EEG COHERENCE DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE

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Increases in EEG coherence specific to the Transcendental Meditation technique, especially in the alpha and theta bands, indicate increased ordering of brain wave activity during practice of the Transcendental Meditation technique. —EDITORS

The mathematical quantity called coherence provides a measure of the constancy of the relationship between the phases of the EEG at a specified frequency when measured at two spatially separated points of the scalp. As such, it is a sensitive indicator of the degree of long-range order in cortical activity—at least to the extent that such orderliness is mirrored in the EEG.

Central and frontal electroencephalograms from 28 subjects, spanning a range of experience with the Transcendental Meditation technique of from 0 to 15 years, were analyzed by means of a new signal-processing method—the coherence spectral array. In most cases, increases in coherence specific to the Transcendental Meditation technique, particularly in the alpha and theta bands, were observed relative to eyes-closed control periods.

Sleep studies showed that drowsiness and loss of consciousness are accompanied by decreases in coherence. Thus, the present findings indicate that the neurological state reached during the Transcendental Meditation technique differs from drowsiness, sleep onset, and simple eyes-closed relaxation—the difference being a higher degree of long-range ordering in the EEG.

Taken together with the physiological evidence of reduced metabolic rate, the present study supports the conception of a "state of least excitation" reached during the Transcendental Meditation technique and confirms the applicability and predictive value of analogies relating states of consciousness to states of physical systems.

INTRODUCTION

During the past five years, an intellectual discipline called the Science of Creative Intelligence (SCI) (10, 13) has crystallized around the thought of Maharishi Mahesh Yogi. Among the more interesting perspectives of the Science of Creative Intelligence is the recognition of striking parallels between features of subjective conscious experience and general principles of the physical sciences. For example, the well-documented spontaneous lowering of the metabolic rate during practice of the Transcendental Meditation (TM) technique (15) (the Transcendental Meditation technique itself being viewed as the applied aspect of SCI) is interpreted as being analogous to the natural tendency of physical systems to relax to states of lower excitation when removed from the more disordered perturbing influences of their environment. Indeed, the remarkable properties of the ground states of quantum mechanical systems of interacting particles and the vacuum state of quantum field theory have led to the bold suggestion (6) that there exists an analogous state of "least excitation of consciousness" and that the Transcendental Meditation technique provides a natural means for experiencing this state.* If this suggestion is followed to its logical conclusion, then the Transcendental Meditation technique could be viewed as a laboratory tool for probing the structure of the hypothesized state, and much of the available data on the physiological and neurological effects during the Transcendental Meditation technique can be reinterpreted as a characterization of the state of least excitation.

*For a discussion of this theory, see the introduction to this volume by Lawrence H. Domash. —EDITORS

To illustrate this point, R. K. Wallace's original data (14) on the consumption of oxygen in 19 subjects during the Transcendental Meditation technique can be re-expressed in each case as a proportion of the expected basal rate for that subject as determined from standard tables using the height, weight, age, and sex. By considering the "deepest" ten-minute segment of the period of the TM technique for each subject (i.e., the segment with lowest oxygen consumption) and using the thus normalized metabolic rate for this segment to estimate the deepest level of rest gained by that subject, one arrives at the histogram given in fig. 1. With the exception of the two subjects (both novices) whose ratios were slightly above unity, the data clearly indicate that during the Transcendental Meditation technique metabolic rates significantly below the predicted basal levels are achieved. More significantly, the clustering of values in the 0.75 to 0.80 range and abrupt fall-off at lower values are just the behavior one would expect if relatively short periods of a "ground state" of metabolic activity were in part responsible for the observed mean 25% below expected basal.

Since the metabolic rate data are at least suggestive of the existence of a unique physiological state, the question then arises whether the neurological correlates of the Transcendental Meditation technique show any qualitative features that could be interpreted as being indicative of a style of functioning distinctly different from that encountered in the more familiar states of consciousness.

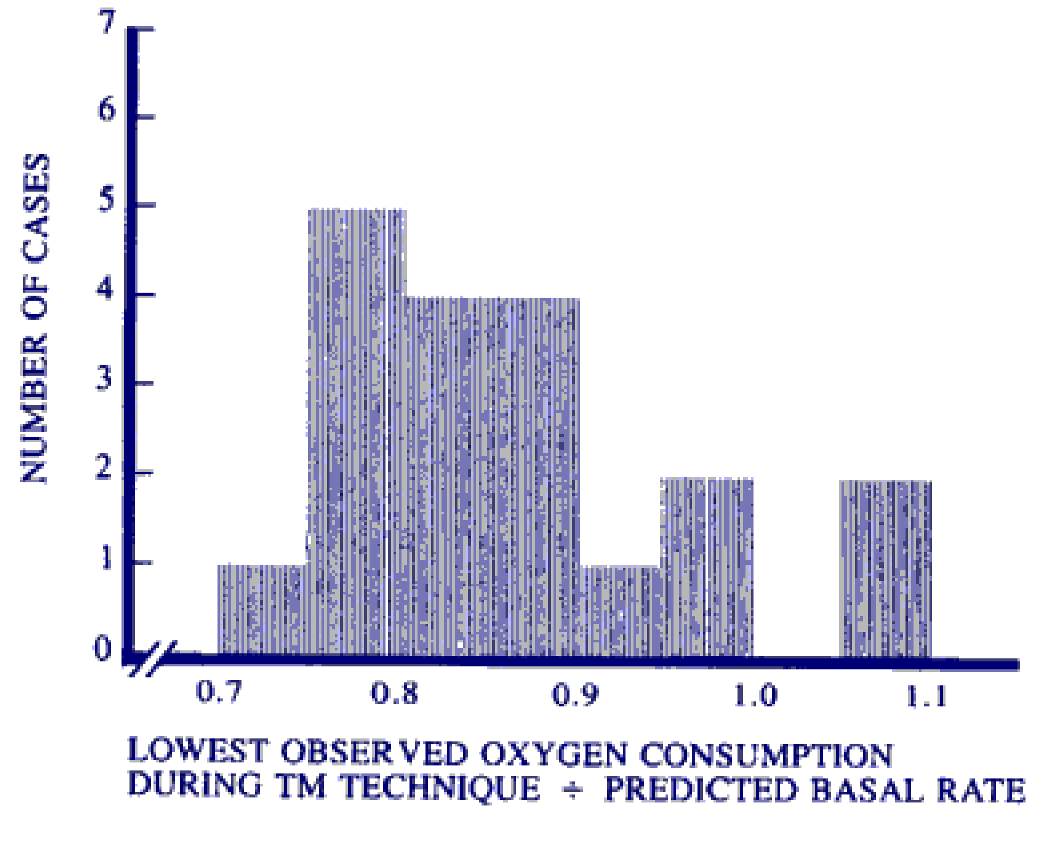


FIG. 1. REDUCED CONSUMPTION OF OXYGEN DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE: INDIVIDUAL SUBJECT DATA. Oxygen consumption was measured (14) at ten-minute intervals during a half-hour period of the Transcendental Meditation technique. The minimum oxygen consumption thereby determined for each subject was then expressed as a fraction of the expected basal rate as computed from age, sex, height, and weight. The histogram shows the distribution of these ratios for the 19 subjects studied.

In particular, it has been suggested (5, 12) that a state of least excitation should be characterized by a high degree of "orderliness" of brain function, perhaps even long-range spatial ordering analogous to that observed in coherent states of matter at low temperatures (e.g., superconductivity and ferromagnetism).

Some evidence for such ordering is already present in the literature. Banquet (1), who applied spectral analysis to the electroencephalograms (EEG) of 12 subjects practicing the Transcendental Meditation technique, called particular attention to a constant tendency towards synchronization of the anterior and posterior channels in the alpha, theta, and (in advanced subjects) beta bands during the Transcendental Meditation technique. In a later study (2) he found significant correlations in the phase of the EEG during the Transcendental Meditation technique between different monopolar derivations of a transverse montage 4 cm above the inion with electrode separation of 4 cm.

On the basis of the foregoing, it may be hypothesized that during the Transcendental Meditation technique, long-range ordering in the EEG should increase as indicated by an appropriate mathematical measure of the correlation between the activity recorded at different locations on the scalp. To test this hypothesis we have utilized a well-known measure called *coherence* and have determined the coherence both bilaterally and homolaterally between central and frontal derivations for a segment of the clinical EEG data base accumulated in our laboratory during the period August 1974 to June 1975.

In the paradigm employed, each period of the TM technique is immediately preceded and followed by a period of simple eyes-closed relaxation, and attention has been focused upon examples of changes in coherence specific to the TM technique in the different EEG bands. A rich variety of such phenomena has been found, and it is the purpose of this paper to provide representative examples of the more common types of effects specific to the TM technique along with estimates of the frequency of occurrence of each. As no attempt at rigorous statistics or careful controls has been made, the present study should be viewed as taxonomic in the sense that it identifies distinct patterns of spatial ordering in the EEG during the Transcendental Meditation technique, and leaves to future studies the investigation of behavioral and neurological implications.

METHODS

SUBJECTS—As part of an ongoing research program at Maharishi European Research University (MERU), comprehensive EEG measurements were performed on 80 subjects during the period August 1974 to June 1975. From this data base a representative subset of 28 subjects was

TABLE 1

SUBJECT DATA

CATEGORY	SEX	N	AGE (yrs)			MONTHS PRACTICING TM TECHNIQUE		
			Mean	Min	Max	Mean	Min	Max
Novice	M	5	34	19	67	...	...	...
	F	2	37	25	44	...	...	...
Experienced	M	10	28	21	39	55	26	89
	F	11	31	25	45	85	24	190
Totals		28	31	19	67	71	24	190

chosen for analysis in the present study. Pertinent subject data are given in table 1.

Of the seven novices, six were measured (on the same day) before and after their initial instruction in the Transcendental Meditation technique; the seventh was measured two weeks after instruction. With one exception, the experienced meditators were instructors of the Transcendental Meditation technique. The data analyzed in the present study utilized 35 separate runs, repeated measures having been taken on seven of the subjects.

PROCEDURE—The majority of experiments utilized in the present study (and in the data base as a whole) were designed to examine the Transcendental Meditation technique in its normal form, i.e., minimally influenced by the experimental procedure. Each subject, therefore, was seated in a comfortable chair in a room closely approximating the environmental conditions of a modern hotel room, with no specific attempts having been made to exert specific control over either ambient illumination, acoustic level, temperature, or humidity. Gold cup electrodes (9 mm Grass model E5G) were applied to the alcohol-cleansed scalp using Grass EC-2 electrode cream. The montage was monopolar with leads placed at O1, P3, T3, C3, F3, O2, P4, T4, C4, and F4 in the International 10–20 System. Bipolar linkages at F3–F4 and T3–T4 were also frequently recorded, or else these two channels were used for electro-oculograms. No uniform convention on reference electrode placement was in force, with homolateral, contralateral, and linked ears being variously used. The ground was to Cz except in instances where the skin resistance electrocardiogram was concurrently taken, in which case ground was on the hand. In most of the experiments other physiological variables were monitored along with EEG, the common examples being the electrocardiogram, skin resistance, and respiration (thermocouple). Postural changes were observed by means of a closed-circuit video system. Electrode impedances were checked with a Grass model EZM impedance meter and were kept below ten kilohms.

Twelve channels of a Grass model 78B polygraph were used for primary amplification and paper chart recording, with J6 outputs being connected to the digital system described below. The three dB settings of the Grass model 7P511G EEG amplifier filters were at 0.3 Hz and 0.1 kHz, with a notch filter inserted at 50 Hz.

A typical experiment involved five sequential periods: eyes-open precontrol (EO, 5 min), eyes-closed precontrol (EC, 10 min), the Transcendental Meditation technique (TM, 20–30 min), eyes-closed postcontrol (EC, 10 min), and eyes-open postcontrol (EO, 5 min). The subject was verbally signaled over an intercom to switch from one experimental condition to the next, having been briefed in advance on the structure of the experiment. The instruction for the eyes-closed precontrol period was to relax but not to practice the TM technique. In the eyes-closed postcontrol period, the subjects were instructed to follow the customary procedure of taking two to three minutes to come out of the period of the TM technique but not to open the eyes until instructed to do so.

The 12 channels of EEG/EOG (electroencephalogram/electro-oculogram) data output from J6 of the Grass amplifiers and the physiological channels were digitized on-line to 12 bits at 50 samples per second per channel in a Megatek Laboratory Interface (Megatek Corporation, San Diego, California) connected to a Data General NOVA 2/10 minicomputer with 24K of 800 nanosec memory and hardware multiply/divide. Epochs of 5.12 seconds (256 samples per channel) were recorded on a nine-track 45-inch-per-second 800-bytes-per-inch digital tape recorder. Simultaneously with the data acquisition and recording, six channels of the EEG were Fourier transformed and the power spectrum displayed together with the digitized time-domain EEG on a Hewlett-Packard 1310A CRT display, the self-refreshed display being generated in the Megatek Laboratory Interface. The display for each epoch was stored on the magnetic tape along with the raw digitized data. An epoch number contained in the display was keyed to the paper chart record by using computer controlled relays in the laboratory interface to activate the polygraph event marker, a feature that facilitated rapid *ex post facto* data review.

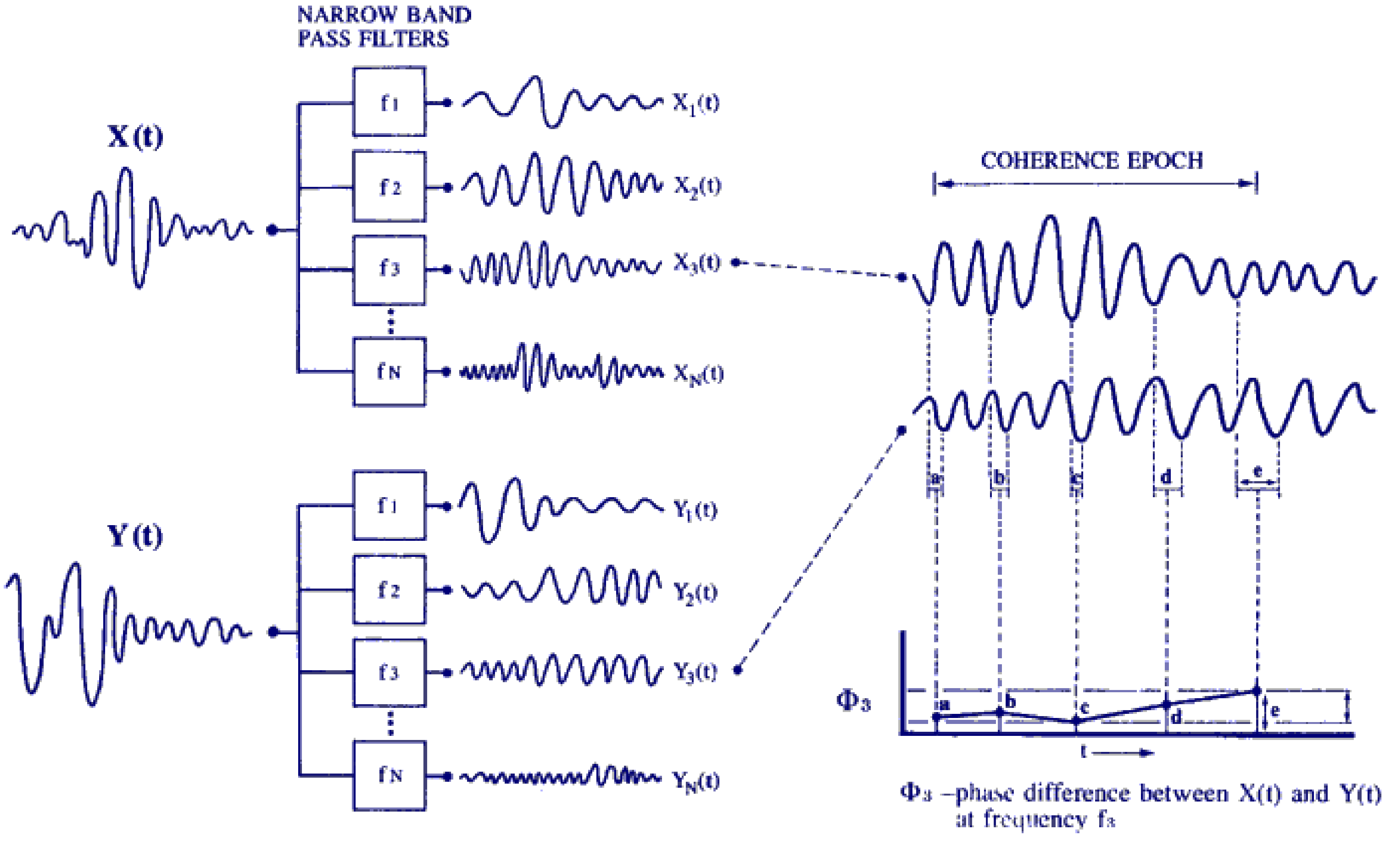
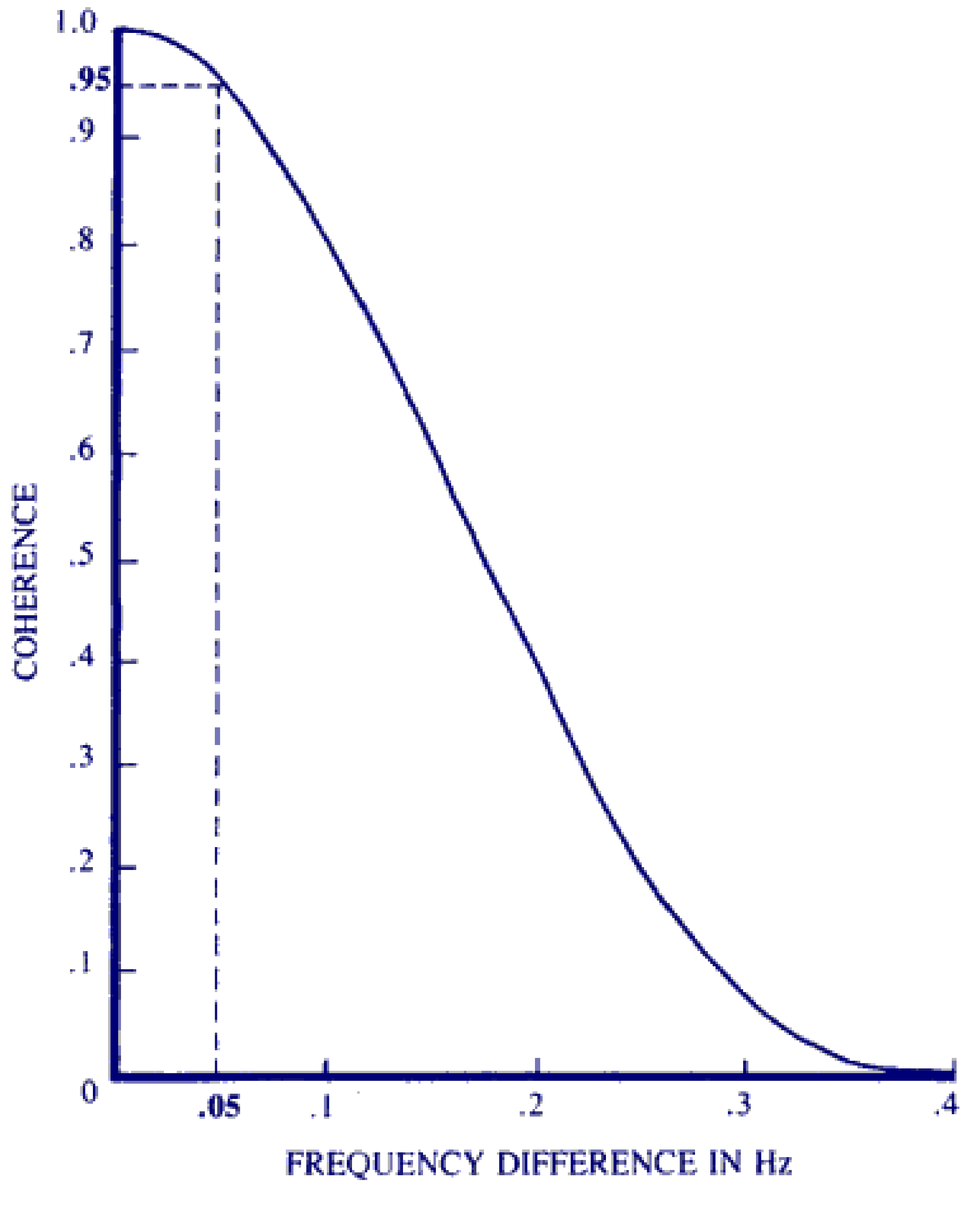


FIG. 2. SCHEMATIC ILLUSTRATION OF COHERENCE AT A GIVEN FREQUENCY. The importance of the relationship between coherence at a given frequency and variability of phase may be clarified by considering two independent signals, X(t) and Y(t), and imagining that each is passed through a bank of narrow band filters. The output of each filter will oscillate in time at a frequency close to the center frequency of the filter with an amplitude that increases or decreases in time as the input signal oscillations respectively occur at a frequency either closer to or further from the frequency to which the filter is tuned. If we now compare the outputs of corresponding filters, say at frequency f_3 as in the figure, then we would find that that the relative phase of these two filtered signals—as measured, for example, by the difference in time between corresponding turning points—in general will vary with time (a–e). Coherence at the frequency of interest is related to the *degree of variablity of the relative phase over a specified time interval—the greater the variability the less the coherence*. See Appendix for details.



TECHNIQUE OF ANALYSIS—The correlation of two EEG signals can be studied with a variety of mathematical techniques. Since frequency analysis has proved so useful in the characterization of the EEG, it was decided to utilize the *coherence spectrum* (see, for example, Dumermuth et al. (7)). The coherence spectrum provides a measure of the correlation between two EEG records for each frequency and attains a high value (i.e., near unity) at a given frequency if the phase relationship between the two channels is nearly constant over the time interval used to measure the coherence. (Mathematical details are given in the Appendix; see fig. 2 for a schematic explanation of coherence.)

To gain an indication of the sensitivity of the coherence

FIG. 3. COHERENCE OF TWO SINUSOIDS WITH UNEQUAL FREQUENCIES. The relative phase between two sinusoidal signals of nearly equal frequency increases linearly with time at a rate proportional to the frequency difference. Thus, as the frequency difference increases, the variation of the phase over a fixed analysis epoch increases, and the coherence decreases according to the function shown in the figure. Coherence in excess of 0.95 implies a frequency difference of less than 0.05 Hz for an analysis epoch of 2.56 seconds.

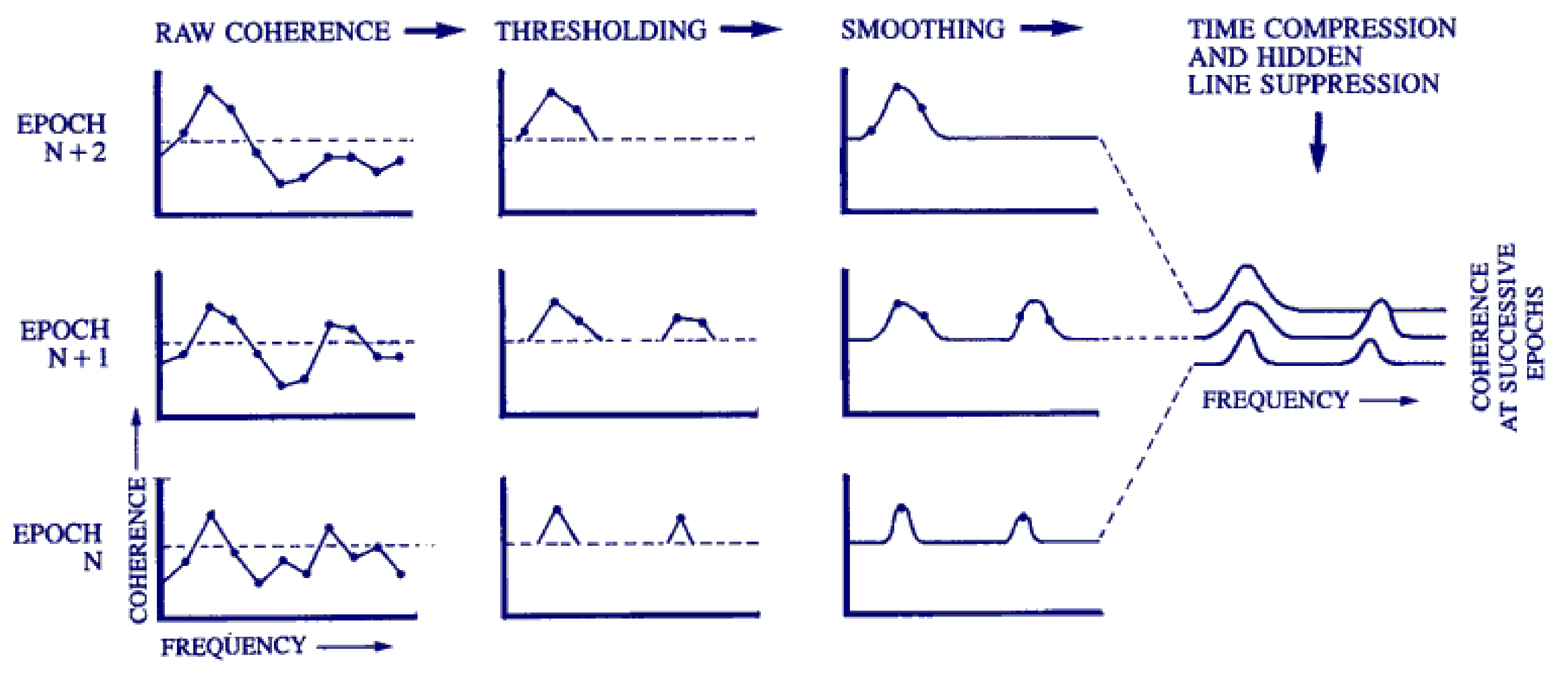


FIG. 4. THE COHERENCE SPECTRAL ARRAY ("COSPAR"). After choosing an epoch duration over which the coherence is to be defined, coherence is computed in each successive epoch at a set of discrete frequencies using the mathematical procedures described in the Appendix. The resulting "raw" coherence spectra are then submitted to a thresholding procedure in which only the *excess* coherence (if any) above the threshold level is retained. The angularly shaped peaks that result are then smoothed. Finally, the successive epochs are plotted one above the other in compressed form, with hidden lines being suppressed to create a three-dimensional effect.

measure to differences between the two signals, the case of two pure sinusoids of slightly different frequencies may be considered. If the frequency of one signal is kept fixed, then fig. 3 shows the coherence at that frequency as a function of the frequency difference between the two signals. Here the time interval with respect to which the coherence is defined is taken to be 2.56 seconds; doubling this interval would have the effect of halving the scale on the frequency axis (see Appendix for details). Note that a frequency difference of only 0.05 Hz is sufficient to reduce the coherence to 0.95.* Therefore, if coherence in excess of 0.95 is found at some frequency in the EEG from two spatially separated locations, one can conclude either that the two signals are synchronized by a common generator (therefore representing spatial ordering over that separation in the EEG) or that they arise from two independent generators whose frequencies happen to lie within 0.05 Hz of one another and that happen to be simultaneously operable. Since this latter circumstance is rather unlikely, the search for commonality in two EEG signals reduces to a search for frequencies at which the coherence is exceptionally strong—e.g., in excess of 0.95. The case for such commonality is obviously considerably strengthened if strong coherence is found at the same frequency for successive analysis epochs.

In order to provide a synoptic display of any existing strong coherence as a function of frequency and time, a mode of graphical presentation has been developed (11) called the *coherence spectral array* or "cospar" for short. It is an adaptation of the compressed spectral array technique (4) ordinarily used to present a time sequence of EEG power spectra in a single channel to instead display successive coherence spectra (relative to two channels). In the specific graphical technique employed in the present study, for each 5.12-second epoch of EEG data, partially overlapping data sets of 2.56 seconds' duration are averaged to obtain a coherence spectrum as a function of frequency within the 0–25 Hz band using the mathematical procedures described in the Appendix. Such spectra for successive epochs are then graphically combined as described in fig. 4.

The resulting cospar displays *excess* coherence (if any) above a given threshold—typically 0.95—as a function of frequency and time. The extreme compression of the spectral array, i.e., the close spacing between adjacent epochs, enables up to 700 epochs to be displayed in a single figure, thereby presenting a concise history of any strong coherence over the entire duration of an experiment. Figure 5 shows a section of an actual EEG record and the associated coherence spectra for two successive epochs.

To emphasize ongoing state-dependent instances of high coherence rather than sporadic events, and thereby to increase the likelihood that a coherence peak represents true long-range order in the EEG, it is useful to apply a (digital) filtering process prior to compression of the successive epochs. Such a procedure, which may be called

*This theoretical analysis must be slightly modified for the discrete coherence estimate used in this study. In this case a simulation revealed a coherence of 0.95 with a frequency difference of 0.08.

temporal continuity filtering, is illustrated in fig. 6. In this process, before a coherence peak is passed to the compressed array, it is required that coherence above threshold be observed in at least two successive epochs at the same frequency. The effect of temporal continuity filtering on an actual cospar is seen in fig. 7. The gain in clarity is striking, and for this reason all cospars analyzed in the present study have been filtered in this manner. Also, as seen in fig. 7, every cospar includes a second part that displays the total coherence for each epoch, this being a suitably defined measure of coherence over the entire 0–25 Hz band (see Appendix for details).

A single filtered cospar has the value of spotlighting correlated frequency components of the EEG recorded at two spatially separated locations, thereby suggesting in some sense a common origin or synchronizing mechanism for such activity. By examining multiple cospars constructed from different channels of simultaneous EEG data, it is possible to infer an approximate localization of coherent activity. For example, if a coherence peak is found in a bilateral central (C3/C4) and in a homolateral left (C3/F3) cospar, but not in a bilateral frontal (F3/F4) or homolateral right (C4/F4) cospar, then the appropriate inferred localization would be near C3, i.e., the derivation *common* to the two cospars displaying the peak. Figure 8 shows four simultaneous cospars obtained from two homolateral (intrahemispheric) and two bilateral (interhemispheric) pairs of central and frontal EEG, with linked-ears reference.* Note the differing levels of coherent activity in the four cases, the relative magnitudes of which may provide a "fingerprint" of the subject.†

The cospars were computed on the NOVA 2/10 minicomputer mentioned earlier and were plotted using a Hewlett-Packard 7040A x-y analogue plotter driven by a hard copy adapter unit contained in the laboratory interface. Smoothing of the coherence peaks was accomplished by exploiting the limited frequency response of the plotter. Thus, the frequency resolution in the coherence spectra is somewhat less sharp than the intrinsic 0.39 Hz (see Appendix). Software for the cospar computation and plotting was written in the version of laboratory BASIC supplied with the laboratory interface. This core-resident language contains drivers for all I/O devices as

*Our experiments indicate that the choice of reference electrode influences the coherence spectra. Symmetry considerations suggest the use of a common reference for all monopolar channels if topographical localization is to be attempted. Linked ears provide a suitable common reference.

†Work is underway in our laboratory to determine whether such fingerprints have behavioral correlates.

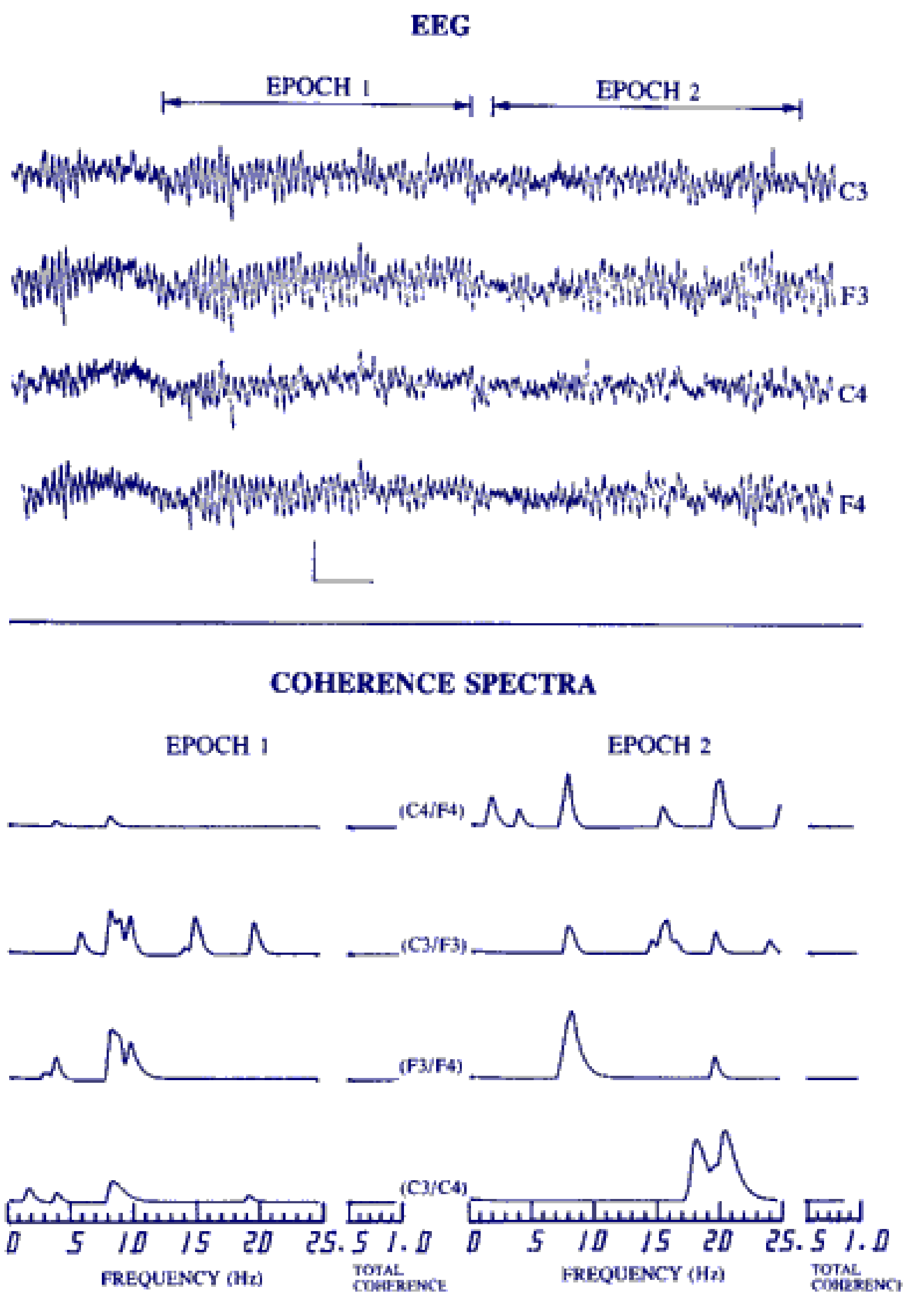


FIG. 5. EEG AND ASSOCIATED COHERENCE SPECTRA. Approximately 12 seconds of monopolar EEG from central and frontal derivations (referenced to linked ears) are shown in the upper part of the figure. In two successive 5.12-second epochs, coherence spectra were computed for the four combinations shown and were subjected to the thresholding (threshold = .95) and smoothing procedures described in fig. 4. Asymmetries in the shapes of the coherence peaks arise from the smoothing procedure. EEG calibration: 50 microvolts, one second.

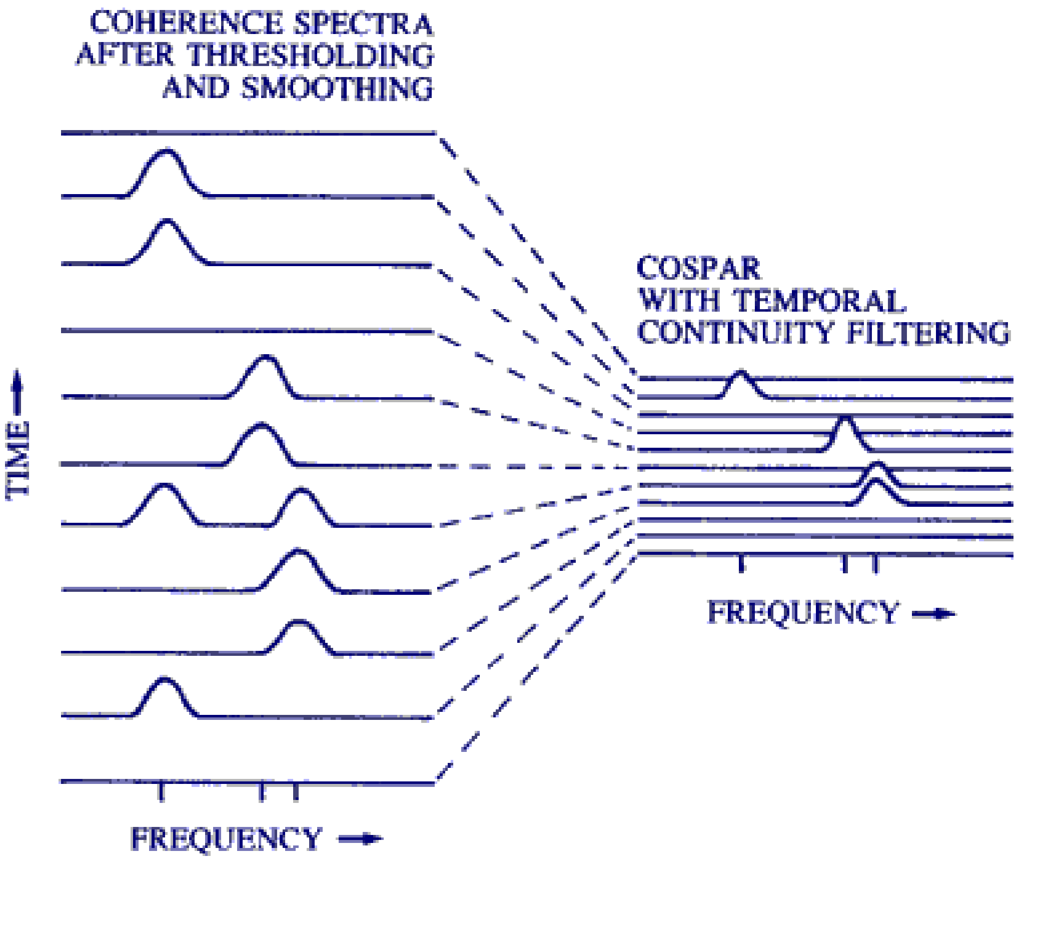


FIG. 6. TEMPORAL CONTINUITY FILTERING. Before a coherence peak is passed to the compressed array, it is required that the previous epoch should also have produced a coherence peak (i.e., above the threshold level) at that frequency.

well as a very efficient FFT (fast Fourier transform) and array arithmetic machine language subroutines callable from BASIC.

No artifact rejection algorithms were felt to be necessary in the calculations, since the temporal continuity filter eliminates most such sporadic events, and those that do survive the filtering process are easily recognizable as such. Similarly, no anti-aliasing measures were taken, since harmonics of 50 Hz alias to either 0 or 25 Hz (the ends of the analysis spectrum).

The statistical properties of the coherence spectrum, smoothed by the segment averaging procedure described in the Appendix, have not been fully explored, and it is thus not presently possible to precisely estimate the confidence limits for the spectral values. This is not a serious limitation in the present study, however, since the concern is with changes specific to the TM technique in the coherence spectra rather than absolute *magnitudes* of the coherence itself.

TOPOGRAPHICAL CONSIDERATIONS—While at least ten monopolar recordings had been taken for most subjects, analysis time limitations dictated that only a limited subset of the possible cospar combinations be computed. On the basis of both Wallace's (15) and Banquet's (1) observations of the tendency of the alpha activity to spread forward to the central and frontal derivations as the period of the TM technique progressed, it was hypothesized that the centro-frontal area would be the most likely place to observe coherence changes specific to the TM technique. Accordingly, the cases examined were limited

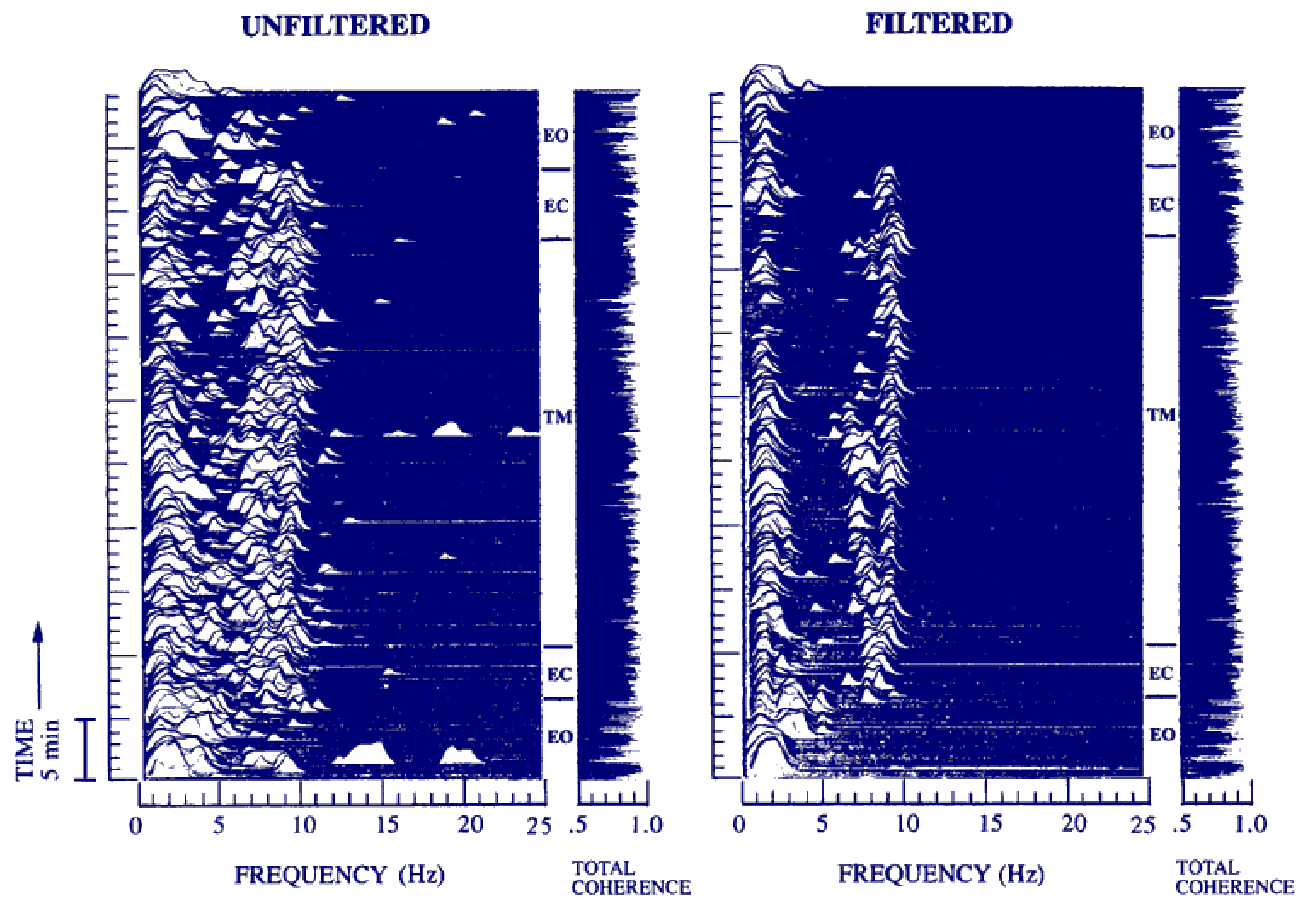


FIG. 7. EFFECT OF TEMPORAL CONTINUITY FILTERING ON ACTUAL COSPAR. A cospar displays coherence above a given threshold level (.95) as a function of frequency for successive 5.12-second epochs. A measure of the total coherence, i.e., taken over the whole 0–25 Hz band, is displayed for each epoch in the right-hand portion of the cospar. To increase the sensitivity of this measure, only the excess total coherence above 0.5 is plotted. The demarcation point between the different experimental conditions is indicated by a horizontal bar in the strip between the two portions of a cospar. (EO = eyes open; EC = eyes closed; TM = Transcendental Meditation technique.) The two cospars shown in this figure were computed from the same EEG data and illustrate the effect of employing temporal continuity filtering. Note the "forking" of the alpha (8–9 Hz) coherence peaks a few minutes after the start of the period of the TM technique, a feature that could not have been discerned in the unfiltered cospar.

Subject: Male, 25 yrs, 72 months' practice of TM technique
Cospars: Bilateral frontal (F3–A1/F4–A2)
Reference electrodes: Homolateral ear

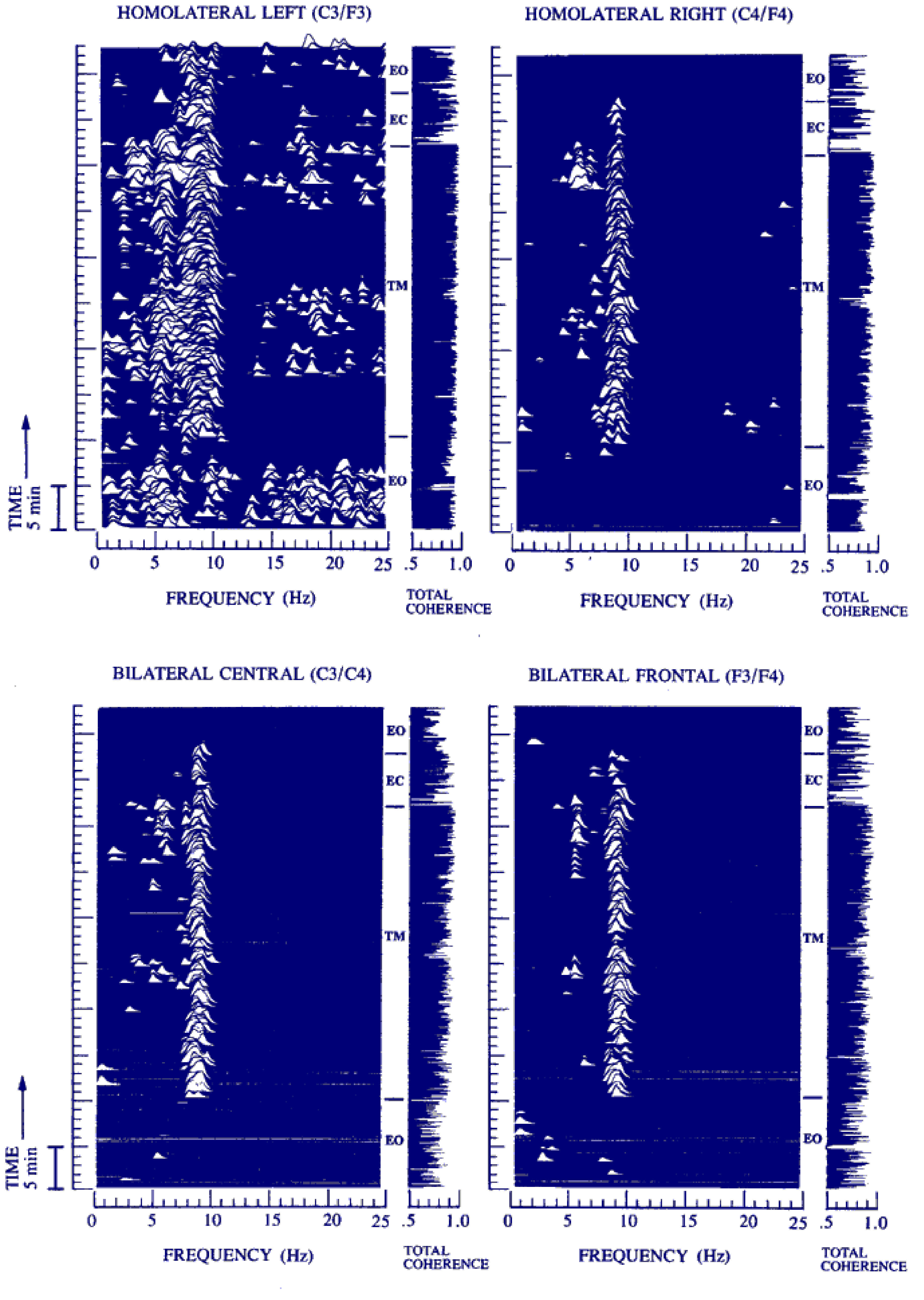


FIG. 8. RELATIONSHIP AMONG DIFFERENT COSPARS FOR SAME EXPERIMENT. The relative amounts of highly coherent EEG activity in the different possible cospars formed from the central and frontal derivations vary from one subject to the next and may constitute a "fingerprint" of the individual. In this example, the homolateral left cospar shows the most coherence. Simultaneous cospars are also useful for approximate localization of focal points of strong coherence. Note the abrupt decrease in total coherence coincident with the end of the period of the TM technique.

Subject: Male, 24 years, 68 months' practice of the TM technique
Reference electrodes: Homolateral ear

to bilateral frontal (F3/F4), bilateral central (C3/C4), homolateral left (C3/F3), and homolateral right (C4/F4). Since the four scalp locations involved in this study occupy approximately the corners of a rectangle 6 × 10 cm on the sides, these figures constitute the distance scale over which long-range ordering of the EEG is being probed.

RESULTS

CHANGES SPECIFIC TO THE TM TECHNIQUE IN THE ALPHA AND THETA BANDS—A total of 108 cospars* were computed for 35 experiments performed on the subjects previously described. The rich variety of effects seen in this data sample defies simple generalization and appears to reflect the wide range of subjective experiences during the Transcendental Meditation technique. In some cases, repeated measures led to quite similar cospars for the same subject on different days, while in other cases periods of the TM technique that differed greatly at the subjective level—particularly with respect to drowsiness (as judged both subjectively and objectively) during the technique—were also found to differ widely in their cospars. Figure 9 shows an example of the former category where, except for a few peaks near 15 Hz on the second day, the patterns are quite similar. Note especially how the coherence peaks in the alpha band are specific to the period of the Transcendental Meditation technique and how the total coherence abruptly drops at the cessation of practice of the technique.

In fig. 10, for a different subject, the alpha coherence is again seen to abruptly begin and end with the beginning and end of the period of the Transcendental Meditation technique. The total coherence in this case does not,

*Three of these were for sleep and sleep onset studies, and two were for a nonmeditator performing a counting exercise in place of the TM technique. The remaining 103 cospars involved a period of the TM technique.

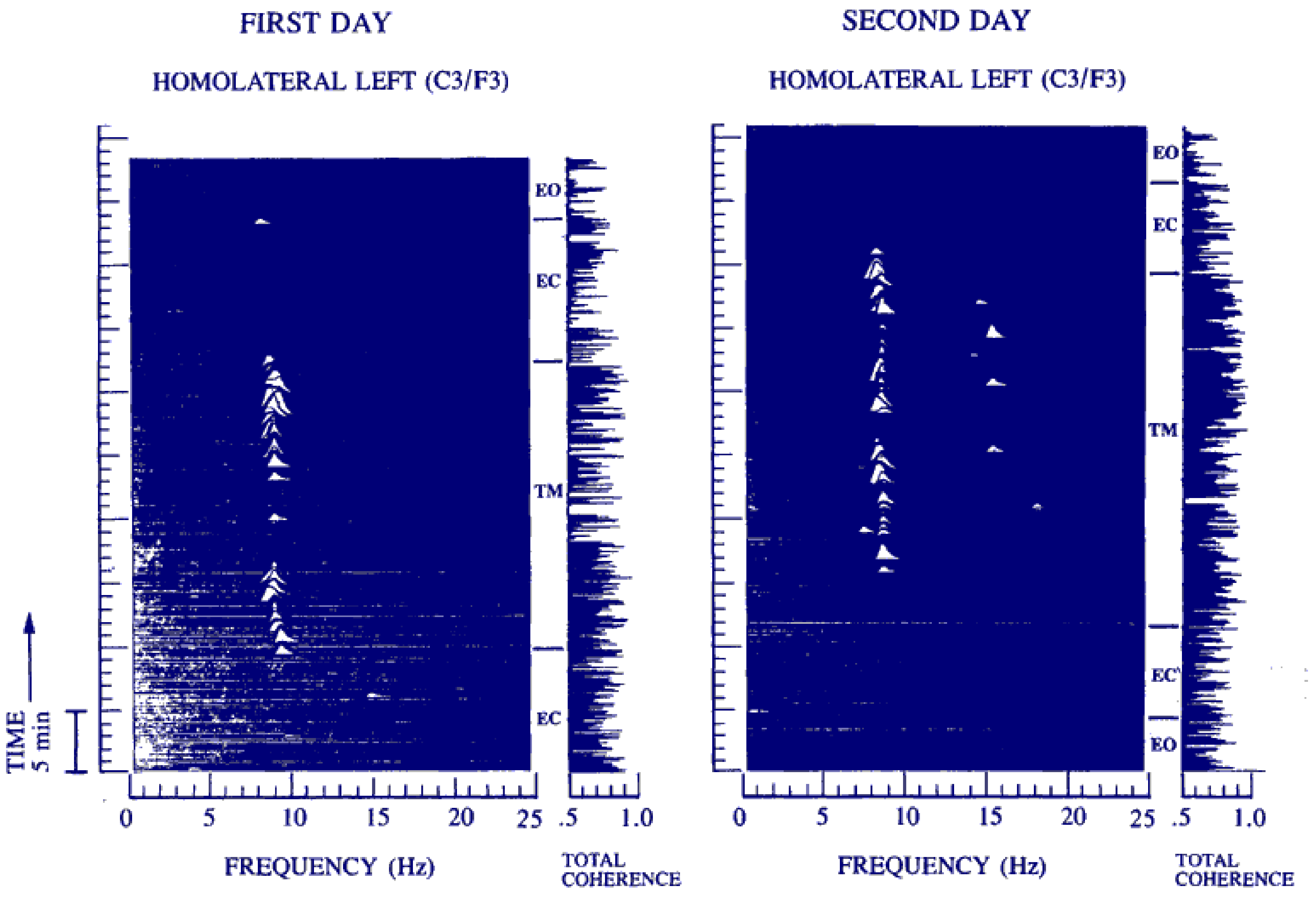


FIG. 9. COSPAR REPEATABILITY: NEW MEDITATOR ON TWO SUCCESSIVE DAYS. While details may vary from one experiment to the next, the overall form of the cospar is often found to be repeatable for a given subject, as seen in this set computed from the EEG taken on successive days. Note that the strong coherence in the alpha band (near 10 Hz) is specific to the period of the TM technique. The appearance of such coherence specific to the TM technique in a new meditator testifies to the immediacy of observable EEG effects with the Transcendental Meditation technique.

Subject: Male, 38 years (est.), two weeks' practice of the TM technique
Reference electrode: Linked ears

however, show any obvious changes among the experimental conditions. An interesting feature of this cospar is the beta coherence peaks near 20 Hz during the eyes-closed precontrol period. These will be discussed more fully later.

Figure 11 shows all four cospars for another run characterized by onset of strong alpha coherence during the period of the Transcendental Meditation technique. Here the total coherence as well showed a marked increase. Note how the alpha coherence is most pronounced in the bilateral frontal and least in the homolateral left cospars. As mentioned earlier, the relative strength of coherence in the different cospars varies from subject to subject. (Compare, for example, fig. 8 with fig. 11.) Delta band coherence appears in the bilateral central cospar at the end of the period of the TM technique and carries over into the eyes-closed postcontrol period. Since these peaks are not seen in the intrahemispheric cospars, nor in the bilateral frontal, it would appear that this coherent activity is specific to the central derivations in this case.

Figure 12 shows yet another example of both increased alpha and total coherence during the Transcendental Meditation technique. In this case, the coherence peaks are seen to spread to lower frequencies in the latter half of the period of the TM technique. Then, instead of disappearing at the end of the period, the peaks abruptly narrow in their frequency extent before fading away. Note at the end of the eyes-closed postcontrol period a reappearance of the broad coherence peaks. This may be due to the common experience of slipping back into practice of the technique in the postcontrol period, since this period is twice as long as the subjects customarily take to open their eyes following the cessation of the technique.

BILATERAL CENTRAL (C3/C4)

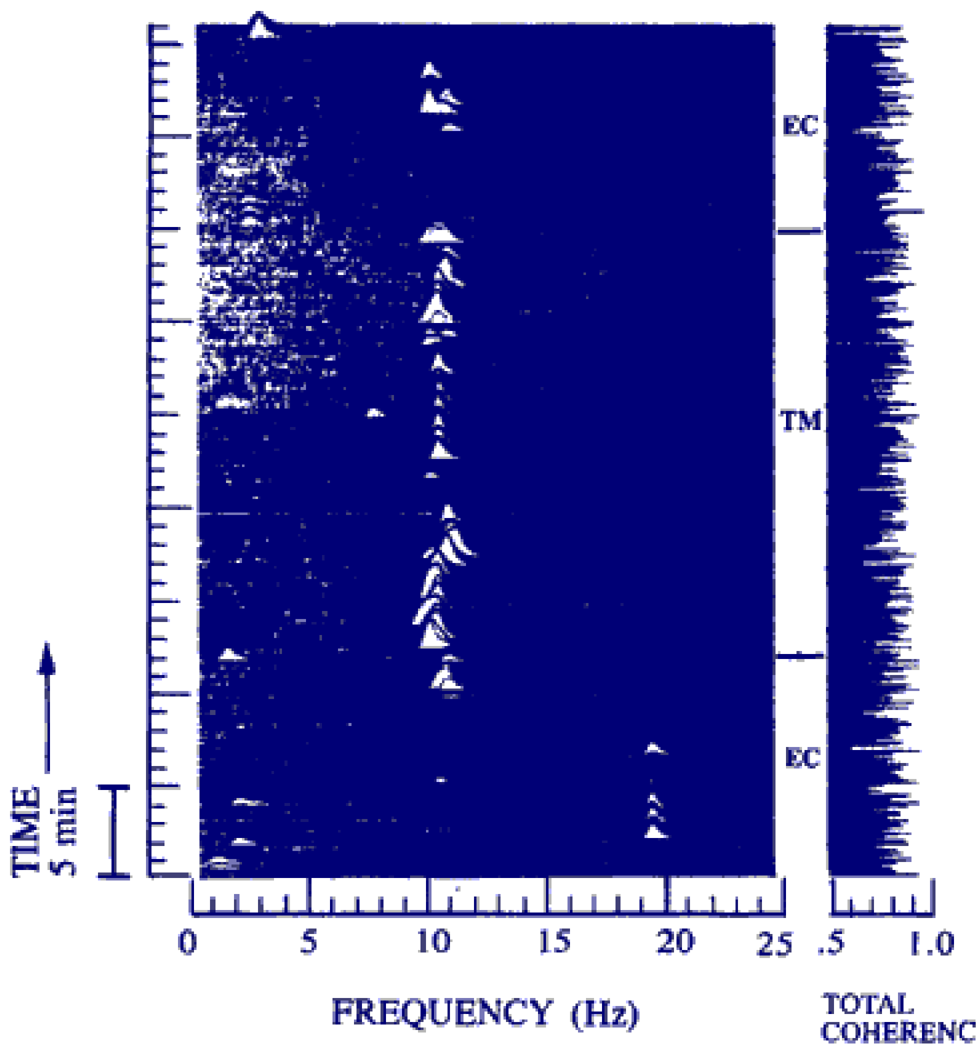


FIG. 10. COHERENCE CHANGES SPECIFIC TO THE TM TECHNIQUE. The coherence peaks near 10 Hz closely coincide with the start and end of the period of the Transcendental Meditation technique. Note the "rebound" of this activity in the latter half of the eyes-closed postcontrol period and also the coherent activity near 20 Hz during the eyes-closed precontrol period (see text).
Subject: Female, 29 years, 49 months' practice of TM technique
Reference electrode: Linked ears

The spreading of the coherence peaks from the alpha band to other frequencies constitutes a second type of change specific to the TM technique in the cospar that is frequently observed, particularly in more experienced meditators. In fig. 13, for example, strong coherence in the eyes-closed precontrol period is essentially limited to the alpha band; yet during the period of the TM technique coherence peaks are found also in the theta and beta bands. In fig. 14 the appearance of theta coherence in the second half of the period of the TM technique, which then abruptly disappears with the cessation of the technique, is the same pattern already seen in figs. 12 and 13. Note also in fig. 14 the "rebound" effect previously seen in fig. 12 where alpha coherence reappears at the end of the eyes-closed postcontrol period.

Examples of coherence changes specific to the TM technique sometimes are seen in one cospar but not another for the very same experiment. In fig. 15, for example, during the TM technique strong coherence develops in the theta band in the interhemispheric (bilateral frontal) cospar, but does not similarly increase in the intrahemispheric cospar. Conversely, the ongoing coherence near 20 Hz shows up in the intrahemispheric but not in the interhemispheric cospars.

Already in fig. 7 it was seen that the spreading of coherence specific to the TM technique can take a well-defined structural form such as a "forking" out from a single set of alpha coherence peaks. A more complex example is shown in the bilateral frontal part of fig. 16, where a distinct new set of peaks near 5 Hz emerges about one-third of the way into the period of the TM technique. This could be associated with a deepening of the experience of the technique, perhaps even the emergence of a separate substate as suggested by Banquet (1). It is especially interesting to note that this process is specific to the frontal cortex. This suggests that bilateral frontal cospars may be the most sensitive for exploring neurological changes in advanced meditators.

BETA COHERENCE—In fig. 10 attention was called to coherent beta activity near 20 Hz appearing during the eyes-closed precontrol period, but disappearing during the Transcendental Meditation technique. A similar effect

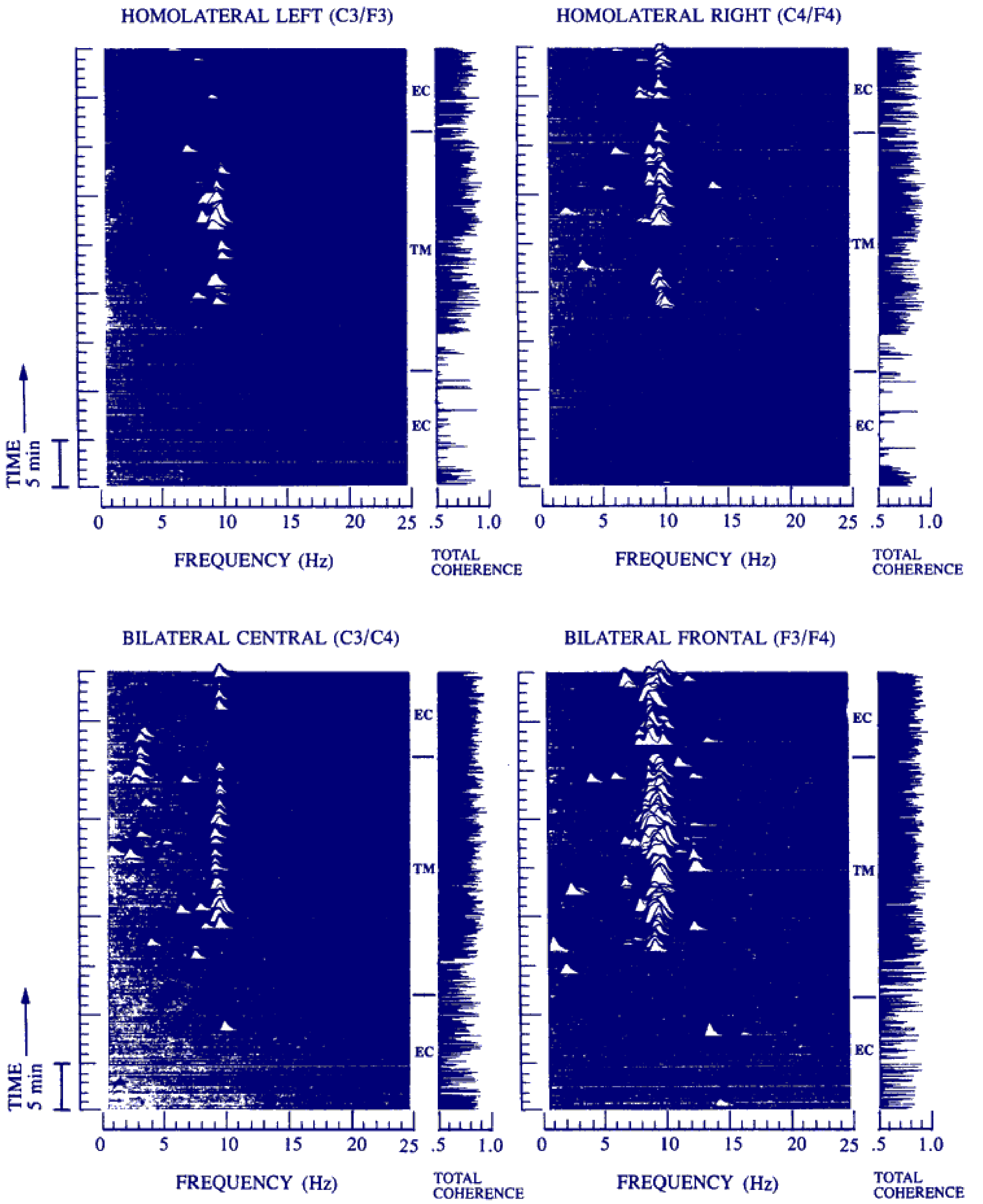


FIG. 11. COHERENCE CHANGES SPECIFIC TO THE TM TECHNIQUE IN SIMULTANEOUS COSPARS. Four simultaneous cospars from the same experiment show increased strong coherence in the alpha band during the Transcendental Meditation technique. Total coherence also shows a marked increase. Strong delta band coherence (near 3 Hz) at the end of the period of the TM technique appears in the bilateral central cospar.

Subject: Male, 27 years, 47 months' practice of TM technique
Reference electrode: Linked ears

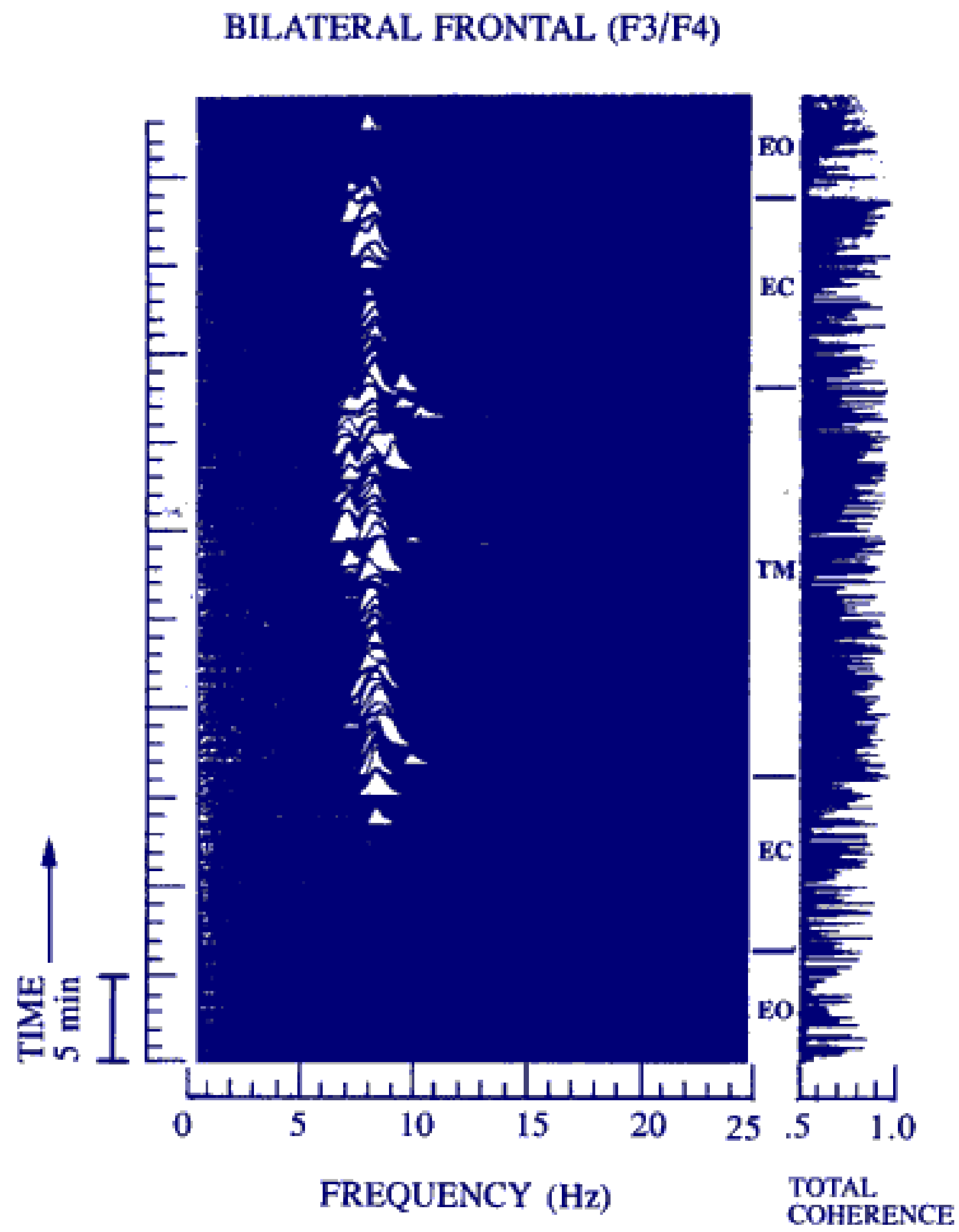


FIG. 12. VARIETIES OF COHERENCE INCREASES SPECIFIC TO THE TM TECHNIQUE. This bilateral frontal cospar shows three different types of increases in coherence specific to the TM technique: (*a*) total coherence increases during the Transcendental Meditation technique; (*b*) alpha band coherence peaks appear with the start of the period of the technique; and (*c*) theta band coherence peaks (near 7 Hz) appear during the latter half of the period of the technique and vanish with the cessation of the technique.

Subject: Female, 44 years, four months' practice of TM technique
Reference electrode: Linked ears

is seen in fig. 17. In other cases, the disappearance of the beta coherence is almost exactly time-coincident with the start of the TM technique. The well-defined and constant frequency of this signal looks suspiciously like artifact —in particular aliasing of the 120 Hz mains harmonic. However, it is difficult to understand its specificity to the TM technique. Also, when a "dummy" ten-kilohm load was inserted in place of the electrodes, the signal vanished, indicating that if it were such interference, it would have had to have been picked up directly at the subject's head, which was quite distant from any source of 120 Hz (mains in the subject room are 50 Hz).

Dumermuth (8) has cited cases where spectral analysis

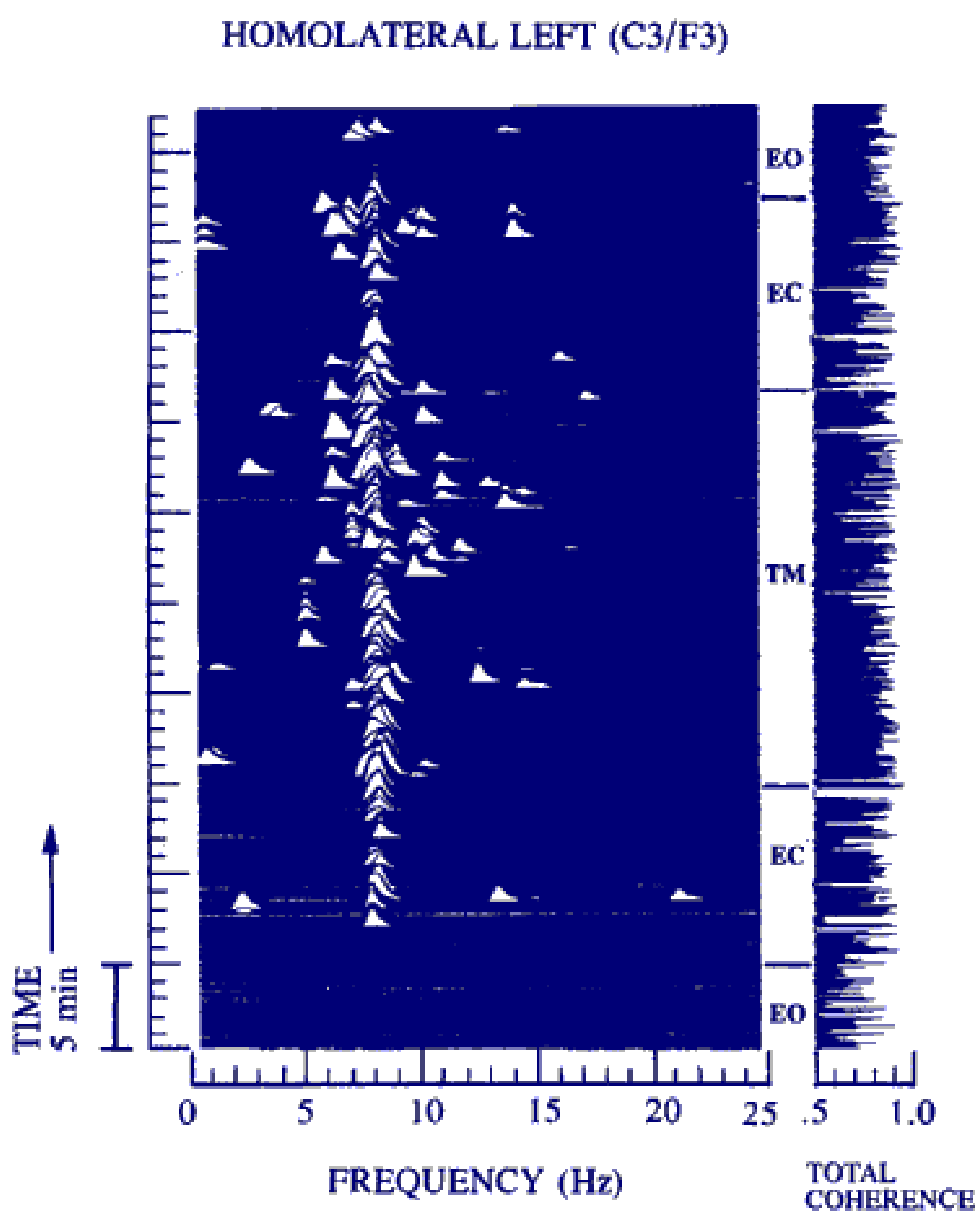


FIG. 13. SPREADING OF COHERENCE TO OTHER FREQUENCIES DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE. This homolateral cospar, computed for the same experiment as fig. 12, shows how strong coherence spreads from about 8 Hz in the alpha band to both lower and higher frequencies during the Transcendental Meditation technique.

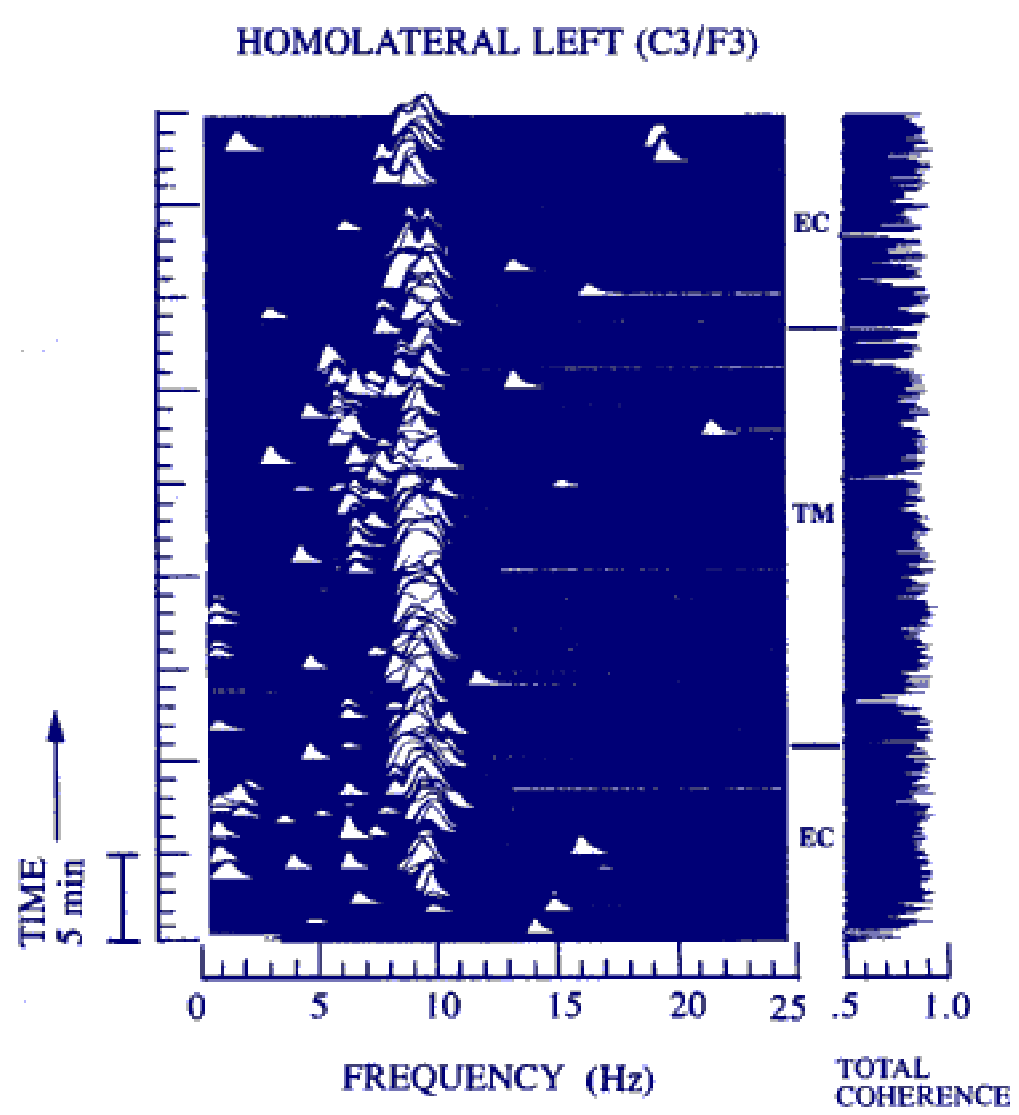


FIG. 14. ALPHA AND THETA COHERENCE DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE. In the latter half of the period of the TM technique, strong coherence in the theta band near 6 Hz appears together with strong alpha band coherence near 9 Hz.

Subject: Female, 31 years, 62 months' practice of TM technique
Reference electrode: Linked ears

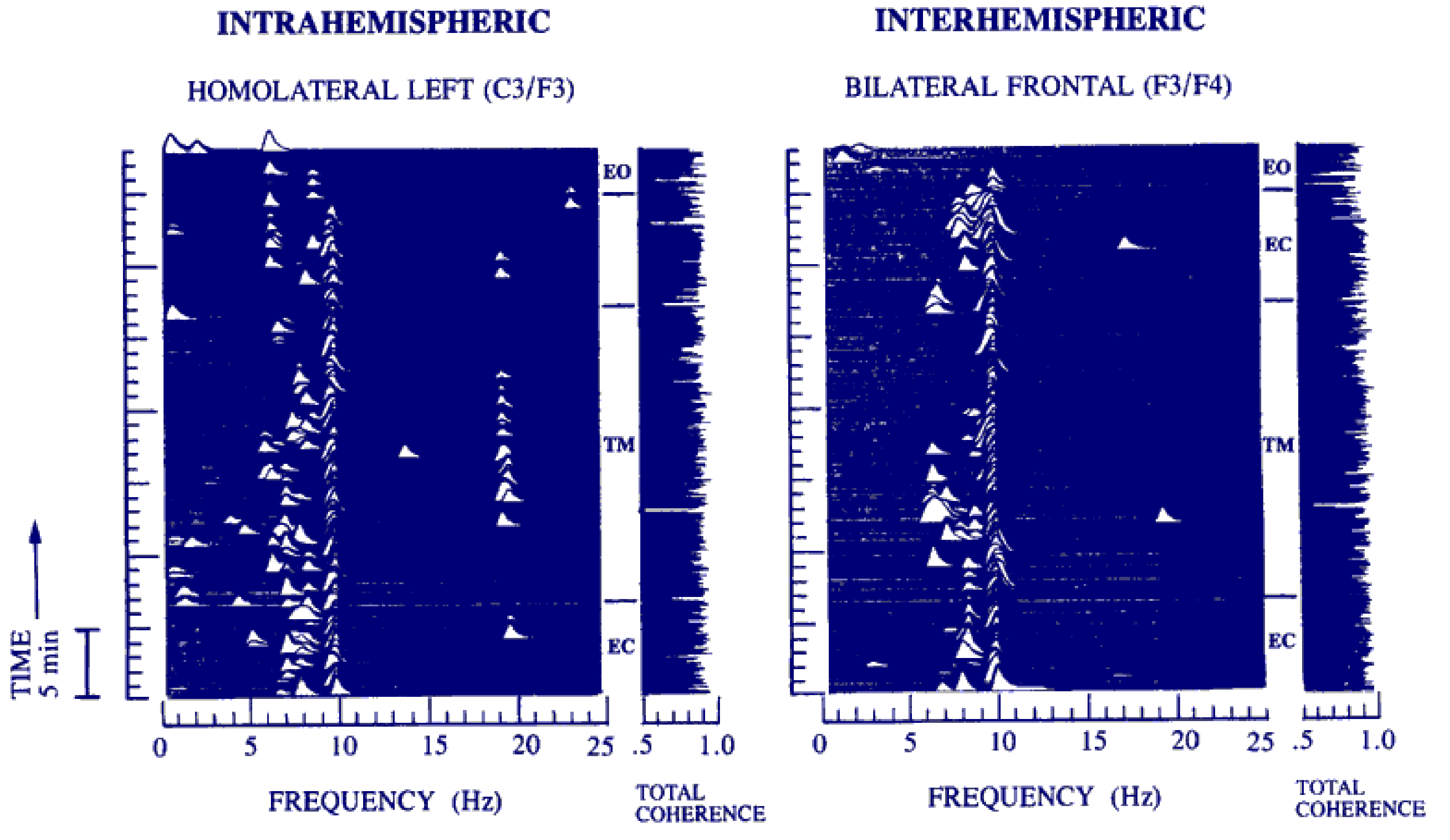


FIG. 15. ALPHA, THETA, AND BETA COHERENCE DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE. Two cospars for the same experiment show different effects specific to the TM technique. While the strong alpha coherence near 10 Hz is a persistent feature of both cospars indicative of restful alertness, strong interhemispheric frontal coherence in the theta band near 6 Hz appears during the TM technique. In the intrahemispheric cospar, ongoing beta coherence peaks (possible artifactual) near 20 Hz are seen during the Transcendental Meditation technique.

Subject: Male, 21 years, 54 months' practice of TM technique
Reference electrode: Linked ears

indicates the existence of harmonics of the alpha frequency in the EEG. This may provide a possible explanation for the observed beta coherence. In fig. 18, for example, there does appear to be a harmonic relation between the beta and alpha coherence peaks in the eyes-closed precontrol period, and likewise in the intrahemispheric cospar of fig. 15. Note in this latter case that the beta coherence is most pronounced *during* the Transcendental Meditation technique in contrast to the cases cited earlier. Banquet (1) has called attention to 20 Hz beta spindles during the Transcendental Meditation technique, noting that they appear to be similar over the scalp. It is possible that the coherent beta activity seen in the present study is the same as that observed by Banquet, in which case its interpretation as a signature of the Transcendental Meditation technique would have to be qualified.

IMMEDIACY OF COHERENCE CHANGES—The immediacy of increases in coherence specific to the TM technique was also investigated in a series of experiments in which subjects were measured immediately prior to and immediately following their initial instruction in the Transcendental Meditation technique; that is, the period of the technique and the eyes-closed relaxation precontrol period were separated by about 12 minutes, during which the technique was being learned. Results for the six subjects varied widely. Figure 19 shows one case in which a distinct increase in alpha band coherence is in evidence, as indicated by the consistency and increased density of coherence peaks during the middle part of the period of the TM technique.

COHERENCE IN A LONG-TERM MEDITATOR—Longitudinal studies of possible neurological change brought about by the Transcendental Meditation technique, and associated with the Science of Creative Intelligence concept of growth in the level of consciousness of the individual, will obviously require a longer span of time than the ten months covered in the present study. Circumstantial evidence does exist, however, in the measurements performed on one subject who had been practicing the Transcendental Meditation technique for 15 years, having learned as a child of ten. This length of practice exceeded by a factor of two that of the other experienced subjects, and it was therefore expected that any developmental changes associated with the technique would be most evident in this particular subject. In fact, it was found that

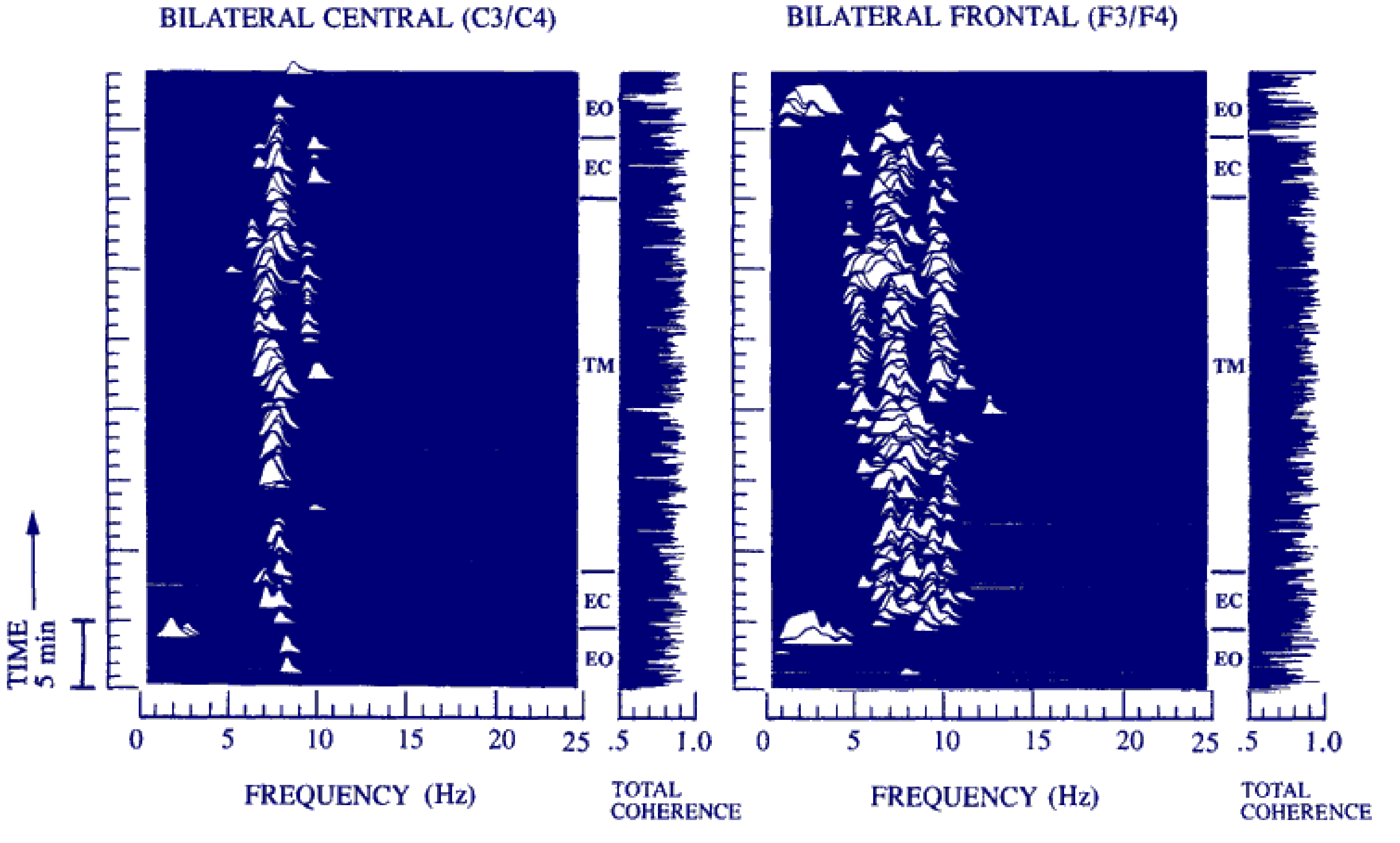
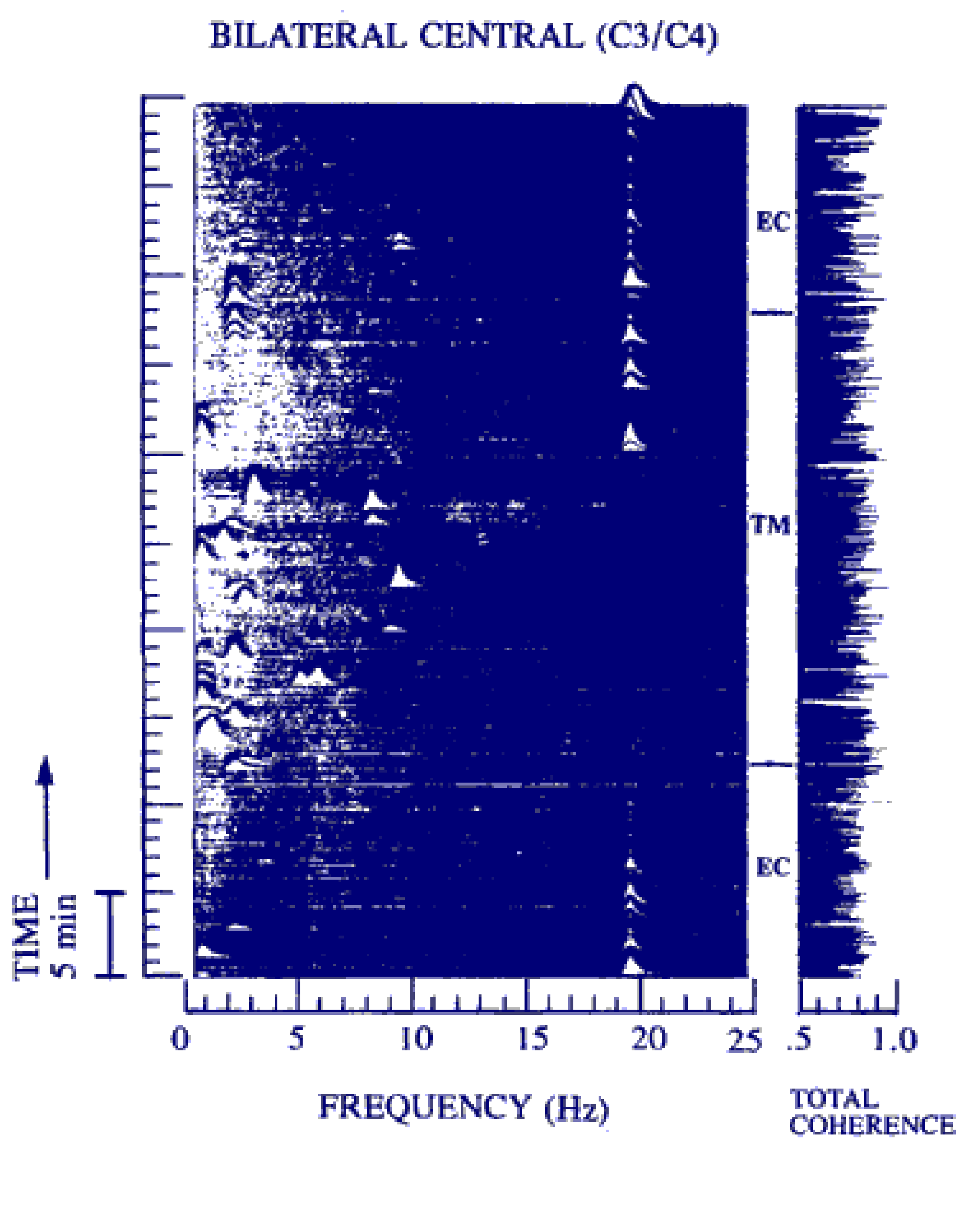


FIG. 16. COSPAR CHANGES DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE. Simultaneous bilateral cospars show how strong coherence spreads to other frequencies during the Transcendental Meditation technique. In the central cospar, strong alpha coherence near 10 Hz appears half way into the period of the TM technique. In the frontal cospar, strong theta coherence near 5 Hz begins about one-third of the way into the period of the technique. These effects may be associated with a deepening of the state produced by the TM technique.

Subject: Female, 25 years, 24 months' practice of TM technique
Reference electrodes: Homolateral ear



the highest total coherence levels (both during and outside of the period of the TM technique) were measured on this subject. Furthermore, the cospar—fig. 20—showed many unique features. The most obvious such feature is the fully developed coherence in the beta band, which may (as has been suggested above) be harmonically related to the alpha and theta band activity. Note also the abrupt onset of theta coherence with the start of the period of the TM technique and the subsequent onset of coherence even in the delta band. Indeed, the broad spectral regime over which the strong coherence extends during the heart of the period of the TM technique indicates great synchrony of the EEG between the left central and left

FIG. 17. BETA COHERENCE. This cospar shows an example of strong beta coherence near 20 Hz, which disappears with the start of the period of the TM technique. While possibly an artifact (see text), it has been seen in several subjects.

Subject: Female, 30 years, 83 months' practice of TM technique
Reference electrode: Linked ears

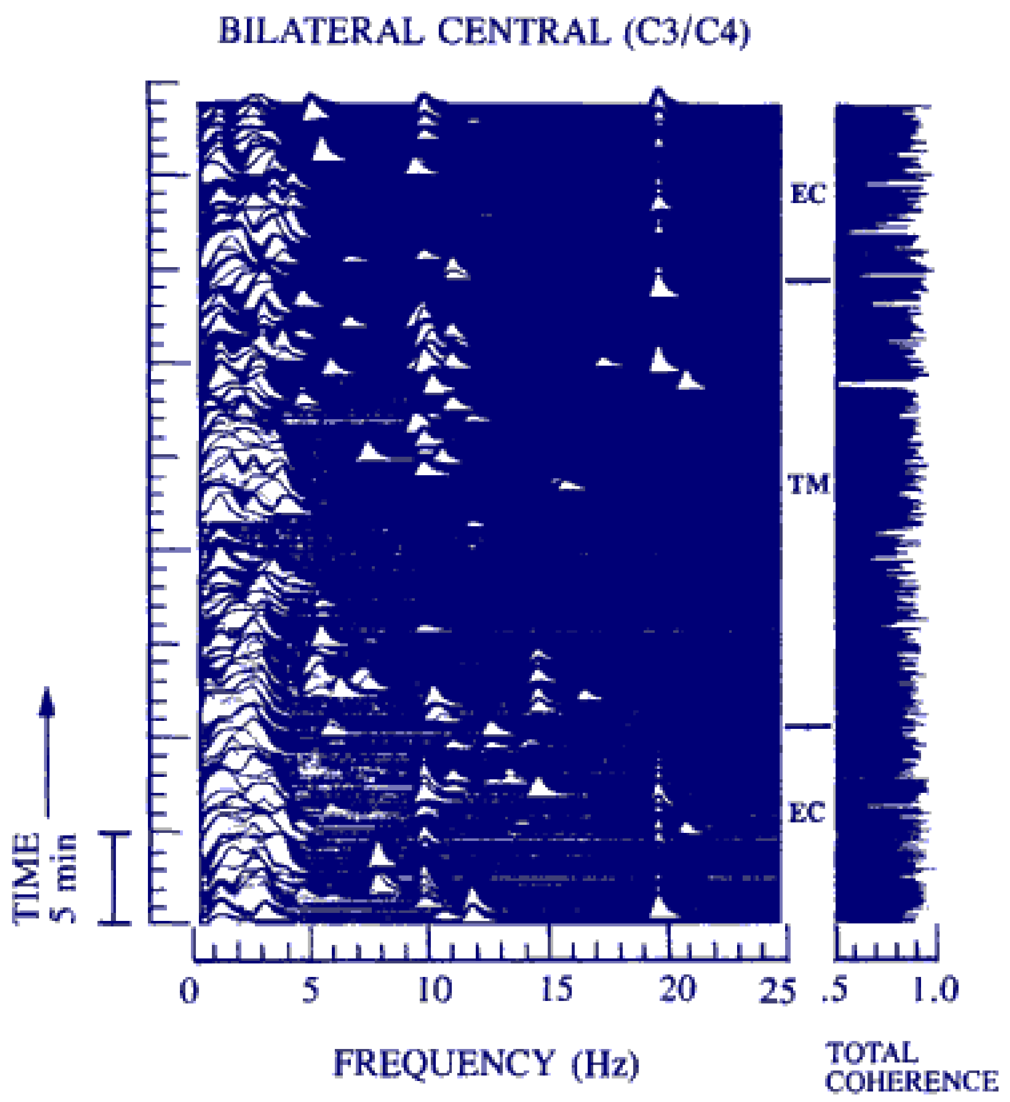


FIG. 18. BETA COHERENCE. A second example of the disappearance of a strongly coherent signal near 20 Hz with the start of the period of the Transcendental Meditation technique.
Subject: Female, 31 years, 62 months' practice of TM technique
Reference electrode: Linked ears

frontal derivations.* It is significant to note also that concurrent respiratory measurements showed that during the entire period of the technique, the breathing alternated (about every 30 seconds or so) between the ordinary pattern seen during eyes-closed relaxation and a markedly reduced level of activity barely detectable on the monitoring instruments.† As such, this subject demonstrated a textbook example of "transcending" as it is described in the Science of Creative Intelligence.

*Note that the data of fig. 5 were those of this particular subject taken towards the end of the period of the TM technique. The strong similarity of C3 and F3 are in fact evident.

†These experiments were performed by Professor John T. Farrow with a mask system utilizing a pneumotachograph and real-time determination of oxygen and carbon dioxide concentrations in the inspired and expired air via a gas mass spectrometer.

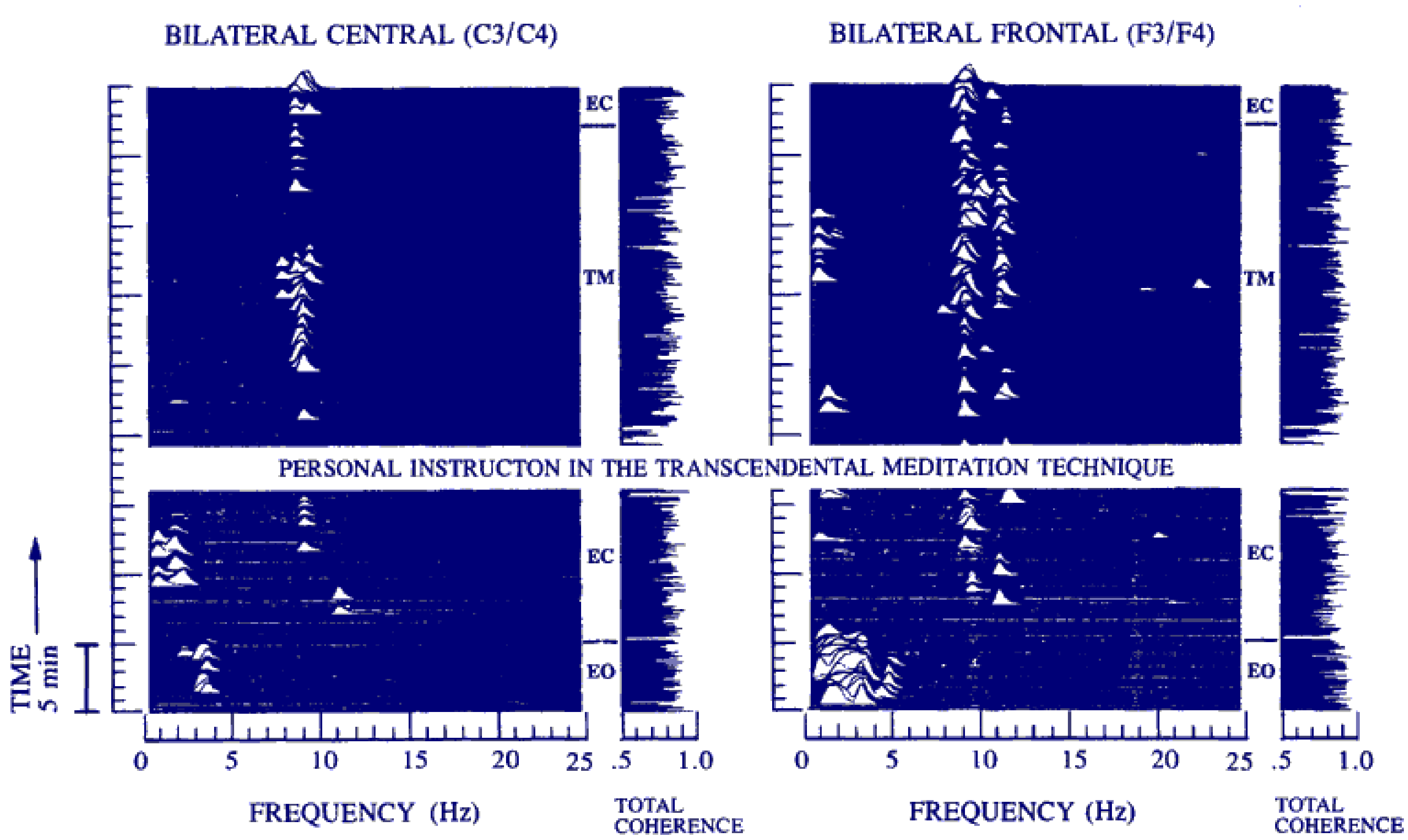


FIG. 19. COSPARS IN THE FIRST EXPERIENCE OF THE TM TECHNIQUE. This experiment was performed on the day of instruction in the Transcendental Meditation technique. The difference between simple eyes-closed relaxation and the subject's first experience of the TM technique is most apparent in the bilateral central cospar, which shows an increased level of strong alpha coherence during parts of the period of the TM technique.
Subject: Female, 25 years
Reference electrodes: Homolateral ear

HOMOLATERAL LEFT (C3/F3)

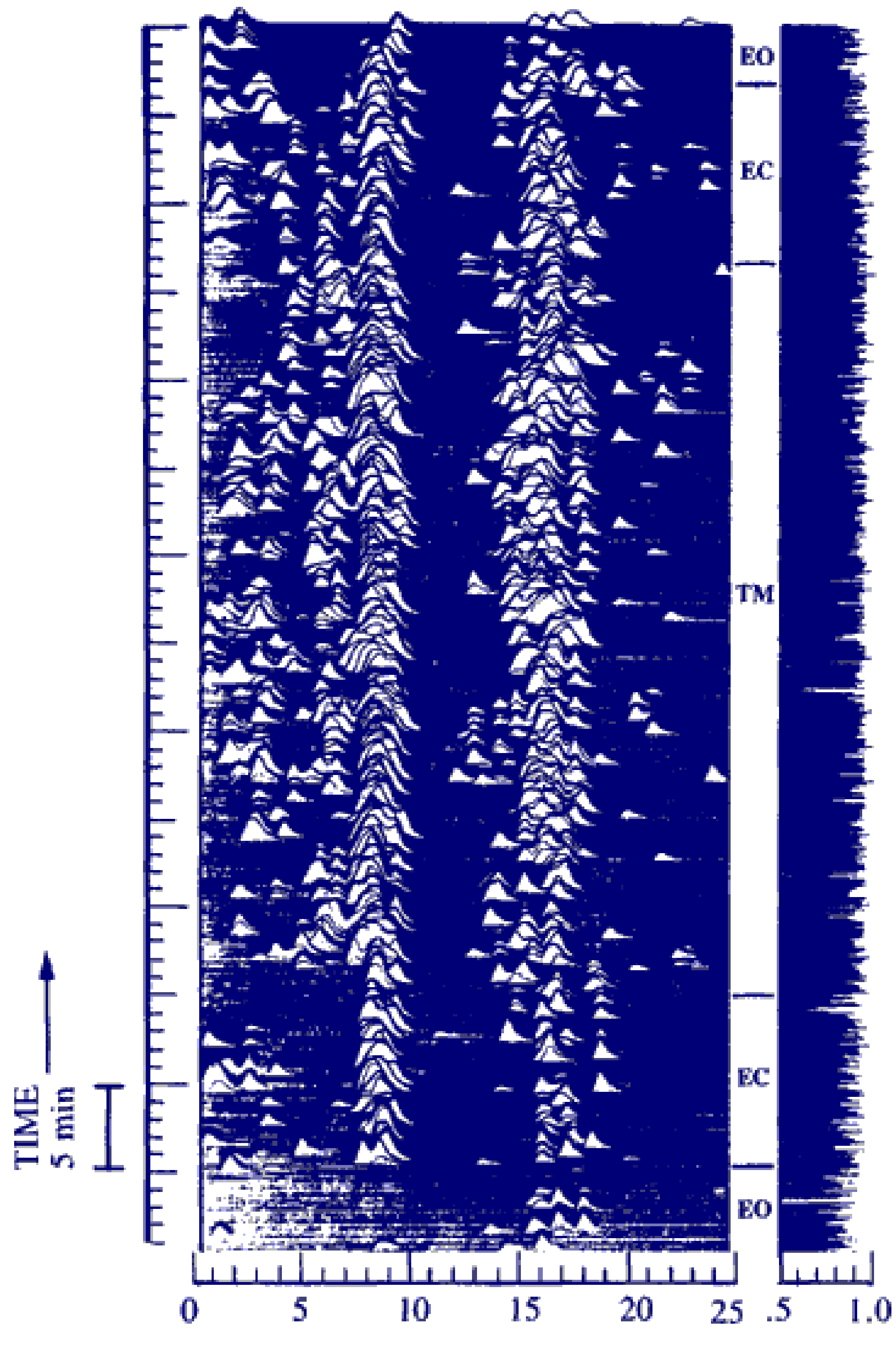


FIG. 20. COSPAR OF A LONG-TERM MEDITATOR. In the most experienced subject studied, the highest levels of coherence were found. Note how during the period of the Transcendental Meditation technique the coherence peaks extend over a major portion of the 0–25 Hz band. The strong beta coherence—possibly harmonically related to the alpha/theta activity—is particularly unusual. Strong theta coherence near 6 Hz begins abruptly with the start of the period of the technique.

Subject: Female, 26 years, 15 years' practice of TM technique
Reference electrode: Linked ears

COHERENCE DURING SLEEP—In the foregoing examples the emphasis was on the distinction between the EEG of the Transcendental Meditation technique and that of substates of wakefulness. To shed further light on the interpretation of strong coherence, sleep studies were performed. Figure 21 displays simultaneous homolateral cospars for a subject falling asleep while sitting up in bed. Sleep onset was determined by postural changes monitored by a closed-circuit video system and by the appearance of low voltage, mixed frequency EEG activity. At sleep onset the consistent chain of alpha coherence peaks stops and is replaced by an erratic pattern of coherence peaks extending into the delta band. Concurrently, the total coherence begins to systematically decline. When the subject is fully asleep the coherence peaks have vanished and the level of total coherence is low and erratic.

In fig. 22, taken from the middle of a night's sleep, the relationship of the cospar to the sleep stages can be discerned. Note how in REM sleep the total coherence rises markedly and coherence peaks appear in the delta band and to a lesser extent in the theta band. Also noteworthy is the fact that sleep spindles are sufficiently coherent to register on the cospar.

From both figs. 21 and 22 it is quite clear that the patterns of sustained alpha (and theta) coherence seen during the Transcendental Meditation technique are not at all similar to those of sleep. Indeed, when a break in the continuity of alpha coherence is seen, such as during the period of the TM technique shown in fig. 23, it is generally indicative that the subject has fallen asleep during the technique, as judged by postural changes and the appearance of low voltage, mixed frequency EEG activity. Falling asleep during the TM technique is a natural process that occurs when the nervous system is too fatigued to sustain experience.* In such cases clear changes in coherence specific to the TM technique are usually absent, as one might expect.

STATISTICAL SUMMARY OF EFFECTS SPECIFIC TO THE TM TECHNIQUE—In a given cospar, the existence of coherence peaks, i.e., values of coherence in excess of the threshold level at certain frequencies and times, depends primarily on the threshold setting and to a lesser degree upon the choice of reference electrodes. The same factors also influence whether changes in coherence specific to the TM technique will appear in a cospar or not, as may be deduced from the examples in which multiple cospars for a single experiment were shown. Thus, the cospar should be viewed simply as a filter—a mathematically complex one to be sure—which produces a pictorial output from a pair of input EEG channels. As long as the filter parameters (i.e., the threshold level and reference electrode choice) are kept constant so that the same filtering process is being applied to all data, then the cospar becomes an unbiased tool for spotlighting instances of enhanced coherence and increased long-range order in the EEG. While particularly useful for sensing coherence changes from one experimental condition to the next within a given experiment, it can also be used for intersubject comparisons of the degree and topography of strong coherence.

To assess the relative incidence of various types of coherence changes specific to the Transcendental Meditation technique, as well as to gauge the general utility of the cospar for studying the EEG correlates of the TM technique, a semi-quantitative analysis was performed on

*Failure to recognize the distinction between sleep during the Transcendental Meditation technique and the technique in the absence of sleep can easily lead to the erroneous identification of the Transcendental Meditation technique with various substates of sleep.

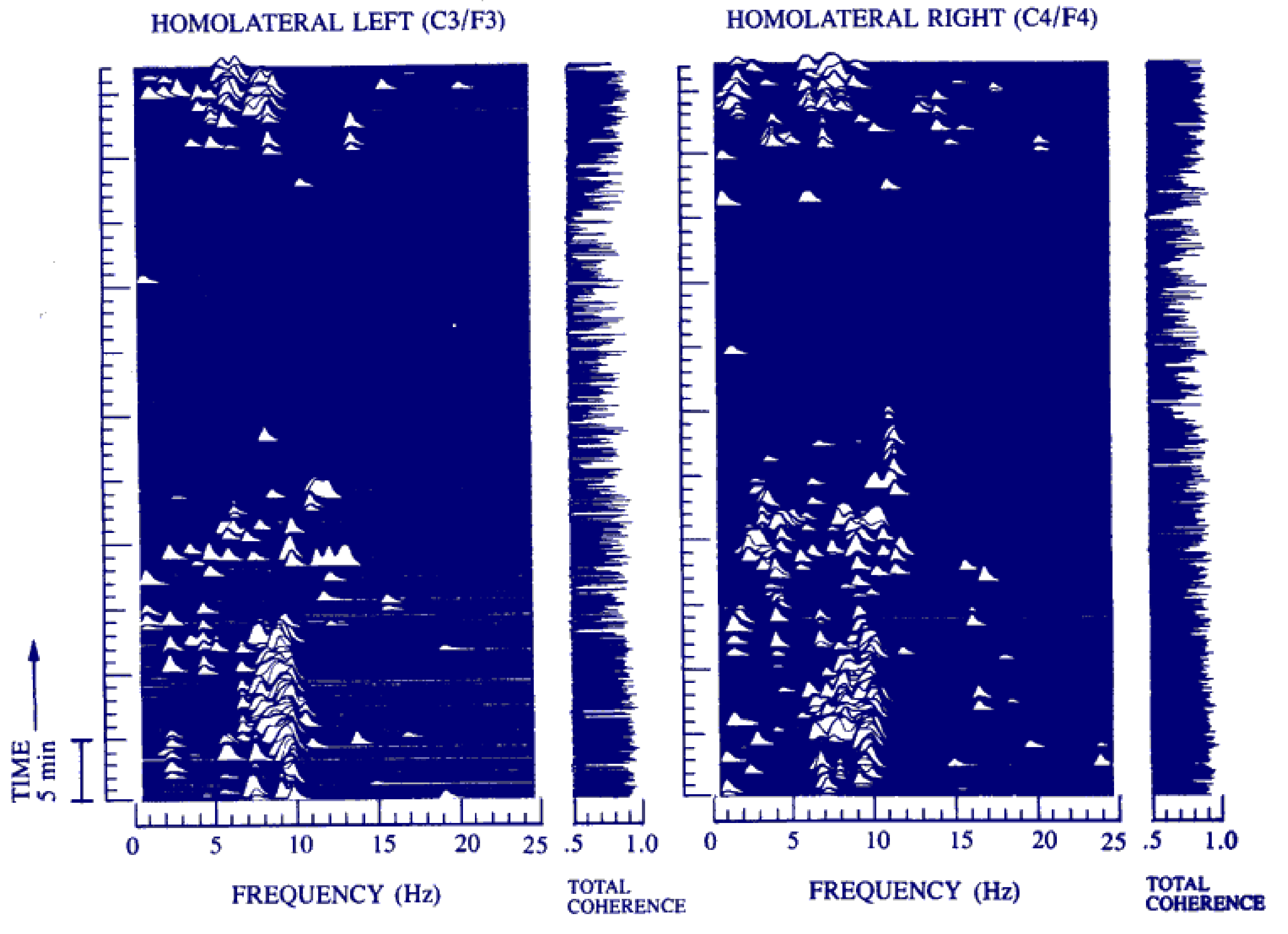


FIG. 21. COSPARS DURING SLEEP ONSET. This experiment, not involving a period of the Transcendental Meditation technique, monitored a subject as he fell asleep in bed in the sitting position. Onset of sleep (as judged by EEG criteria and postural changes) is first signaled by the break in the continuity of the alpha coherence peaks and the subsequent progressive diminution of the total coherence. Reappearance of coherence peaks towards the end of the experiment coincides with arousal of the subject by the experimenter.
Subject: Male, 27 years, 42 months' practice of TM technique
Reference electrodes: Contralateral ears

the 103 cospars generated in the present study for 32 experiments that involved a period of the technique. Three independent scorers rated each cospar as follows: (*a*) an integer (0 to 5, with 5 being the strongest), called the coherence strength index, measuring by visual inspection the overall amount of coherence peaks showing in the alpha + theta bands during the Transcendental Meditation technique; and (*b*) a determination of whether a change specific to the TM technique in the cospar was evident and an identification of the type of change. In particular, the scorers focused on the times of transition between eyes-closed control periods (both pre- and post-) and the period of the TM technique and ascertained whether a change in the height and/or density of coherence peaks occurred and also whether there was an evident change in the frequency range over which the coherence peaks extended. The ratings of the three scorers were generally consistent, and in each case a concensus score was obtained by majority rule. The results are shown in table 2.

The coherence strength index averages show that the frontal bilateral cospars tended to show the highest levels of strong coherence. Interestingly, the intrahemispheric cospars differed little between left and right in their averaged scores, although differences in the incidence of the various types of effects specific to the TM technique were noted. In all, about half of the cospars showed effects specific to the TM technique, with the highest incidence being in the homolateral left cospars.

Of all the changes specific to the TM technique that were noted, the most common was an increase in the height and/or incidence of coherence peaks in the alpha band with onset of the period of the TM technique *but* without a marked decrease at the end of that period. (A typical example of this type of change would be that of fig. 12.) Second most frequent was the spreading of coherence peaks to other—generally lower—frequencies during the Transcendental Meditation technique (e.g., fig. 13). Third most frequent was the type of effect shown

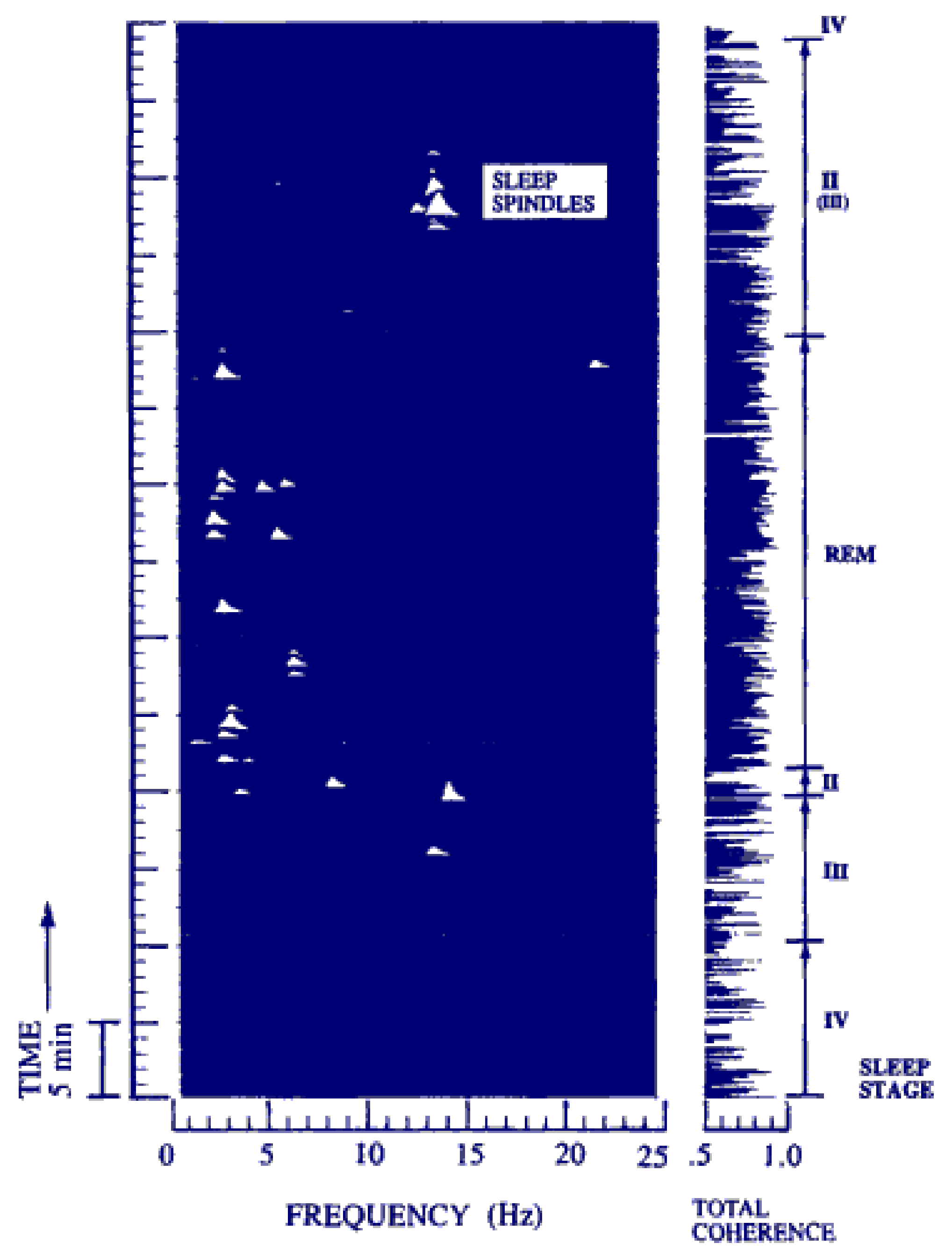


FIG. 22. COSPAR DURING SLEEP. This experiment monitored a nonmeditator during a portion of the night's sleep including both REM and non-REM stages. Note the absence of coherence peaks and low level of total coherence during Stage IV and the higher level of total coherence during REM sleep. The sleep spindles near 14 Hz are a characteristic feature of Stage II sleep.
Subject: Male, 19 years, nonmeditator
Reference electrode: Linked ears

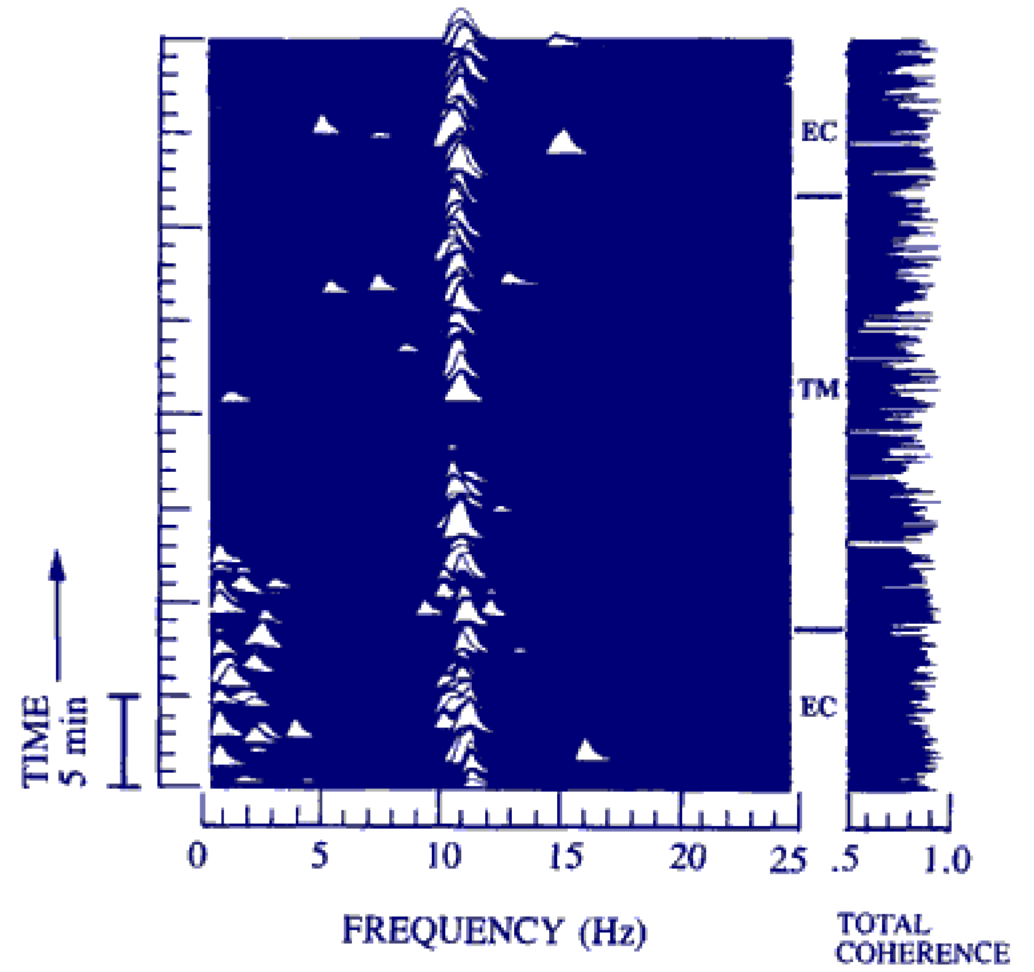


FIG. 23. DROWSINESS DURING THE TRANSCENDENTAL MEDITATION TECHNIQUE. Drowsiness during the Transcendental Meditation technique appears on the cospar as a break in the continuity of the alpha coherence peaks. Frequently, as in this example, the period of drowsiness passes and the alpha coherence returns.
Subject: Female, 29 years, 49 months' practice of TM technique
Reference electrode: Linked ears

in fig. 9, viz., abrupt onset of strong coherence with the start of the Transcendental Meditation technique *and* abrupt decrease at the end of the technique. In the "Other" category of table 2, no single type occurred more than three times in all.

In 12 of the 32 experiments summarized in table 2, linked-ears reference was used and a full set of four cospars was computed. In nine of these experiments, one of the cospars was clearly dominant over the other three in the coherence strength index; in two experiments dominance was shared by two cospars, and in one experiment there was no clear dominance. The topographical distribution of such dominance is shown in table 3. Interestingly, all 12 experiments showed effects specific to the TM technique in at least one cospar; in eight experiments the dominant cospar showed such effects.

It appears then that if a single pair of scalp locations is to be utilized in a search for instances of strong coherence

TABLE 2

STATISTICAL SUMMARY OF EFFECTS SPECIFIC TO THE TRANSCENDENTAL MEDITATION TECHNIQUE

	COSPAR TYPE				
	Interhemispheric		Intrahemispheric		
	Central	Frontal	Left	Right	Totals
Number of cospars	29	29	23	22	103
Average coherence strength index	1.7	3.0	2.6	2.6	2.5
% cospars showing effects specific to TM technique	45	48	61	59	52
Type of effect specific to TM technique:					
A	7	6	3	3	19
B	3	1	5	2	11
C	2	4	3	6	15
Other	1	3	3	2	9
Totals	13	14	14	13	54

Effects specific to the TM technique:

A: Coherence increase with onset of TM technique; no decrease during eyes-closed postcontrol

B: Coherence increase with onset of TM technique and decrease during eyes-closed postcontrol

C: Spreading of coherence peaks to other frequencies with onset of TM technique

Other: Various mixtures of effects of onset of technique and end of technique

TABLE 3

DISTRIBUTION OF DOMINANT COHERENCE

COSPAR TYPE	NUMBER OF CASES
Bilateral frontal	4
Homolateral right	3
Homolateral left	2
Bilateral frontal & homolateral left	1
Bilateral frontal & homolateral right	1
No dominance	1
Total	12

specific to the TM technique, the left and right frontal (i.e., F3 and F4 referenced to linked ears) represents the best choice of those studied. Furthermore, one would expect to observe examples of changes specific to the technique in about one-half of these bilateral frontal cospars. In most experiments, however, it is expected that an example of increase in coherence specific to the technique would be observed in at least one member of a complete set of four cospars. Therefore, any detailed study of coherence changes during the Transcendental Meditation technique should involve the examination of the four cospars for each experiment.

DISCUSSION

While the present study was not designed to constitute a critical statistical test of the hypothesis that EEG coherence increases as a direct result of the Transcendental Meditation technique, it has nevertheless provided (*a*) strong indications that this may in fact be the case; (*b*) analytical/graphical tools for studying coherence in general; and (*c*) essential data for the intelligent design of the in-depth experiments that would be required to test such hypotheses fully.

Many of the examples of increases in alpha and theta band coherence specific to the TM technique were so unambiguous that (barring the possible but unlikely circumstance that these were artifacts of the protocol itself, e.g., arousal effects associated with signaling the subject to begin or end the technique) it can be fairly claimed that the Transcendental Meditation technique, in some cases at least, is definitely associated with a higher incidence of strong coherence than simple eyes-closed relaxation. Furthermore, the sleep studies showed a marked trend towards *decreased* alpha/theta coherence with loss of awareness. Thus, it would seem that the Transcendental Meditation technique produces a higher incidence of strong coherence in the alpha/theta band than is experienced in the normally encountered substates of wakefulness and sleep, and that this feature in fact provides a unique EEG "signature" of the physiological state reached during the technique.

The present findings therefore extend the pioneering work of Wallace (14) and Banquet (1, 2) in which the existence of sustained alpha and theta activity during the Transcendental Meditation technique was clearly noted. It now appears that this characteristic activity tends to occur in a highly coherent form among the central and frontal derivations. Equivalently, it may be said that the EEG exhibits a high degree of long-range spatial order—at least over distances of the order of 10 cm—in these bands during the Transcendental Meditation technique. Evidently, any neurological model of the state reached during the TM technique must be able to account for this observation, and it is expected that the present study will thereby contribute to the realization of such a model.

Modeling aside, however, the most striking outcome of the study is felt to be its validation of the practical *predictive* value of the Science of Creative Intelligence as applied to states of consciousness and their physiological correlates. In particular, the SCI concept of a highly ordered state of least excitation of consciousness reached during the Transcendental Meditation technique is supported by the present EEG findings as well as by the original results of Wallace on metabolic rate. Thus, while scientists may not be accustomed to seeking practical value from concepts derived from a Vedic tradition thousands of years old, the relevance of this knowledge to twentieth-century physiology and neurology is rapidly becoming evident. Indeed, the richness and subtlety of the theoretical and practical knowledge of the human nervous system offered by Maharishi Mahesh Yogi through the Science of Creative Intelligence seems in many ways to go far beyond the present accomplishments of the neurosciences. It is therefore hoped that the present study will encourage other researchers to look deeply into the perspectives of the Science of Creative Intelligence on the structure of human consciousness and to view them as timely clues for new approaches to the scientific understanding of man.

APPENDIX

COMPUTATION OF COHERENCE SPECTRA—Consider two channels of EEG data, X(t) and Y(t), which are simultaneously sampled at a sampling frequency f Hz. Define the data sets $\{X\}_{t_0,N}$ and $\{Y\}_{t_0,N}$, consisting of N successive samples starting with time t_0 and denote the jth element of each set by X_j and Y_j, respectively:

$$\begin{aligned} \{X\}_{t_0,N} &= \{X_0, X_1, \ldots, X_{N-1}\};\ X_j = X(t_0 + j/f) \\ \{Y\}_{t_0,N} &= \{Y_0, Y_1, \ldots, Y_{N-1}\};\ Y_j = Y(t_0 + j/f) \end{aligned} \quad [1]$$

By Fourier series analysis, one obtains an expansion of the form

$$X_j = \sum_{k=0}^{N/2} [A_{x,k}\cos(2\pi jk/N) + B_{x,k}\sin(2\pi jk/N)] \quad [2]$$

with a similar expression for Y_j in terms of the cosine and sine amplitudes $A_{y,k}$ and $B_{y,k}$. From these amplitudes, the "raw" in-phase and quadrature cross-spectra $C_{xy,k}$ and $Q_{xy,k}$ are determined from the relations

$$\begin{aligned} C_{xy,k} &= A_{x,k} A_{y,k} + B_{x,k} B_{y,k} \\ Q_{xy,k} &= B_{x,k} A_{y,k} - B_{y,k} A_{x,k} \end{aligned} \quad [3]$$

To improve the statistical properties of these cross-spectral estimates, it is in general necessary to smooth (i.e., average) them in some appropriate fashion. Denoting this (as yet unspecified) smoothing process by boldface type, the coherence function at frequency kf/N, $\gamma^2_{xy,k}$, is defined by

$$\gamma^2_{xy,k} = \frac{(\mathbf{C}_{xy,k})^2 + (\mathbf{Q}_{xy,k})^2}{(\mathbf{C}_{xx,k})(\mathbf{C}_{yy,k})} \quad [4]$$

We may also define a total coherence function for the band [k1, k2] by

$$\Gamma^2_{xy;k1,k2} = \frac{\sum_{k=k1}^{k2} [(\mathbf{C}_{xy,k})^2 + (\mathbf{Q}_{xy,k})^2]}{\sum_{k=k1}^{k2} (\mathbf{C}_{xx,k})(\mathbf{C}_{yy,k})} \quad [5]$$

A number of different smoothing procedures may be employed, the choice among them being determined by several factors, including computation speed, available computer memory, and, more important, the time over which the EEG signals of interest are expected to be coherent. Dumermuth et al. (9), for example, smooth by a technique wherein rather long epochs—typically 20 or 40 seconds—are chosen, resulting in closely spaced frequency spectra (of spacing 0.05 or 0.025 Hz), which can then be averaged over frequency bands with the desired resolution (typically 0.375 Hz). In this frequency averaging approach,

$$\mathbf{C}_{xy,k} = \sum_{j=-W}^{W} G_j C_{xy,k-j} \quad [6]$$

where the G_j are a set of weighting coefficients with

$$\sum_{j=-W}^{W} G_j = 1 \quad [7]$$

While the long epoch lengths may be appropriate for the study of sleep EEG's, we felt that the important EEG signals during TM might only be coherent for a few seconds, in which case we would not want the smoothing process to mix data obtained more than a few seconds apart. One customary way of achieving this goal would be to construct a fictitious expanded data set $\{X\}_{t_0,N'}$ $\{Y\}_{t_0,N'}$, obtained by adding N′−N zeroes to the data sets [1],

$$\begin{aligned} \{X\}_{t_0,N'} &= \{X_0, X_1, \ldots, X_{N-1}, 0, 0, \ldots, 0\} \\ \{Y\}_{t_0,N'} &= \{Y_0, Y_1, \ldots, Y_{N-1}, 0, 0, \ldots, 0\} \end{aligned} \quad [8]$$

and then applying [6] to these expanded sets. Since this procedure is not well suited to a minicomputer where available core is limited, we have developed a variant of what is known as the "segment averaging" (see, for example, Bendat and Piersol (3, pp. 191, 332, 333)) technique, wherein smoothing is obtained by averaging the value at each frequency over a number of different data segments,

$$\mathbf{C}_{xy,k} = \sum_{j=0}^{M-1} G_j C_{xy,k}[\{X\}_{t_j,N}, \{Y\}_{t_j,N}] \quad [9]$$

where the t_j are the starting times for the data sets used in the computation of the cross-spectra, and the G_j are given weighting coefficients satisfying

$$\sum_{j=0}^{M-1} G_j = 1 \quad [10]$$

In our procedure, we use overlapping data sets in [9] obtained as follows: We start with a basic sample in each channel of 256 elements obtained over a 5.12-second epoch. We then define 19 overlapping* 128-point subsets of this sample,

subset 1: $(X_0, X_1, \ldots, X_{127}), (Y_0, Y_1, \ldots, Y_{127})$
subset 2: $(X_7, X_8, \ldots, X_{134}), (Y_7, Y_8, \ldots, Y_{134})$
subset 3: $(X_{14}, X_{15}, \ldots, X_{141}), (Y_{14}, Y_{15}, \ldots, Y_{141})$
subset 19: $(X_{126}, X_{127}, \ldots, X_{253}), (Y_{126}, Y_{127}, \ldots, Y_{253})$

and successively apply the fast Fourier transform algorithm (FFT) to each subset, obtaining thereby the Fourier amplitudes

$$A^{(p)}_{x,k}, A^{(p)}_{y,k}, B^{(p)}_{x,k}, B^{(p)}_{y,k}$$

for the pth subset, where p = 1, . . . , 19. We then form (see [3])

$$\begin{aligned} C^{(p)}_{xy,k} &= A^{(p)}_{x,k} A^{(p)}_{y,k} + B^{(p)}_{x,k} B^{(p)}_{y,k} \\ Q^{(p)}_{xy,k} &= B^{(p)}_{x,k} A^{(p)}_{y,k} - B^{(p)}_{y,k} A^{(p)}_{x,k} \end{aligned} \quad [11]$$

and smooth according to

$$\begin{aligned} \mathbf{C}_{xy,k} &= \frac{1}{19}\sum_{p=1}^{19} C^{(p)}_{xy,k} \\ \mathbf{Q}_{xy,k} &= \frac{1}{19}\sum_{p=1}^{19} Q^{(p)}_{xy,k} \end{aligned} \quad [12]$$

Equation 4 is then used to obtain the coherence function $\gamma^2_{xy,k}$ at the 65 frequencies f_k given by

$$f_k = \frac{25k}{64}\text{Hz} \qquad k = 0, \ldots, 64 \quad [13]$$

*The use of overlapping segments in cross-spectral estimation has been discussed by Welch (16).

In the coherence spectral arrays shown in the text, the components at $k = 0$, $k = 1$, and $k = 64$ have been omitted, since they contain aliased contributions from the 50 Hz mains. Similarly, in computing the total coherence function from equation [5], $k_1 = 2$ and $k_2 = 63$.

The mathematical significance of the coherence function [4] is clarified by noting that if X and Y are pure sinusoids, then it can be shown to be equivalent to

$$\gamma^2_{xy,k} = (\mathbf{cos}\vartheta_{xy,k})^2 + (\mathbf{sin}\vartheta_{xy,k})^2 \qquad [14]$$

where $\vartheta_{xy,k}$ is the phase angle between the kth frequency components of channels X and Y during a given data subset, and the bold face again denotes the smoothing process. Evidently, if this phase relationship is constant over the time employed in the smoothing, $\gamma^2 \rightarrow 1$ and the deviation of the coherence from unity may then be viewed in this example as a measure of the nonconstancy of the phase relationship between the two signals.

In the more general case of nonsinusoidal signals, i.e., the EEG, deviations of the coherence from unity can arise also because of *intensity* (i.e., $\sqrt{A^2 + B^2}$) fluctuations in either or both channels from one data subject to another, even if the phase relationship is constant. Thus, strictly speaking, a coherence value close to unity implies *both* phase constancy *and* intensity stability in the EEG activity at the two derivations for the frequency of interest. Since in practice it appears that phase variability is the primary impediment to achieving the near unity coherence required for registration in the cospar, this aspect—rather than intensity stability—has been emphasized in the text.

As an application of equation 14, we may compute the coherence of two pure sinusoids that differ in frequency by f Hz. If the time over which the coherence is defined is T seconds, then since the relative phase of the two signals increases linearly with time according to phase $= 2\pi ft$, we find

$$\text{coherence} = \left(1/T\int_0^T \cos(2\pi ft)\,dt\right)^2 + \left(1/T\int_0^T \sin(2\pi ft)\,dt\right)^2 \qquad [15]$$

$$= \frac{2}{(2\pi fT)^2}\,(1 - \cos(2\pi fT))$$

This is the function plotted in fig. 3 of the text.

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