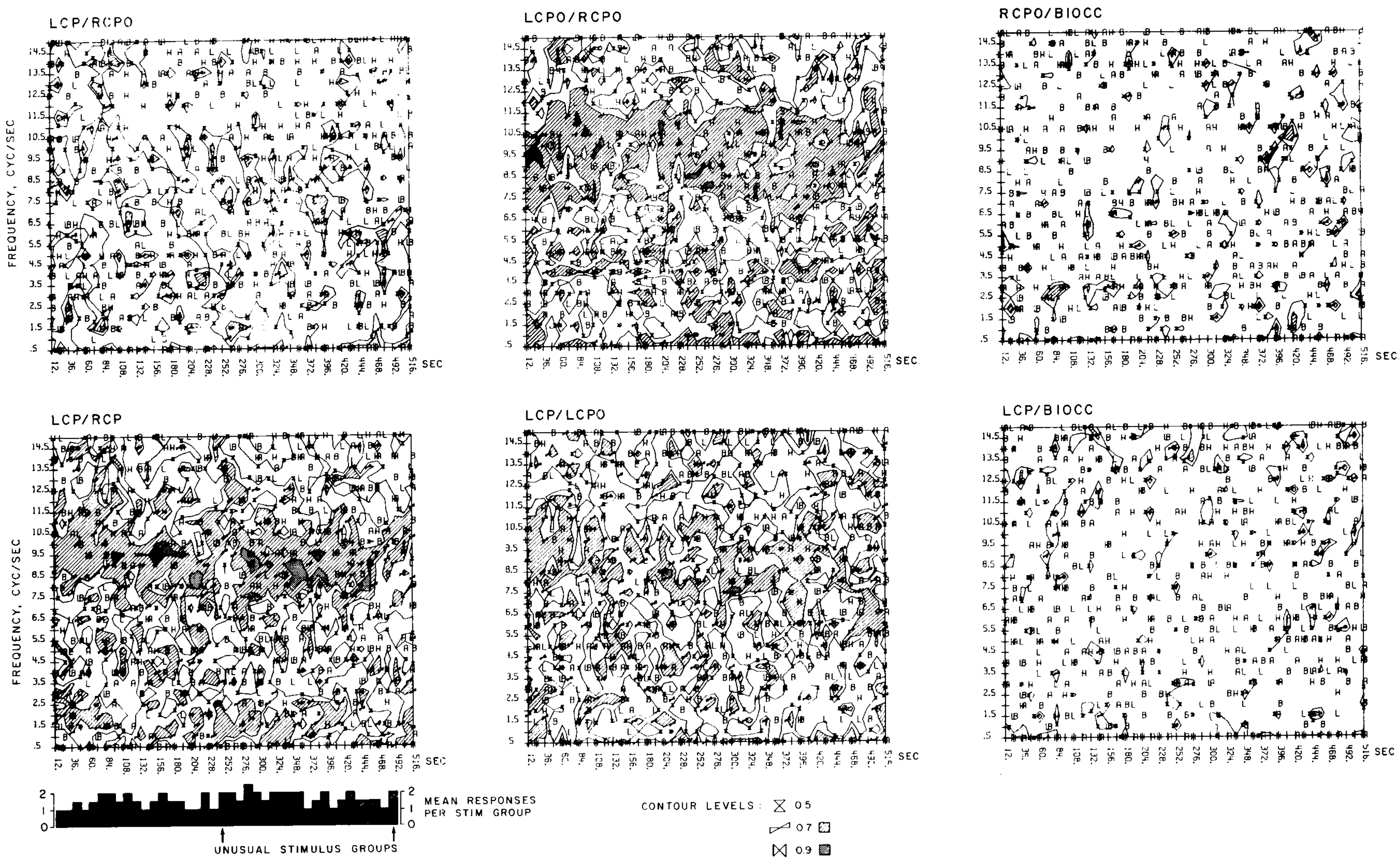


INTERPRETATION: THE 11 CYC/SEC ALPHA-WAVE GENERATOR IN THIS SUBJECT IS STRICTLY A-P ORIENTED. 10.5 CYC/SEC ACTIVITY IN THE BI-OCCIPITAL LINKAGE MAY BE KAPPA.

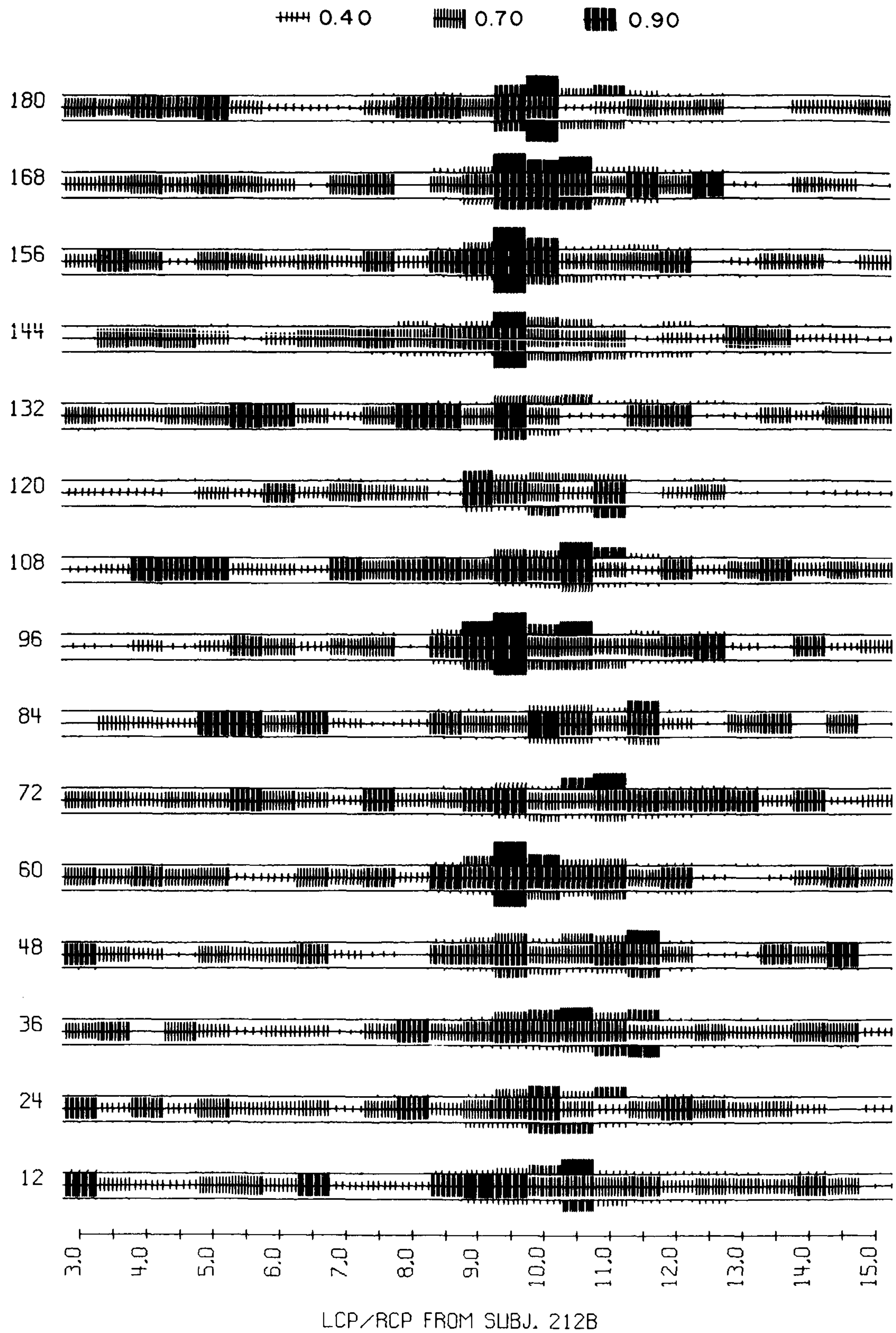
PATTERNS OF AUTOSPECTRAL INTENSITY
SUBJECT 212 AUDITORY VIGILANCE TASK



SELECTED CONTOURS OF COHERENCE
(LINEAR PREDICTABILITY)
AUDITORY VIGILANCE TASK SUBJECT 212

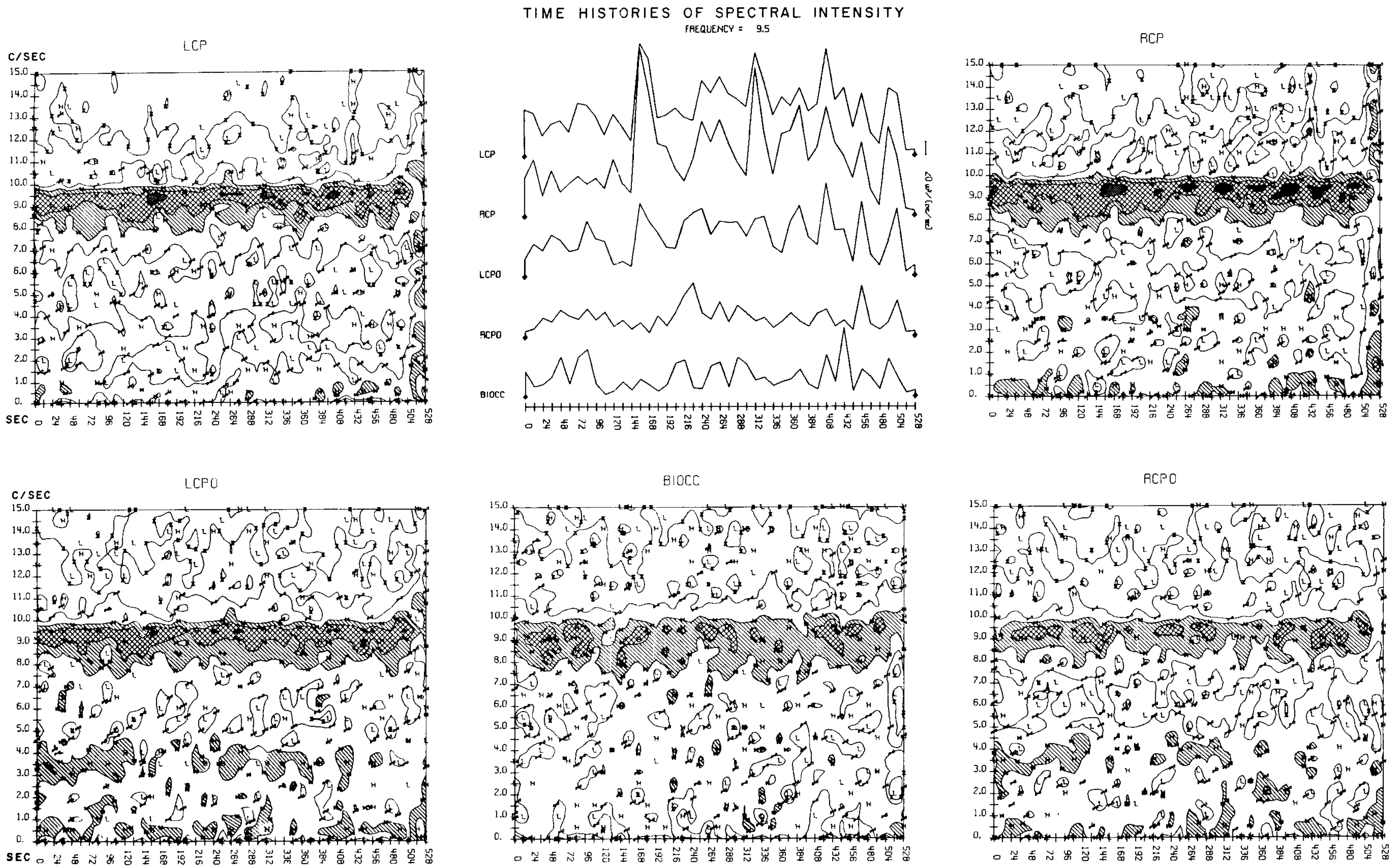


PATTERNS OF SPECTRAL SHARING
IN AUDITORY ATTENTION



PATTERNS OF AUTOSPECTRAL INTENSITY

SUBJECT 213 AUDITORY VIGILANCE TASK

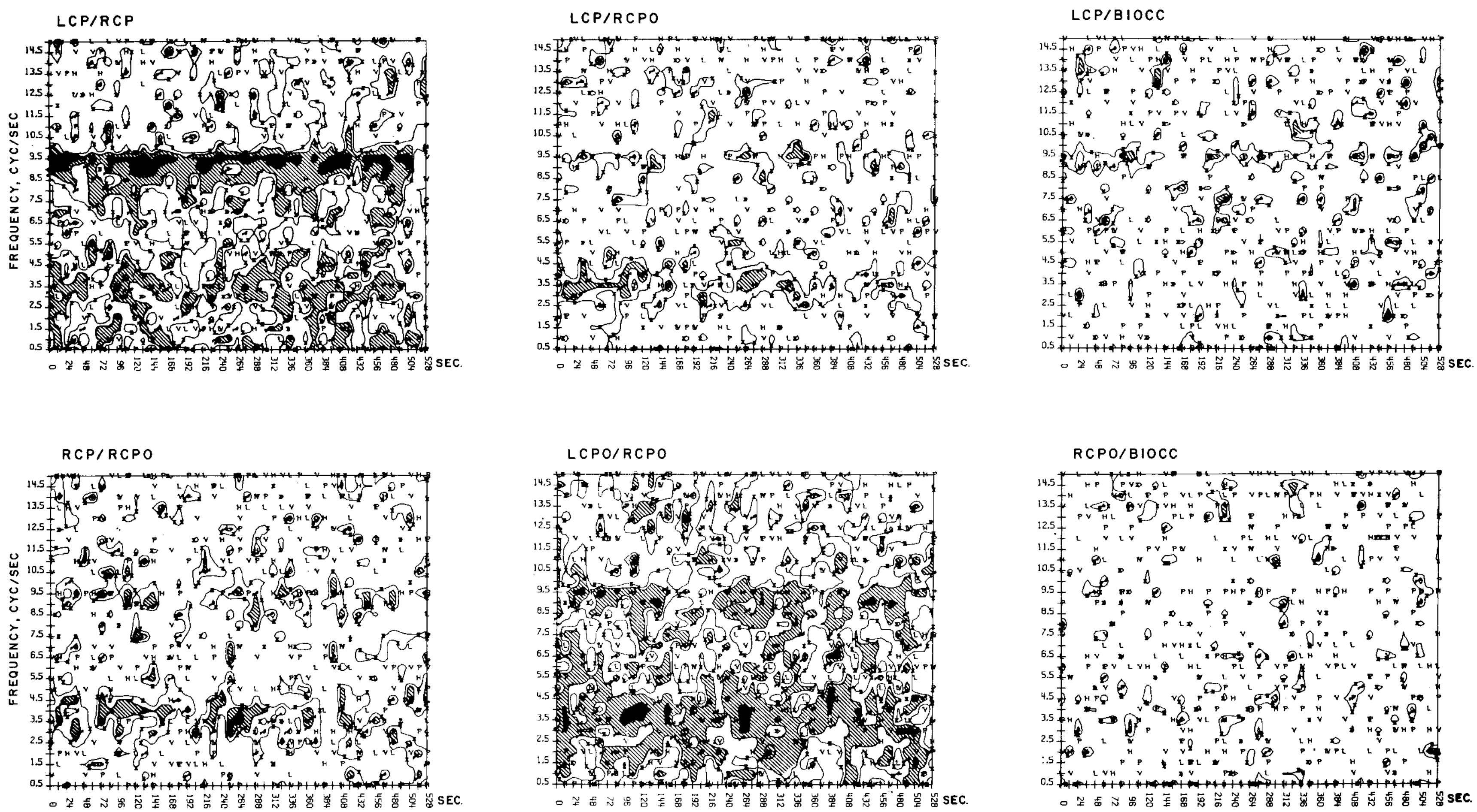


THIS SUBJECT MADE NO ERRORS.

LEVELS

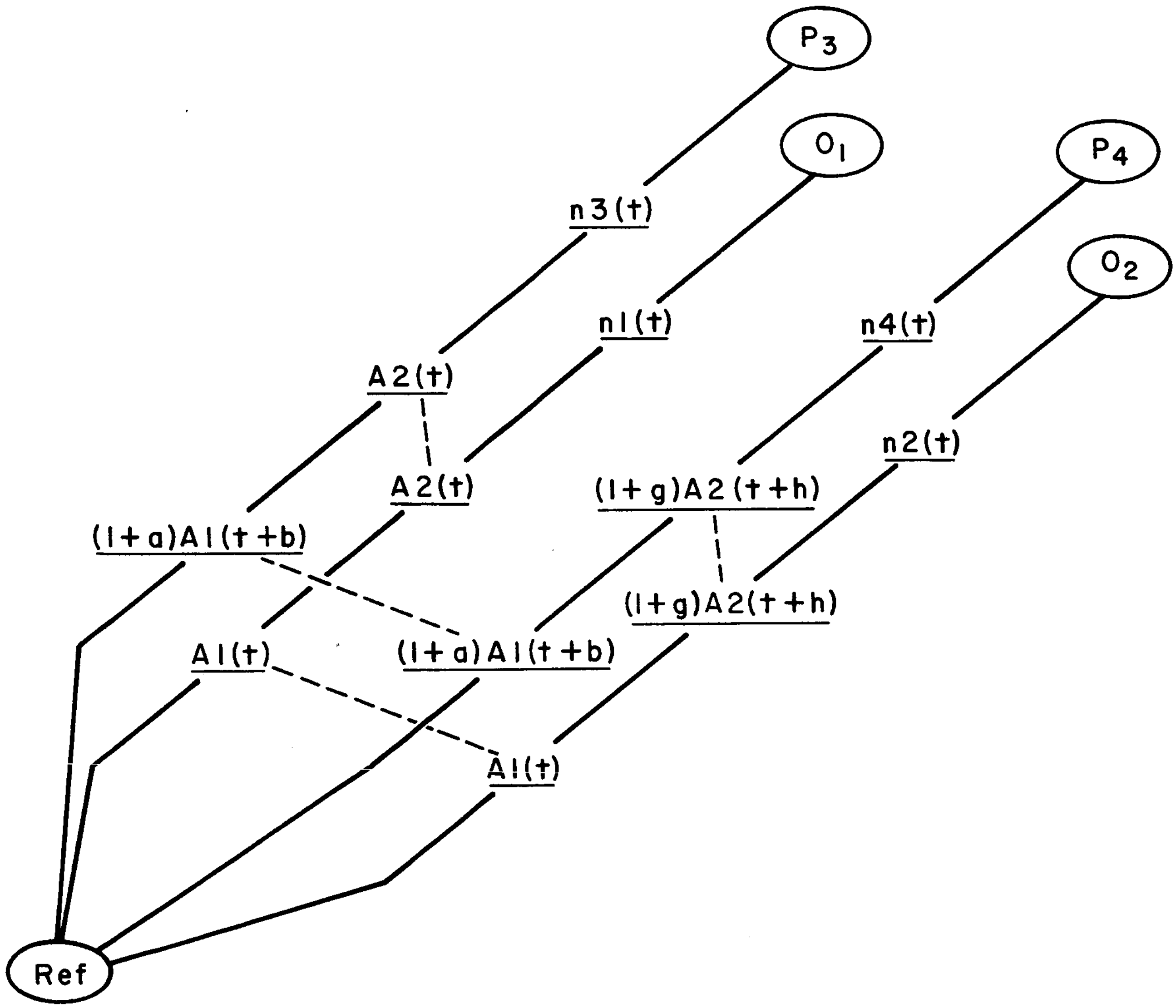
= 1	= 10	10-30		
= 3	= 30	30-100		
	= 100	>100		

SELECTED CONTOURS OF COHERENCE
AUDITORY VIGILANCE TASK SUBJECT 213



THIS SUBJECT MADE NO ERRORS.

CONTOUR LEVELS: 0.5
0.7
0.9


P3
O1
P4
O2
n3(t)
n1(t)
n4(t)
A2(t)
n2(t)
A2(t)
(1+g)A2(t+h)
(1+a)A1(t+b)
(1+g)A2(t+h)
A1(t)
(1+a)A1(t+b)
A1(t)
Ref