NASA-CR-65018

RESULTS OF ELECTROENCEPHALOGRAPHIC EXAMINATIONS UNDER THE INFLUENCE OF VIBRATION AND CENTRIFUGING IN THE MONKEY.

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FACILITY FORM 602

N65-32718	
(ACCESSION NUMBER)	(THRU)
34	1
(PAGES)	(CODE)
CR 65018	04
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

GPO PRICE $ ________

CSFTI PRICE(S) $ ________

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

Running Title: EEG in vibration and centrifuging.

If accepted, please send proofs to:

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Introduction

The EEG recorded in transverse and longitudinal acceleration and during vibration of the whole body has been shown in previous studies (Adey *et al*. 1961; Adey *et al*. 1963; Winters *et al*. 1963; Adey 1964; McNutt 1963) to provide a close correlation with levels of consciousness, as these may be modified by embarrassment of cerebral circulation or by intense somesthetic barrages during vibration (Harris *et al*. 1963; Mandel *et al*. 1962).

Necessarily, such studies impose rigorous requirements on the entire sensing and recording system to ensure freedom from contamination of the records by connecting lead artifacts or environmental magnetic fields, particularly during vibratory stimuli (Adey *et al*. 1963). Our previous studies employed anesthesia and shaking after death as additional controls in support of the physiological basis of the apparent EEG "driving" induced by vibration. We have extended these observations in comparison of the effects of shaking in normal monkeys and those deprived of vestibular inputs by bilateral eighth nerve section. A recent communication from Nicholson and Guignard (1964) dismissed EEG driving during vibration as an artifact. Extensive computer analysis of our data here provides further evidence, however, that the phenomenon has a physiological basis, and emphasizes the need for both adequate methods of data acquisition in such tests, and the value of more sophisticated analysis than simple visual inspection of paper records.

We have also tested the effects on the EEG of compound positive accelerations in simulation of an actual booster profile, and observed concurrent changes in cerebral and cardiac functions following a high G "pulse."

Method and Material

As in previous studies (Adey et al. 1963), Macaca nemestrina monkeys (body weight 4 to 6 Kg) were stereotaxically implanted with bipolar recording electrodes in amygdala, hippocampus, nucleus centrum medianum and midbrain reticular formation.

Centrifuging tests were performed in the facilities of the University of Southern California collaboratively with Dr. J. P. Meehan, and compound accelerations were tested there with the collaboration of Dr. R. Hoffman, of NASA Ames Research Center. Vibration studies were performed with the generous assistance of the Douglas Aircraft Company, Santa Monica. Data acquisition involved simultaneous recording on 8 or 16 channel chart recorders, and on 7 channel Precision Instruments or 14 channel Ampex tape recorders. Coding for subsequent computer analysis was arranged with 3 figure binary coded decimal numbers recorded every 20 sec on both chart and magnetic tape recorders. Voice protocols were also recorded.

Initial analyses of some of this material have been with a Sanei frequency analyzer, using resistance and capacitance filter networks, with five filter ranges covering 3-6, 6-8, 8-13, 13-25 and 25-45 c/sec. Each analysis epoch was 10 sec. in duration. Much more comprehensive analyses were performed on substantially larger amounts of data, using digital computations developed in this laboratory for display of cross-spectral functions, including shared amplitudes, phase angles and coherence functions. Editing and digital conversion of the analog tapes was performed on an SDS 930 computer, and spectral computations performed on an IBM 7094 computer. Automated display of much of the spectral analyses was then completed on the SDS 930.

In the vibration tests, three normal animals and three others, with the eighth nerves bilaterally sectioned through a suboccipital approach to the posterior cranial fossa, were used. These operated animals were allowed a six month recovery period, during which the initial profound ataxia and spatial disorientation subsided, and walking and skilled body movements were resumed. Repeated caloric stimulations were performed, including preoperative controls. No evidence of nystagmus was seen in postoperative tests, although it was regularly elicited preoperatively. They were carefully blindfolded during vibration.

Results

A. Effects of Vibration

The complex stimulus patterns initiated by vibration of the whole body challenge the neurophysiologist to distinguish in EEG records those changes which may relate reliably to physiological responses in brain tissue. These distinctions may rest on both qualitative and quantitative evaluation, but in either case, require detection of differentials in the pattern of EEG activity during the vibratory stimulus which would assist in specification of such phenomena as EEG "driving" at the shaking frequency as physiological or artifactual.

Our use of comprehensive spectral analysis has aided materially in achieving such an experimental design. Unlike frequency analysis, spectral analysis allows specification of a gamut of shared relations between two wave trains, on a wave by wave basis, for such parameters as shared amplitude, phase angle, and quite importantly, the coherence or linear predictability of relations between channels. The actual techniques have been described in detail elsewhere (Walter 1963; Walter and Adey 1963; Adey 1965; Walter et al. 1965), but it may be emphasized that their utilization for analysis of massive amounts of multichannel data is only possible by digital computation.

Briefly, we have examined the effects of vibration over a spectrum from 5 to 40 c/sec, using 0.25 inch double amplitude between 5 and 13 c/sec, and 2G peak-to-peak in the range from 13 to 40 c/sec, in both ascending and descending sequences of frequencies. Each EEG channel was examined for auto-spectral density in resting records, and at intervals of one cycle across the shaking spectrum from 5 to 29 c/sec. Similar spectral density analyses were made for the table and head accelerometers. It was thus possible to compare peaks of spectral density in the EEG with those in the accelerometers. Cross spectral analyses, with calculation of coherence, were then prepared. They sensitively indicated significant levels of shared activity between cerebral structures on the one hand, and also, the degree of interrelation between cerebral electrical activity and head and table oscillations. It is not possible to present here the detailed aspects of all the subtle interrelations so revealed. We may merely emphasize that induced EEG rhythmicity occurring at certain frequencies of whole body vibration has the characteristics of a physiological "driving," and appears distinguishable from superficially similar phenomena of artifactual origin.

1. Autospectra of EEG records from cortical and deep structures at rest and during vibration.

A three dimensional display has been adopted to allow a synoptic view of changing spectral density in a particular lead across a complete "sweep" of vibration frequencies. Each analysis was performed on 20 sec of EEG record, and the EEG autospectrum displayed on the ordinates, the vibration frequencies on the abscissae, and spectral density on the Z axis.

a. Changes in EEG autospectra of normal monkeys induced by vibration.

Surface leads from visual cortex typically showed little or no evidence of driving below 9 c/sec, despite powerful head movements. In the example shown (Fig. 1A), shaking at 6 c/sec was accompanied by the highest spectral peaks at 2, 4 and 5 c/sec, and only a broad peak from 6 to 9 c/sec at lower energy levels. With 9, 11 and 12 c/sec shaking, the highest peak occurred at the shaking frequency, as in previous studies (Adey et al. 1963) but other peaks of almost equivalent intensity occurred in the range from 2 to 7 c/sec. The highest energy peak in this series of spectral analyses occurred at 11 c/sec with 11 c/sec shaking. In the range of shaking frequencies from 12 to 14 c/sec, the highest EEG energy peaks were at 9 c/sec, with smaller peaks at the shaking frequencies. Shaking at 15 to 17 c/sec showed highest energy peaks at the shaking frequency, but major peaks also appeared at 2, 4 and 9 c/sec. Thus, the selective character of driving at the shaking frequency, and the occurrence of maximum peaks at frequencies other than that of the shaker, and not harmonically related to shaking frequencies clearly support an origin other than in an electromechanical artifact.

Similar dissociations between EEG spectral peak and the frequency of shaking occurred in the midbrain reticular formation and in nucleus centrum medianum (Fig. 1C and D). In the midbrain reticular formation, despite strong head shaking at 5 c/sec, the EEG power at 5 c/sec was low, with a broad peak from 6 to 9 c/sec, and lesser peaks from 2 to 4 c/sec. Similarly with 7 c/sec shaking, no peak occurred in the EEG spectrum. Spectral peaks at the shaking frequency did occur with 9 and 10 c/sec shaking, but no such peak occurred with 12 c/sec shaking, despite high EEG spectral energy at 7, 8 and 9 c/sec. Similarly, with 14 and 15 c/sec shaking, no EEG peak occurred at the shaking frequency, and highest EEG energy was at 9 c/sec. Shaking at 17 c/sec produced a small peak at the shaking frequency.

In nucleus centrum medianum, maximum EEG energy at shaking frequencies occurred only in narrow sectors of the shaking spectrum, at 10 and 11 c/sec, and in the range from 15 to 17 c/sec. During 5 c/sec shaking, the highest energy in the EEG spectrum was at 22 c/sec, with a smaller peak at 5 c/sec, and minor deflections at 8 and 11 c/sec. No "driving" peaks occurred with 7 or 9 c/sec shaking, and with 12 c/sec shaking, EEG spectral energy at that frequency was lower than in the range 1 to 8 c/sec. Beyond 12 c/sec, vibration produced definite EEG spectral peaks at the shaking frequency, but in vibration at 13 and 14 c/sec, these peaks were smaller than those in the EEG spectra between 2 and 9 c/sec.

The amygdaloid baseline spectrum exhibited a jagged contour, with peaks at close intervals from 4 to 20 c/sec (Fig. 1E). No increments occurred in these peaks in the lower shaking range from 5 to 11 c/sec. In the range from 13 to 17 c/sec, shaking produced small peaks at those frequencies, but the general contour of the EEG spectra retained a striking resemblance to controls throughout the vibration sweep.

b. EEG autospectra during vibration after bilateral eighth nerve section.

Certain differences were noted in these EEG records in comparison with those from intact animals (Fig. 2). Subcortical leads from centrum medianum, and, in lesser degree, from the midbrain reticular formation, showed a greater tendency to "driving" at shaking frequencies than in the intact subjects. While the evidence from the limited series available here cannot be considered categoric indication of a qualitative difference, its consistency and the general spectral characteristics support such a view. Moreover, the findings may bear directly on earlier work on interaction of spinal and vestibular afferents in brainstem evoked potentials (Gernandt and Gilmans 1960).

In the visual cortex (Fig. 2A), deep valleys, or "forbidden zones" occurred at close intervals across the baseline EEG spectrum, particularly at 11 and 13 c/sec. This jagged contour was sustained in essential features through the major part of the vibration sweep. "Driving" of the EEG at shaking frequency occurred at 9, 11, 13 and 16 c/sec, but was associated with higher peaks in other parts of the EEG spectrum, usually in no simple harmonic relation to the shaking frequency.

In the amygdala (Fig. 2B), EEG spectral peaks at low shaking frequencies were clearly displaced from the driving frequencies. Thus, with 7 c/sec shaking, the highest EEG spectral peak occurred at 6 c/sec, with secondary peaks at 12 and 14 c/sec. Similarly, with 9 c/sec shaking, no peak was found at that frequency, but peaks were noted at 13 and 14 c/sec. A peak at 11 c/sec occurred in the EEG spectrum with shaking at that frequency. Faster vibration from 13 to 18 c/sec produced broad peaks in the EEG spectrum, often asymmetric with respect to the shaking frequency.

In the hippocampus (Fig. 2E), strong head movements with 7 c/sec vibration did not elicit an EEG spectral peak at that frequency. Faster shaking at 9 to 12 c/sec produced minor EEG "driving" peaks, but the major energy of the spectrum remained in the range 3 to 7 c/sec.

Records from nucleus centrum medianum changed strikingly at different parts of the vibration sweep, and contrasted sharply with those in the intact animal (Fig. 2C). Excellent "driving" occurred at shaking frequencies from 9 to 18 c/sec, with evidence of substantial first-harmonic components. In much of the vibration sweep, however, these driven peaks were lower than the energy at 1 to 3 c/sec. Moreover, driving at the fundamental frequency was observed in some cases to be low, as at 5 c/sec, whereas evoked EEG harmonic peaks at 15, 20 and 25 c/sec were disproportionately larger than would be anticipated from harmonic content of either shake table or head displacement.

Driving was also seen in the midbrain reticular formation (Fig. 2D), and exhibited both a selectiveness in relation to shaking frequencies, and more obvious driving peaks in the range from 11 to 17 c/sec than in the intact subject described above.

2. Coherence between EEG records from different structures, and between EEG records and accelerometers.

From cross spectral analyses, we have derived phase angles, shared amplitudes and coherence functions relating pairs of records. These parameters have been determined on a cycle by cycle basis across the

EEG spectrum at each shaking frequency. Sharply varying phase angles were noted in adjacent frequencies of the EEG spectrum. Only the coherence functions will be discussed here, for a limited series of interrelations. The coherence function (Walter 1963) provides a sensitive measure of linear interrelationships. A high coherence between brain record and the shake table would be expected to support the presence of purely mechanical artifacts if it occurred in the EEG spectrum exclusively at shaking frequencies; and at all shaking frequencies associated with violent head movements, without manifesting sharply selective peaks at different parts of the vibration sweep. On the other hand, high coherences between different cerebral structures, either at shaking frequencies when coherences with head or table accelerometers were low, or away from shaking frequencies where spectral energies were high, would support a physiological basis for the driving phenomenon. Representative examples will be discussed from extensive analyses in normal animals, and after eighth nerve section.

a. Coherence between cerebral structures and their relations with head and table accelerometers in the intact animal.

i) Coherence between centrum medianum and the visual cortex in resting records reached significant levels only at 17 and 18 c/sec in the following example (Fig. 3). Shaking below 10 c/sec produced no significant coherence levels at fundamental vibration frequencies. Thus, shaking at 5 c/sec produced significant EEG coherence at 6 and 22 c/sec, but remained low at 5 c/sec. Coherence was similarly low at 7 c/sec during shaking at that frequency, but significant at 10 c/sec. Shaking at 9 c/sec produced significant coherence at 2 and 18 c/sec.

Coherence became significant at the shaking frequency with 11 c/sec vibration, but was strikingly low in similar analyses with 12 c/sec vibration. Vibration in the range 12 to 17 c/sec produced significant coherence peaks at shaking frequencies.

Emphasis may be placed on the appearance of high coherence levels between these structures at various EEG frequencies unrelated to concurrent shaking frequencies, and absent from baseline records before or after shaking. Examples of these plastic and transient interrelations may be seen in the significant coherence at 6 and 22 c/sec with 5 c/sec shaking, and in coherence at 22 c/sec with 14 c/sec shaking. They may imply aspects of cerebral system organization, with ephemeral sharing of activity elicited by the vibratory volleys, and not detectable by previous techniques.

ii) Shared activity between midbrain reticular formation and visual cortex during vibration. As in the series just described, coherence in baseline records was significant only in a narrow range at 9 c/sec, and while this coherence persisted during shaking at many frequencies, the significant coherence "windows" interrelating midbrain and visual cortex opened remarkably during vibration, and mostly at frequencies quite unrelated to the shaking rate (Fig. 3D). Thus, shaking in the range from 5 to 11 c/sec evoked significant coherence at 1, 6, 9, 14, 16 and 22 c/sec, and in no case did these induced coherences relate to fundamentals or simple harmonics of the applied vibration. Moreover, in addition to the statistically significant coherences cited, "submerged" peaks of coherence occurred at other than shaking frequencies, and approached but did not reach significant levels.

iii) Interrelations of visual cortex and nucleus centrum medianum with head and table accelerometers. For both these structures, coherence with the table accelerometer did not reach significant levels at fundamental driving frequencies with shaking rates below 11 c/sec, although significant coherence peaks appeared at other frequencies in the EEG spectrum (Fig. 3B, C, E and F). Shaking at rates beyond 11 c/sec was associated with significant coherence at the fundamental frequency, and at both harmonically related and some harmonically unrelated higher EEG frequencies.

Similarly, coherence between EEG activity in these structures and a head accelerometer sensing vertical displacement was low at fundamental driving frequencies below 10 c/sec, despite violent head movement in this shaking range. In the range from 11 to 17 c/sec, shaking produced many coherent relationships at fundamental driving frequencies, and at harmonically related and unrelated EEG frequencies.

b. Coherence between cerebral structures and table accelerometer after bilateral eighth nerve section.

Coherence was measured between the table accelerometer and the visual cortex, hippocampus, amygdala, midbrain reticular formation, and centrum medianum (Fig. 4). The pattern of some relationships at shaking frequencies below 10 c/sec resembled that in the intact animal, with poorly developed coherence with the EEG at fundamental driving frequencies in the visual cortex, hippocampus and midbrain reticular formation. On the other hand, centrum medianum and the amygdala showed strong coherences in this range at fundamental shaking frequencies. With faster shaking at 11 to 18 c/sec, both midbrain and centrum medianum leads showed a wide range of coherent EEG frequencies, but visual cortical and amygdaloid leads continued to show coherences mainly in close relation to fundamental driving frequencies. They thus differed from behavior of these leads in intact animals. Section of the eighth nerves thus appeared to be without striking effect on the patterns of coherence between table accelerometer and cerebral structures during shaking, although some enhancement of coherence may occur with structures closely related to somatic sensory pathways, including nucleus centrum medianum and midbrain reticular formation.

B. Effects of Acceleration

Our previous studies have indicated the effects of both longitudinal and transverse accelerations on EEG records (Adey *et al*. 1961; Winters *et al*. 1962; Adey 1964). Although dramatic EEG changes accompany cerebral circulatory embarrassment in longitudinal acceleration to blackout ($-G_x$), the present study has concerned itself rather with those effects arising in transverse accelerations in "eyeballs in" and "eyeballs out" configurations ($+G_y$ and $-G_y$), where these may also be compounded with spinning the support couch around an axis collinear with that of the transverse acceleration ($+G_x$). Such simulations may accurately reproduce the acceleration profile experienced in attainment of orbital flight with small boosters.

1. Effects of compound accelerations on neocortical and limbic EEG records.

The simulation profile of Fig. 5A indicates the acceleration peaks and their typical time course in attainment of orbital flight. In view of the complexities of the experimental paradigm, only one animal was subjected to detailed testing with EEG recording as described here. Further tests are proceeding.

The effects in the visual cortex (Fig. 5C) of the initial 12G acceleration were minor, with a small peak in energy in the 3 middle frequency bands from 6 to 25 c/sec as the acceleration reached its peak and suddenly declined. No significant peaks occurred in the low G loading of the second stage. With stopping of the centrifuge (indicated by the 1G vertical line), however, there was a rapid increase in energy levels between 6 and 13 c/sec, persisting for most of the coasting phase.

Commencement of the final orbital injection phase, with 5G of transverse acceleration and concomitant 100 r.p.m. spin, evoked a quite different pattern of energy distribution from simple acceleration. Marked energy peaks occurred in the low frequency bands from 3 to 8 c/sec. Energy distribution rapidly resumed the characteristics of control records at the end of the injection phase.

The amygdala (Fig. 5D) showed similar changes. A moderate increase in energy in the low frequency bands from 3 to 8 c/sec occurred in the "coasting" phase, with a cyclic periodicity in peaks of 30 to 50 sec. Evidence of this periodic peaking was detectable at higher frequencies but diminished progressively in the range from 13 to 45 c/sec.

In the hippocampus (Fig. 5B), no significant changes in spectral content accompanied either initial or terminal phases of the boost simulation, although the energy levels in the coast phase rose moderately, and exhibited the cyclic changes described in the amygdala.

In summary, it would appear that changes lasting through the coasting phase may have been induced by the preceding high G pulse in the first stage of booster acceleration, and may relate to cardiovascular readjustments and concomitant changes in cerebral oxygen tension occurring with such a pulse, as described by Kovalenko, Popkov and Chernyakov (1963).

2. Interrelations between cardiac irregularity and paroxysmal EEG activity following high G loading.

The pulse rate slowed as the acceleration approached the initial 12G peak (Fig. 5C). During the following coasting phase, paroxysms of high amplitude slow waves appeared in many areas, including visual cortex, amygdala, hippocampus and midbrain reticular formation (Fig. 6D). A consistent accompaniment of these paroxysms were missed beats in the EKG. The heart was regular between these epochs, with minor rate variations attributable to a sinus arrhythmia. The missed beats appeared within 2 sec of the onset of the slow wave paroxysm, and recurred at intervals of about 2 sec.

No comparable abnormalities were detected following combined centrifuging and spinning at lower accelerations around 5G (Fig. 6E). These EEG phenomena occurred only after much higher accelerations and may relate to readjustment in cerebral vascular mechanisms. It is noteworthy that abnormalities in cardiac regularity always followed the onset of the cerebral dysrhythmia.

Discussion

In the complexities of multidimensional data derived from EEG records during such stimuli as whole body vibration over a wide frequency range, no single paradigm of experimental design, and no single technique of analysis is likely to provide unequivocal evidence of physiological or artifactual origin of particular facets of interrelationships that rest on periodicities in electrophysiological records. Even where electromechanical artifacts in sensing electrodes and recording leads have been essentially precluded, positive identification of physiological mechanisms has remained difficult. Our previous studies (Adey et al. 1963) indicated a profound reduction in vibration-induced driving during deep barbiturate anesthesia, and its disappearance on death of the animal. This driving activity at shaking frequencies appeared limited to frequencies in the range 10 to 15 c/sec. In this respect, careful attention to our recording techniques revealed differentials with barbiturate anesthesia not detected by Nicholson and Guignard (1964). Absence of such differentials would surely confirm the origin of such potentials in the swamping of the EEG by larger electrostatic artifacts in connecting cables and plug attachments.

If an artifactual origin were still to be postulated for driven rhythms showing such frequency-selective characteristics, it would be necessary to seek a basis in local tissue relations with the implanted electrodes, since cables and plug systems are inherently precluded. Yet physically adjacent regions of brain tissue, such as the amygdala and hippocampus, or the midbrain reticular formation and nucleus centrum medianum, separated by only a few millimeters and presumably subjected to closely related vibration forces, have consistently shown distinctly different patterns of driving. In these circumstances, an artifactual origin seems highly unlikely.

Coherence studies of linear predictability between EEGs from different brain regions, and between cerebral structures and head and table accelerometers strongly support this view. Significant levels of coherence were induced between cortical and subcortical leads by shaking, at frequencies harmonically unrelated to shaking rates, and thus supportive of a physiological system interrelationship. Moreover, coherences between the EEG and head and table accelerometers were often observed to be low at the fundamental shaking frequency, but were then often high at harmonics having low energy, and also at frequencies not harmonically related to the shaking rate.

Questions thus arise as to the possible physiological origin of the EEG driving. The present study has shown that vestibular influxes are not essential, and, indeed, that driving in midbrain and cortical structures may increase after vestibular denervation. In converse experiments, Gernandt and Gilmans (1960) found that evoked potentials in the medulla were greatly augmented after section of the dorsal columns of the spinal cord, suggesting that these spinal influxes normally inhibit medullary responsiveness to vestibular stimulation. Evidence here from records in the centrum medianum suggests that the converse may also be true. We have previously suggested an origin in mechanoreceptors of thoracoabdominal structures. We have observed thoracoabdominal resonance at shaking frequencies of 10 to 15 c/sec, and have noted mechanical coupling of these resonances into cervical structures. Oldendorf (1963) has drawn attention to coupling between cerebral and extracranial structures through the cranial blood pool, with evidence that intracerebral radioisotope distribution may fluctuate synchronously with respiration.

The possibility that direct mechanical excitation of cerebral tissue may occur during vibration, either transcranially or by hydraulic coupling through vascular or cerebrospinal fluid channels, remains a matter for speculation. Weiss (1964) has drawn attention to the dynamics of membrane-bound incompressible bodies, and to the possible role of such incompressibility in neuronal mechanisms. The fascinating complexities of the responsiveness of the central nervous system to kinetic stimuli merit further consideration in face of physical stresses not previously encountered in primate evolution.

Summary

The effects of whole body vibration over the range from 5 to 40 c/sec on cortical and subcortical EEG activity have been tested in the intact monkey (Macaca nemestrina) and after bilateral section of the vestibular nerves. Extensive computed analyses were made of auto- and cross-spectra, including calculations of shared amplitudes, phase angles and coherence.

Induced EEG rhythmicity occurring at certain frequencies of whole body vibration had the characteristics of a physiological "driving," and appears distinguishable from superficially similar phenomena of artifactual origin. Autospectral density plots showed little or no evidence of EEG driving below 9 c/sec, despite powerful head movements. Driving at the shaking rate was frequency selective and maximal in the range 10 to 15 c/sec. However, in many instances, maximum EEG energy peaks occurred at other than shaking frequencies, and without harmonic relationship to shaking frequencies.

Coherence (linear predictability) was high between cortical and

subcortical leads at EEG frequencies unrelated to concurrent shaking frequencies, and absent from baseline records before or after shaking. This may imply aspects of cerebral system organization with ephemeral sharing of activity elicited by the vibratory volleys. Coherence between head and table accelerometers and cortical and subcortical leads were below significant levels at fundamental driving frequencies below 11 c/sec, although significant coherence peaks appeared at other EEG frequencies. Shaking in the range 11 to 17 c/sec produced many coherent relationships at fundamental driving frequencies, and at harmonically related and unrelated EEG frequencies.

Bilateral section of the eighth nerve did not abolish this driving. Physiological mechanisms which might underly this driving are discussed, including the role of abdominal, thoracic and cervical tissues.

Brief centrifuging to high G levels was followed by paroxysmal cortical and subcortical slow wave activity, associated with missed cardiac beats.

Acknowledgments

The physiological investigations in this study were supported by Contract AF (49) 638-1387 from the U. S. Air Force Office of Scientific Research, and computer analysis by Contract NASA NAS 9-1970 from the National Aeronautics and Space Administration. Mr. Neil Fitzmorris assisted materially in surgical procedures. Miss Hiroko Kowta, Miss Suzanne Bawin and Mr. Rudolph Sabbot have prepared the illustrations.

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Legends to Figures

Fig. 1. Models of autospectral contours in normal monkey before and during shaking at decreasing frequencies from 17 to 5 c/sec. EEG spectrum is depicted on ordinates, vibration spectrum on abscissae, and spectral power on Z-axis (in microvolts squared per cycle per second) for visual cortex (A), amygdala (B), nucleus centrum medianum (C), midbrain reticular formation (D), and head accelerometer (E).

Fig. 2. Models constructed as in Fig. 1 for EEG spectra in monkey after bilateral vestibular nerve section, for visual cortex (A), amygdala (B), centrum medianum (C), midbrain reticular formation (D), hippocampus (E) and table accelerometer (F).

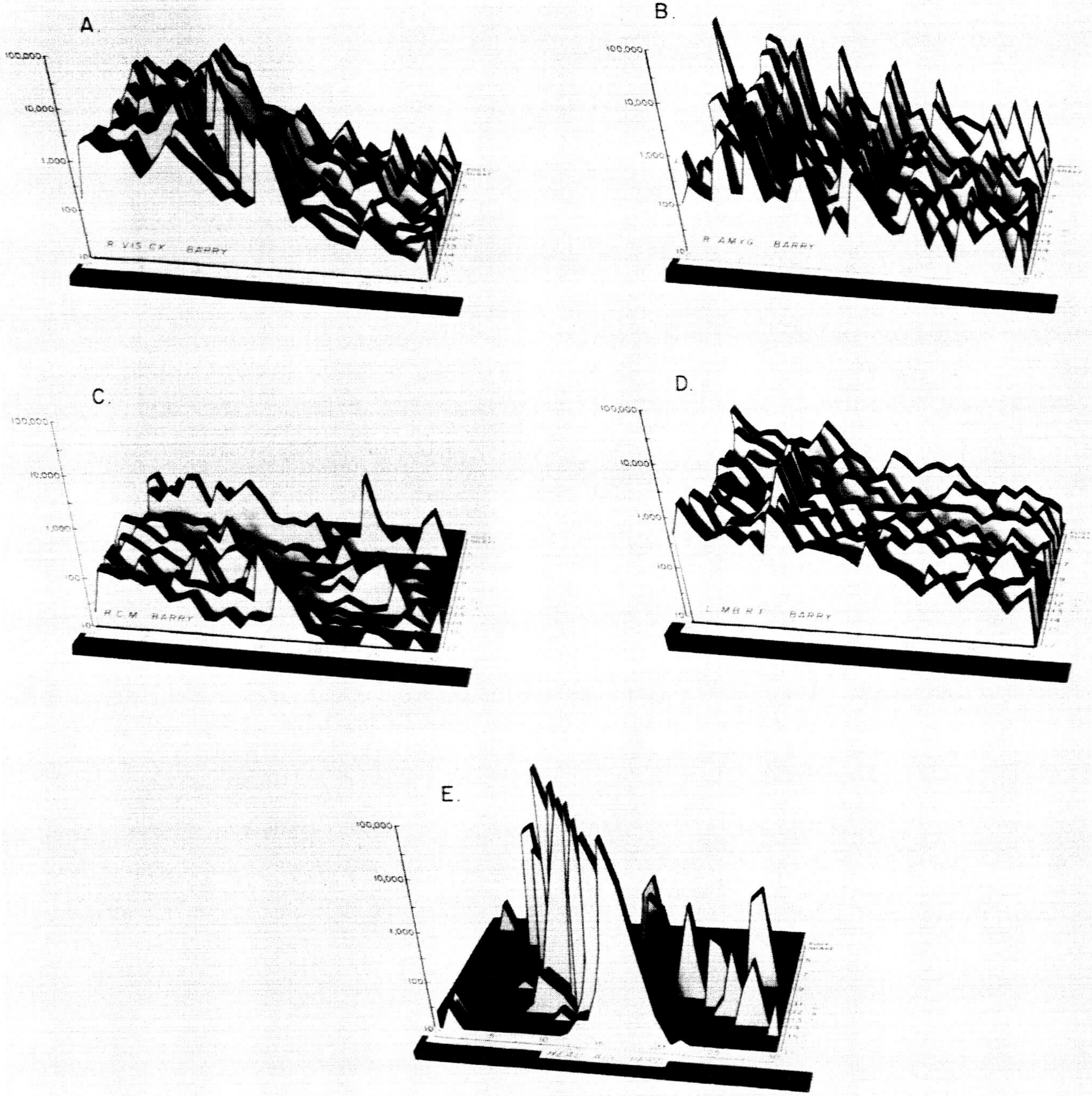
Fig. 3. Plots of coherence (linear predictability) between centrum medianum and visual cortex (A), vertical head accelerometer (B), and table accelerometer (C) during vibration. Similar plots are shown between visual cortex and midbrain reticular formation (D), head accelerometer (E) and table accelerometer (F). Ordinates show EEG spectrum, abscissae the vibration spectrum, and Z-axis the level of coherence. With 12 degrees of freedom, coherence levels were significant above 0.516. Significant coherence levels at the shaking frequency are shown in solid black, and at points away from the shaking frequency in stipple (see text).

Fig. 4. Plots of coherence as in Fig. 3 between the table accelerometer and visual cortex (A), amygdala (B), centrum medianum (C), midbrain reticular formation (D), and hippocampus (E), after bilateral 8th nerve section. With 24 degrees of freedom, coherence levels were significant above 0.516.

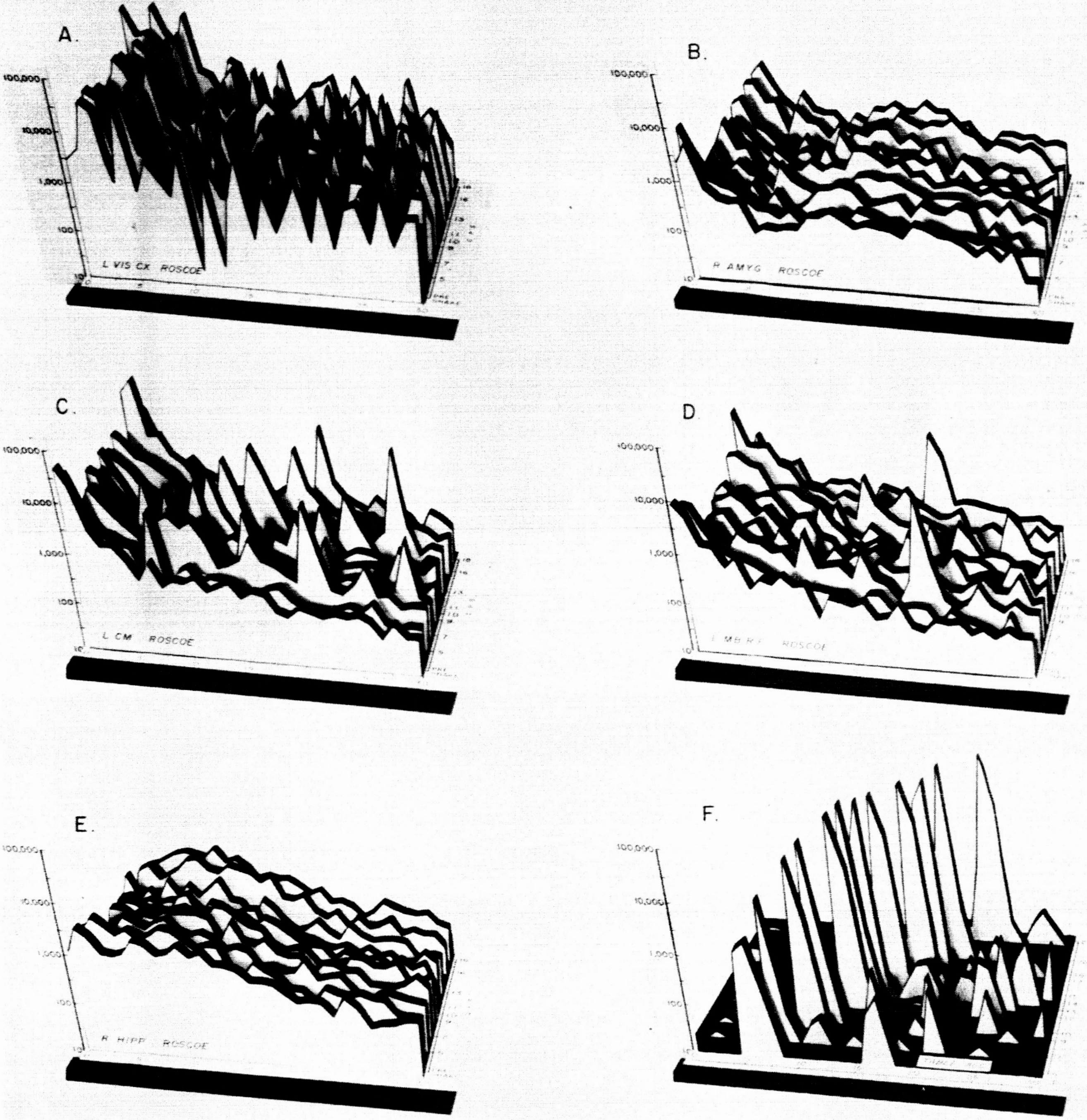
Fig. 5. Effects of compound transverse and spin accelerations on EEG during booster profile for attainment of orbital flight (A). Frequency analyses show major changes in energy distribution following high G "pulse" in hippocampus (B), visual cortex (C) and amygdala (D).

Fig. 6. Paroxysms of high amplitude slow waves in cortical and subcortical structures (D) during resting phase after 12G acceleration, showing missed cardiac beats during EEG paroxysms, but not in intervening intervals. Effects of spin and centrifuge on EEG are clearly evident (E). Abbreviations: L. VIS. CX., left visual cortex; R. AMYG., right amygdala; R. HIPP., right hippocampus; R. MB. R. F., right midbrain reticular formation; EKG, electrocardiogram.

AUTOSPECTRAL CONTOURS DURING VIBRATION
NORMAL MONKEY

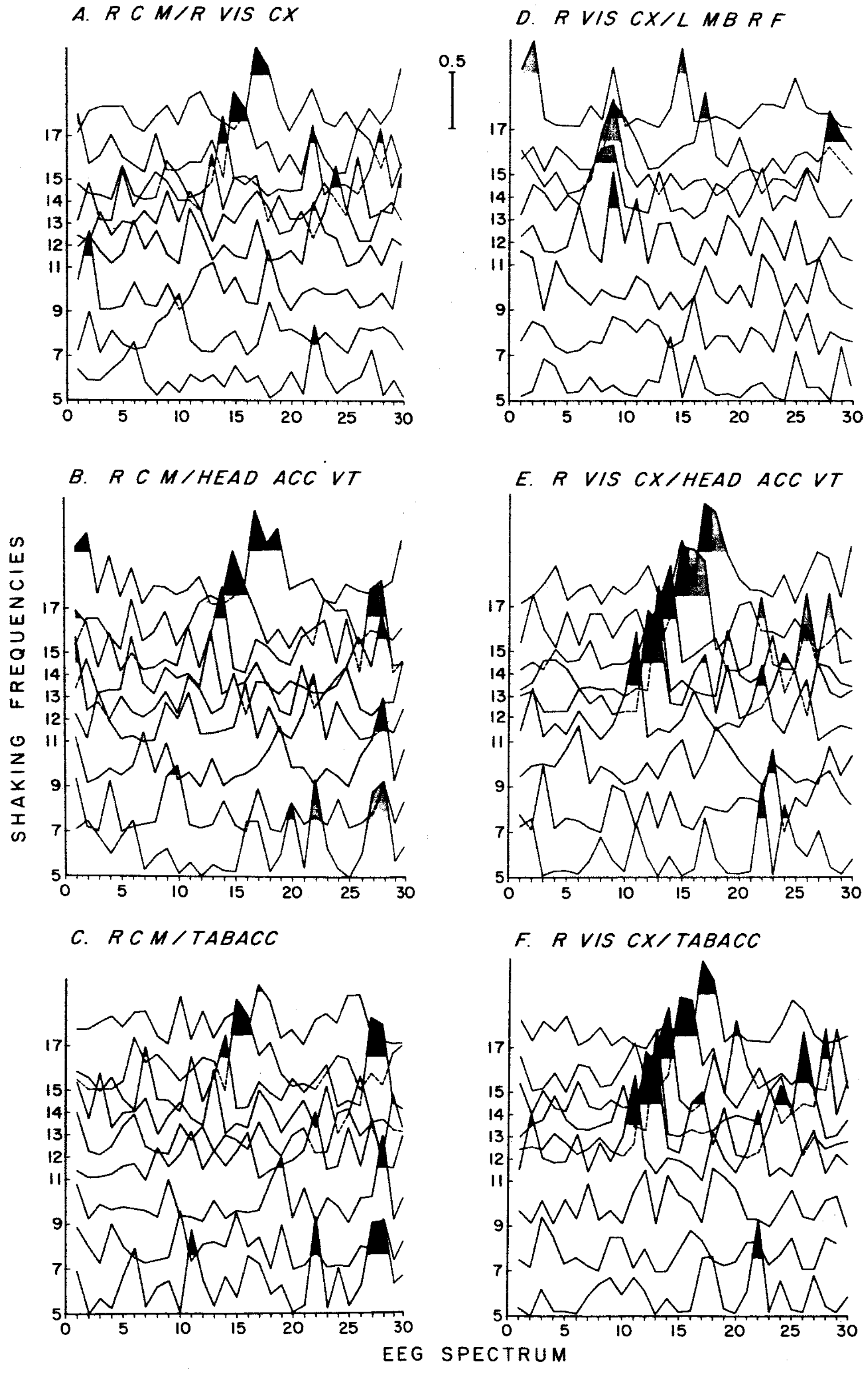


AUTOSPECTRAL CONTOURS DURING VIBRATION AFTER BILATERAL VESTIBULAR NERVE SECTION



PLOTS OF COHERENCES (LINEAR PREDICTABILITY) DURING VIBRATION – NORMAL MONKEY

SIGNIFICANT LEVEL AT 0.516

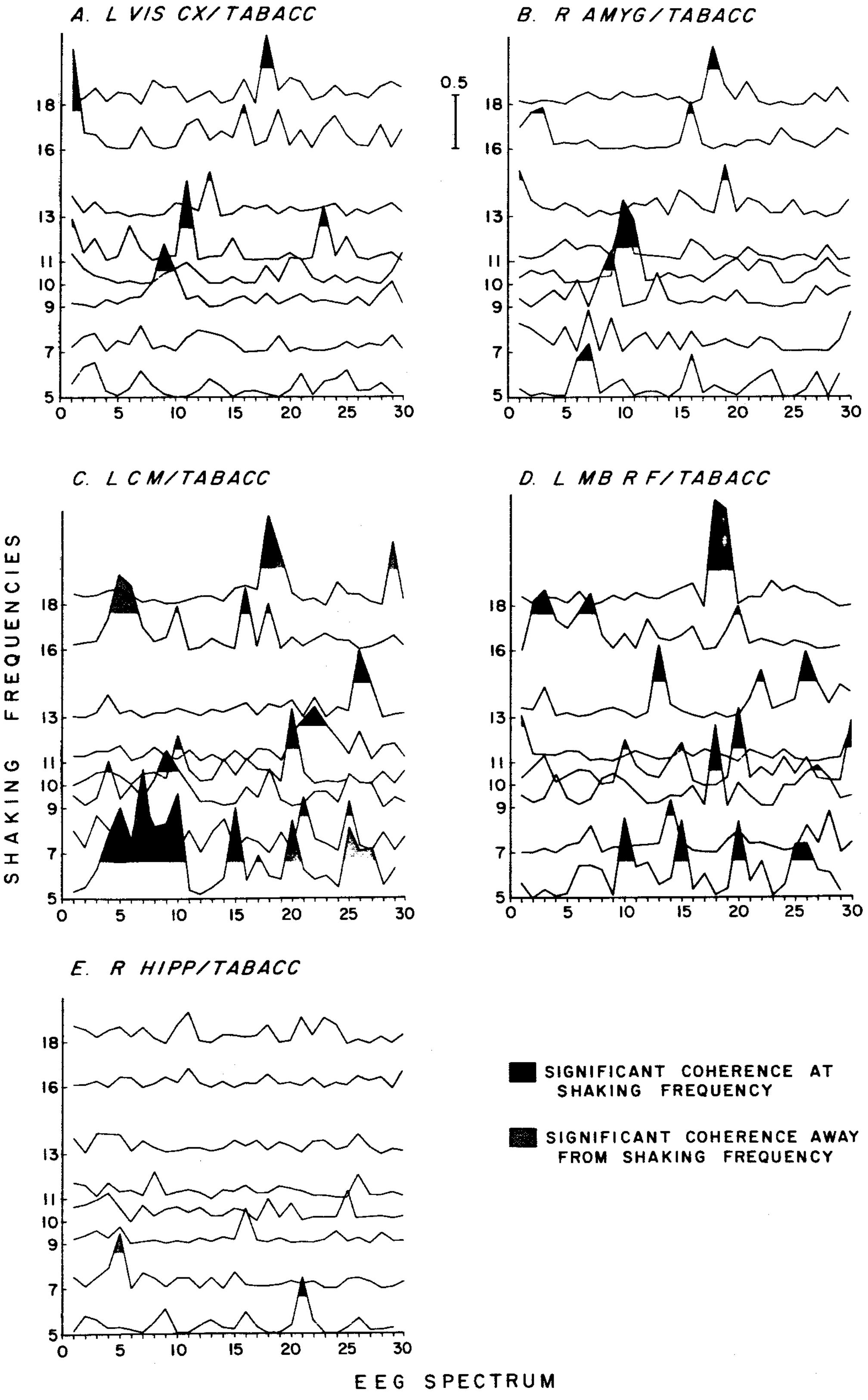


■ SIGNIFICANT COHERENCE AT SHAKING FREQUENCY

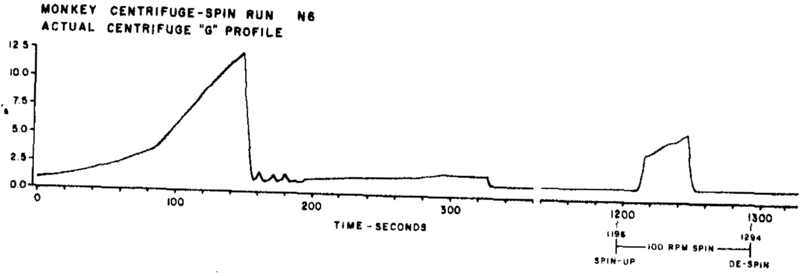
▨ SIGNIFICANT COHERENCE AWAY FROM SHAKING FREQUENCY

PLOTS OF COHERENCES (LINEAR PREDICTABILITY)
DURING VIBRATION - AFTER 8th N. SECTION

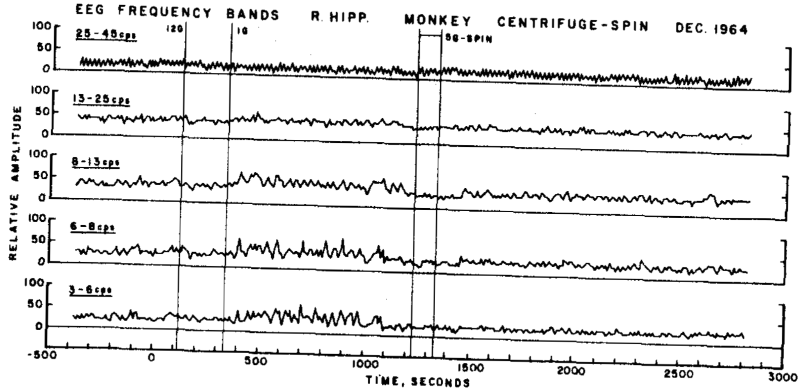
SIGNIFICANT LEVEL AT 0.326



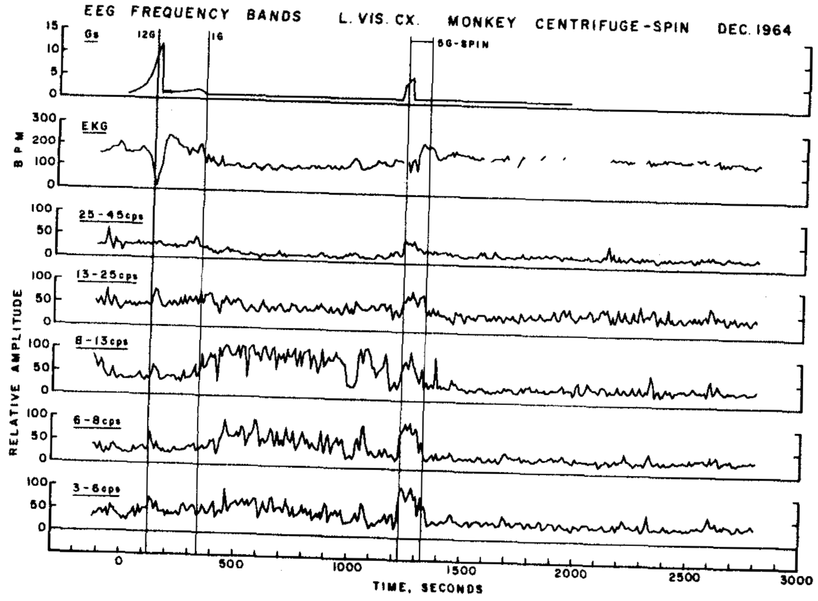
A.


MONKEY CENTRIFUGE-SPIN RUN N6
ACTUAL CENTRIFUGE "G" PROFILE
G's
12.5
10.0
7.5
5.0
2.5
0.0
0
100
200
300
1200
1300
TIME - SECONDS
1196
1294
100 RPM SPIN
SPIN-UP
DE-SPIN

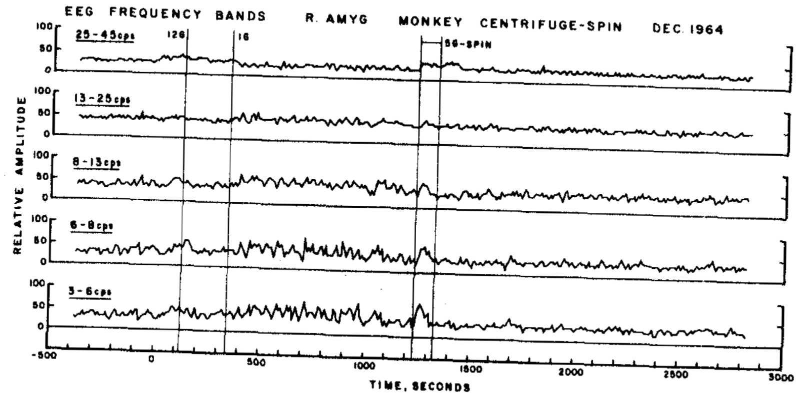
.B.


EEG FREQUENCY BANDS R. HIPP. MONKEY CENTRIFUGE-SPIN DEC. 1964
25-45cps
13-25cps
8-13cps
6-8cps
3-6cps
12G
1G
5G-SPIN
100
50
0
RELATIVE AMPLITUDE
-500
0
500
1000
1500
2000
2500
3000
TIME, SECONDS

C.


EEG FREQUENCY BANDS L. VIS. CX. MONKEY CENTRIFUGE-SPIN DEC. 1964
Gs
15
10
5
0
12G
1G
5G-SPIN
EKG
BPM
300
200
100
0
25-45cps
13-25cps
8-13cps
6-8cps
3-6cps
100
50
0
RELATIVE AMPLITUDE
0
500
1000
1500
2000
2500
3000
TIME, SECONDS

D.


EEG FREQUENCY BANDS R. AMYG MONKEY CENTRIFUGE-SPIN DEC. 1964
25-45cps
13-25cps
8-13cps
6-8cps
3-6cps
12G
1G
5G-SPIN
100
50
0
RELATIVE AMPLITUDE
-500
0
500
1000
1500
2000
2500
3000
TIME, SECONDS

MONKEY CENTRIFUGE-SPIN RUN

EYEBALLS-OUT CENTRIFUGING, WITH ADDED SPIN ABOUT DORSO-VENTRAL AXIS N6 DEC., 1963

PLATE 2: