THE SLEEP CYCLE AND SUBCORTICAL-CORTICAL EEG RELATIONS IN THE UNRESTRAINED CHIMPANZEE

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Abstract

The sleep cycle and subcortical-cortical EEG relationships were studied in the unrestrained chimpanzee. Sleep was recorded for 7 consecutive nights from each of 3 chimpanzees via biotelemetry techniques. The animals averaged 6.5% of their total nocturnal sleep time in Light Sleep (LS), 53.9% in Medium Sleep (MS), 20.3% in Deep Sleep (DS) and 19.3% in rapid eye movement sleep (REM). The mean duration of the chimpanzees' sleep cycle was 86 min. A "first night effect" was evidenced by a lower percentage of REM, a higher percentage of Light Sleep, more time spent in the Awake stage, and longer latencies to the onset of both Deep Sleep and REM.

Computer analysis techniques were used in the description of the physical parameters of the EEG to investigate subcortical-cortical relationships during the various stages of the sleep cycle. During REM, nonREM and the Awake stages of the cycle the cortex and each subcortical area studied were found to have their own characteristic patterns of spectral density. The spectral density patterns of the ventral anterior thalamus and the midbrain reticular formation most resembled those of the cortex while the patterns of the thalamic centre median and hippocampus were least like those of the cortex.

Coherences between subcortical areas and cortex were found to be either a) higher during the stages of sleep than in the Awake stage, as between the midbrain reticular formation and cortex; b) higher during some stages of sleep but lower in others than in the Awake stage, as between ventral anterior thalamic nucleus and cortex; or c) relatively low in all stages of the cycle, as between the hippocampus and cortex.

The unrestrained chimpanzee's sleep cycle as well as his subcortical-cortical EEG patterns were found to compare closely with that for man.

THE SLEEP CYCLE ANS SUBCORTICAL-CORTICAL EEG RELATIONS IN THE UNRESTRAINED CHIMPANZEE

Introduction

Electroencephalographic sleep studies on man have usually been performed in the laboratory environment with the subject lying comfortably in bed. The slight stress or novelty of this experimental situation is known to have marked effects on man's sleep cycle. For instance, Agnew et al (1966) found that the first night of laboratory sleep, a night usually omitted from baseline data collection, contained more awake periods, less rapid eye movement (REM) sleep, and more stage changes than on subsequent nights. There were also longer latencies from beginning of sleep to the onset of both deep slow wave sleep and REM sleep.

Most previous investigations of sleep in the chimpanzee have been conducted and animals restrained in a chair or couch (Adey et al, 1963; Rhodes et al, 1965; Rickles, 1965). The stress inherent in severity of restraint and the unnatural sleeping position was found to have a dramatic effect on the chimpanzee's sleep cycle, affecting both deep slow wave sleep (Rickles, 1965) and REM sleep (Adey et al, 1963; Rickles, 1965). Under these conditions, the animals were found to spend less than 6% of nocturnal sleep in the REM stage, with the first occurrence of this stage, if it appeared at all, preceeded by three to five hours of sleep (Adey et al, 1963; Rickles, 1965). On occasion deep slow wave sleep was also found to be completely absent (Rickles, 1965). The present study has investigated the chimpanzee's sleep cycle and the subcortical-cortical EEG relationships under less stressful conditions. Electroencephalograph recordings were obtained via biotelemetry from unrestrained chimpanzees sleeping in their home cages in the laboratory vivarium.

Method

a. Subjects.

The subjects were three tamed immature chimpanzees named Dinky, Charlie and Kelly, weighing 14.7, 13.4 and 16.8 Kg respectively. Several months prior to the recording sessions, the animals were implanted under phencyclidine hydrochloride (Sernylan) anesthesia. Electrodes were placed with the aid of a Trent Wells stereotaxic instrument, using coordinates from the chimpanzee atlas of Delucchi *et al* (1965). Stainless steel bipolar electrodes with poles 2 mm apart and 1 mm bared tips were used in all subcortical locations. The electrodes were placed in some or all of the following areas: hippocampus (A7, L16 to 19, H+2.5); amygdala (A14 to 15, L15 to 19, H0); inferotemporal cortex (A4, L32, H-5.5); ventral anterior thalamic nucleus (A12, L6 to 7, H+22); centre median of the thalamus (A4, L5, H+16); midbrain reticular formation (P1, L4, H+10); nucleus ruber (A3, L3 to 4, H+8); caudate nucleus (A22, L8, H+26).

Cortical screws were placed extradurally in the occipital, parietal, and frontal areas of the cranium. Wire EOG leads were placed in the lateral orbital ridges of the left and/or right eyes in the first two animals, while the third had leads placed in the ventral lateral and medial dorsal orbit of the right eye. Stainless steel wire leads were also inserted in the dorsal neck muscles for EMG monitoring. All recording leads were soldered to a specially designed array of 3 Winchester M9 plugs which were fastened in a holder and mounted to the skull with dental cement.

b. Procedure.

The three subjects, along with five other chimpanzees, were housed separately in a large vivarium containing eleven fiberglass and stainless steel cages. The cages measured 4 ft. high, 3 ft. deep, and 2 ft., 3 in. wide. One cage of the vivarium had been modified to allow behavioral monitoring of the chimpanzees during the night by a closed circuit, infrared TV system. A 4-channel FM/AM biotelemetry system described in detail in an earlier report (McNew et al, 1968) was employed to transmit a cortical and subcortical EEG, the EOG and the EMG. This data along with a chronolog time code were recorded on a Grass Model 6 Electroencephalograph (paper speed--15mm/sec) and magnetic tape for subsequent computer analysis. Position and movements of the chimpanzees were monitored via the TV system and noted on the paper record.

Before the onset of the experiment, the subjects were trained and well-adapted to wearing the telemetry pack strapped to the back with a short connecting cable leading from the head plug to the pack. The week preceeding each chimpanzee's recorded sleep sessions, the subject was transferred to the viviarium cage that had been modified for TV monitoring. The monitoring cage thus became the home cage. Following adaptation, each chimpanzee's sleep was recorded for seven consecutive nights. The nightly sessions began at 5:30 pm and continued until 7:00 am. The vivarium lights automatically went off daily at 6:00 pm and on at 6:30 am. For each chimpanzee the same occipito-parietal cortical site, EOG and EMG leads were used during all the sessions while the subcortical site varied from night to night.

c. Criteria for evaluation of sleep stages.

For evaluation of sleep patterns, five categories were used:

awake (Aw), light sleep (LS), medium sleep (MS), deep sleep (DS) and REM (see Fig. 1). The sleep stages were analyzed by visual inspection of the paper record supplemented by direct observation via closed circuit TV. The following criteria were used.

Awake (Aw): Animal awake; behaviorally alert or moving; high amplitude irregular EMG; abundance of eye movements and blinks apparent in the EOG; low voltage fast cortical EEG. Alternately, the animal judged to be awake, either in sleep position or behaviorally inactive excepting movements to and from sleep position; decrease in amplitude of EMG; sporadic or occasional eye blinks and eye movements; some slowing and increase in amplitude from the awake low voltage fast cortical EEG with apparent rhythmicity in the alpha and beta frequency range.

Light Sleep (LS): Chimpanzee in sleep position; decreased and regular EMG; absence of eye blinks and only occasional eye movements observed in EOG; some increase in amplitude and decrease in frequency in the cortical EEG to alpha and theta range; absence of delta slowing.

Medium Sleep (MS): Animal in sleep position; EMG remains regular; eye movements absent; cortical EEG shows delta slowing; high amplitude delta waves present in less than 50% of scored epoch; occasional spindling in the 12 to 15 Hz range and K complexes present.

Deep Sleep (DS): Subject in sleep position. EMG regular; moderate amplitude EEG may be seen in EOG channel; cortical EEG shows delta waves (0.5 to 3 Hz) of moderate to maximum amplitude dominating over 50% of scored epoch.

REM Sleep: The chimpanzee remains in same sleep position for duration of epoch; EMG very regular; occasional brief movements such as facial or limb twitches observed on TV monitor; eye movements; cortical EEG flattening with amplitude similar to light sleep; occasional saw tooth waves of about 4 Hz; K complexes and spindling absent.

An additional criterion of minimum maintenance of the sleep stage for a one minute (3 EEG pages) interval, in which at least 50% or more of that stage was present in each 20 sec interval (1 page) was used in defining an epoch of a sleep stage.

Figure 1

Results

1. Sleep staging

The 3 chimpanzees, during their 13.5 hour nightly recording sessions averaged 11 hrs and 52 min of sleep. Their most frequent sleeping position was curled on the side. Occasionally they would sleep on their stomach but rarely on their back. The amplitude of the EMG taken from the dorsal neck muscles was dependent on the sleep position, or the position of the chimp's head during sleep. The EMG indicated, for the most part, only the animal's state of activity, i.e., awake or asleep, and gross body movements, and did not reliably serve to differentiate the REM stage from other stages of sleep.

Nocturnal sleep was interrupted only infrequently by brief episodes of behavioral awakenings. When interruptions did occur, they usually followed a REM epoch or were near the beginning or the end of the sleep sessions. From the onset of sleep to morning awakenings the animals averaged 27 min in the awake stage. The range of the mean time spent in this stage per session was 49 min on the first recording night to 16 min during the third recording night.

Of the total sleep time (TS) the animals spent an average of 6.5% in light sleep (LS), 53.9% in medium sleep (MS), 20.3% in deep sleep (DS) and 19.3% in stage REM (see Table I). The chimpanzees averaged only 15% REM sleep on the first night compared with 20% on the remaining nights.

Table I

The percentage of LS per session showed a gradual decline from 9.7% during the first night to 3.7% on the seventh night. The MS and DS percentages ranged from 55.4% to 51.9% and 17.6% to 22.9% respectively.

The largest differences between Ss occurred in the light sleep stage, the percentage values for the three Ss being 9.7, 1.9 and 7.9 respectively. The percentage variability of the other three stages was greatly reduced, being 51.2, 58.0, 52.5 for medium sleep, 19.3, 20.3, 21.4 for deep sleep, and 19.8, 19.8, 18.2 for REM.

The time from onset of LS to the first epoch of MS, DS, and REM and the duration of these epochs are given in Table II. The first epoch of MS, DS and REM occurred on the average 10, 27, and 128 minutes respectively, after the onset of sleep. The mean latency to the onset of MS ranged from 24 min on the first session to 2 min on the fifth session. The onset latency of DS was from 37 min to 20 min on the first and seventh nights, respectively, while that for REM showed a nightly decline from 203 min on the first night to 80 min on the seventh night. The duration of the first epoch was 6 min for MS, 22 min for DS, and 12 min for REM sleep.

The duration of the chimpanzees' sleep cycles--the interval from onset of sleep to the end of the first REM epoch and then from the offset of each REM period to the offset of the next REM stage--averaged 93.4 min with a standard deviation of 39.3 min. When the first sleep cycle of the night (onset of sleep to end of first REM) was excluded from the computation, the mean cycle length was 86.3 min, with a standard deviation of 28.9 min. They averaged a total of 7.6 REM cycles per night. The individual REM epochs lasted a mean of 18 min with a standard deviation of 10 min. Table III gives the mean number of REMs, the mean length and the mean range of the REM periods of the three chimpanzees during the seven recording nights.

In the computation of the sleep cycles, interrupted REM intervals (intervals separating two REM epochs belonging to the same sleep cycle) were distinguished from interREM intervals (intervals separating two distinct REM periods belonging to two distinct cycles) by the method described by Kripke et al (1969). The compilation of all intervals separating REM epochs (Fig. 2) shows a bimodal distribution of the interval duration. Intervals of 17 min or less were considered as a consequence of interrupted REM epochs and were included in the previous sleep cycle. InterREM intervals of 25 min or more were assigned to separate sleep cycles.

Figure 2

The distribution of sleep stages during the nightly sessions can be seen in Fig. 3. Fig. 3A is representative of the later nightly sessions where little time was spent in the Aw stage and few stage changes occured. Fig. 3B depicts an early session where 72 min of Aw (the maximum found in the 21 recording sessions) interrupted nocturnal sleep and numerous stage changes were apparent. Two additional sessions of the chimpanzee "Dinky" may be found in an earlier preliminary report (McNew et al, 1968). DS was generally found dominant during the first half of the session, while MS dominated the latter half of the sessions.

Figure 3

2. Cortical and subcortical EEG analysis.

From each nocturnal sleep session five consecutive ten sec epochs of EEG recordings were selected from each stage of a sleep cycle. The digitized cortical and subcortical EEG of these epochs were subjected to spectral analyses (Walter, 1963) using a 360-91 IBM computer. Results from 7 of 21 sessions showing the relationship between the EEG activity of the various subcortical structures investigated and that of the cortex during the sleep cycle stages are presented graphically in Figs. 4, 5, 6 and 7. For each of these seven sessions 250 sec of raw data have been compressed into autospectral and crosspectral contour plots, allowing recognition of patterns of EEG and other relevant details that otherwise might be quite transient and lost. The autospectral plots map the relative spectral intensity or power at each frequency of the spectral analysis for the subcortical structures and for the cortex. The total sum of spectral power divided by 100 (total sumsp.) over the frequencies from 0 to 32 Hz during the 50 sec of each stage is given above the appropriate epochs of the autospectral map.

The selection of intensity levels for the autospectral maps was made by visual inspection of the computer analyzed spectral values on the basis of distinguishing between the different stages of the sleep cycle in the subcortical structures. The specific intensity values from the hippocampus and other brain areas are also dependent upon a variety of variable in the data acquisition system inherent in electrode and amplification differences. The autospectral intensity levels of each contour map were therefore interpreted with respect to the relative changes and not to the absolute changes in intensity.

The crosspectral plot maps the coherence, a sensitive measure of shared activity, at each frequency between the subcortex and cortex. The coherence levels of .44, .57, and .62 of the crosspectral maps represent statistical significance at the .25, .1 and .05 levels of confidence respectively.

Figure 4

<u>i) Hippocampus</u>: Spectral intensity levels of the right hippocampus along with the concomitant spectral values of the left occipito-parietal cortex and the shared activity between the hippocampus and cortex are mapped in Fig. 4A for Aw (lying down), LS, MS, DS and REM stages of sleep.

The spectral power in the hippocampus in Aw, LS, MS, DS and REM was generally concentrated in the high delta (2 to 3 Hz) and theta (4 to 5 Hz) frequency ranges. Relatively high voltage is also apparent in the alpha and beta ranges. Hippocampal slowing through the sleep stages is in the high delta and theta range, peaking at about 5 Hz with little increase in power below 2 Hz. REM sleep is typified by low voltage fast activity similar to the awake stage but with a higher proportion of activity above 16 Hz.

Although a low voltage fast activity characterizes the cortical picture of the awake animal's paper EEG record, the highest spectral density is found at 0 to 2 Hz. The LS epochs depict a broadening of spectral power to the high delta, theta, alpha and low beta frequencies and a lowering of spectral intensity in the lower delta range. The spectral power increase in MS and DS was concentrated in the lower frequencies depicting delta slowing. Spectral density in the REM stage shows relatively more power from 2 to 14 Hz than in awake records; the peak at 4 Hz reflects saw tooth waves apparent in the paper record.

The sum of spectral intensities in the hippocampus increased from awake to LS, decreased in MS, increased sharply in DS, and then decreased greatly to its lowest power in REM sleep. The sum of spectral intensity in cortical EEG records increased from Aw through DS and then decreased in power in REM to a level slightly above both Aw and LS.

The progression of sum of spectral power through the sleep cycle between the cortex and hippocampus in this session was not consistent in cycles of hippocampal activity in other sessions. The relative total spectral power of MS and DS was reversed in one case (relatively low power in DS and high power in MS), and in another case waxed and waned in the same sequences as the cortical records.

The coherence map shows a sparcity of shared activity between the hippocampus and cortex from epoch to epoch within the various stages of the sleep-wake cycle.

ii) Amygdala: Contour plots of the spectral intensity in the right amygdala EEG along with corresponding values of the left occipito-parietal cortex and the coherences between the activity of these structures are given in Fig. 4B. The spectral intensity in the amygdala in the Aw (moving chimpanzee), LS, MS, DS and REM is concentrated in delta frequencies. Spectral peaks at 4 to 5 Hz and 23 to 24 Hz are seen in MS and REM respectively. The 23 to 24 Hz spectral peak in REM reflects uncal spindling often apparent in this stage and occasionally in the other stages of the sleep-wake cycle. Low voltage fast activity was found in all stages, especially in Aw.

In the cortex during the same time intervals the spectral power was concentrated below 3 Hz in all stages of the cycle. Intensity in the higher frequencies above 20 Hz dropped from the awake moving chimpanzee to the sleeping chimpanzee. In LS and REM there was a reduction of power concentration in the delta range and thus proportionately greater intensities in the theta, alpha and beta frequencies.

The sum of spectral intensity in the amygdala decreased from Aw to LS, and then increased through MS and DS. In REM the total spectral power fell to its lowest level. Concurrent values in the cortex showed a slight reduction of spectral power from Aw to LS and then increases of power through DS followed by a decrease in REM to a sum greater than that found in Aw and LS.

The coherences between the amygdala and cortex were generally low.

Figure 5

iii) Caudate: The contour maps of the autospectral values of the left caudate and the right occipito-parietal cortex and the crosspectral coherence values of these structures are seen in Fig. 5. In the caudate, the intensity peaked at 0 to 1 Hz in all stages of the cycle. The power was concentrated below 2 Hz in Aw, LS and REM stages with broadening to 3 Hz in MS and to 4 Hz in DS. The sum of spectral intensities decreased from Aw to LS in the caudate while in the cortex the reverse was seen. In both structures, sum of power then increased in slow wave sleep followed by a sharp reduction in power in stage REM giving comparatively a very low voltage EEG picture in this stage.

The coherence levels between the caudate and cortex were found to be high in LS in the middle frequencies, 6 to 16 Hz, and consistently high from epoch to epoch at 27 Hz in MS, 17 Hz in DS, and 31 to 32 Hz in REM.

iv) Ventral anterior thalamic nucleus: Spectral analysis of the right ventral anterior thalamic nucleus EEG and simultaneous activity of the left occipito-parietal cortex is depicted in Fig. 6.

EEG power levels in the ventral anterior thalamic nucleus, typically low in comparison with the cortex and hippocampus, peaked at less than 1.0 Hz throughout the sleep cycle. Spectral intensities at higher frequencies dropped off in LS with occasional peaks between 17 and 26 Hz. In MS spectral power increased with additional peaks in the theta (4-6 Hz) and alpha (11-12 Hz) ranges. Concurrent power increases in these sleep stages were also seen in the cortex. In REM, a general reduction in spectral intensity above 2 Hz occurred.

Total EEG spectral power in the ventral anterior thalamic nucleus in the various stages of sleep followed the pattern in cortex but with proportionately smaller power increases in MS and DS.

Coherences between this thalamic nucleus and the cortex were generally high, especially in the Aw and LS stages in the theta, alpha and beta frequency ranges. In LS, high coherences appeared with notable consistency from epoch to epoch at 6 to 12 Hz. During one epoch of LS, very high coherences can be seen from 4 to 12 Hz, and between 15 and 32 Hz (Fig. 6). In the REM stage consistently high coherences occurred at 3 to 4 Hz, 7 to 8 Hz and 10 Hz.

Figure 6

v) Centre median: The centre median, like the ventral anterior thalamic nucleus, has relatively low voltage EEG. Spectral maps of the right centre median and the simultaneous activity in the left occipito-parietal cortex is given in Fig. 6B. Spectral intensity was concentrated at 0 to 1 Hz in all stages of the cycle with fast activity apparent throughout. Relatively high amplitude theta activity was shown by occasional peaks in LS, MS and DS. Proportionately high voltage fast activity was found in LS and REM. The sum of spectral power across the range 0 to 32 Hz for the various stages of the sleep cycle does not always reflect the progression of cortical changes. For those epochs selected for the session mapped, the spectral power decreased from Aw to LS, then increased through DS, followed by a decrease in REM to a level similar to that of MS. The concurrent power in the cortex increased from Aw to LS, through DS and then decreased in REM to a sum of power well below MS to a level slightly above Aw. In epochs from another animal, the centre median more closely followed the progression of changes in relative power seen in the cortex, except in REM sleep, where again it was comparatively high. In the latter animal, the sum of power in the REM stage was less than that of MS but well over twice that of LS. The greater power in REM was particularly apparent in frequencies above the delta range.

Coherences between centre median and occipito-parietal cortex were generally high at all stages of sleep. Consistently high coherences from epoch to epoch were found at 8 Hz in Aw, 4 to 14 Hz in LS, 4 to 15 Hz in MS, 3 to 18 Hz in DS, and from 3 to 4, 5 to 8, 10, and 16 Hz in REM.

Figure 7

vi) Midbrain reticular formation: EEG spectral values for the left midbrain reticular formation and left occipito-parietal cortex are given in Fig. 7A. In the reticular formation, the peak of spectral power was concentrated at 0 to 1 Hz in Aw, LS, MS, and REM stages, and broadened to 4 Hz in DS. Moderate spectral power was found in the higher delta and theta range, peaking at 4 to 6 Hz in LS, MS and DS. The spectral peak at 4 Hz in REM reflects saw tooth waves also found in the concurrent cortical EEG. Low voltage fast activity was most apparent in the reticular formation in the Aw stage and then to a lesser degree as sleep deepened due to proportional increases of power in the lower frequencies. In REM, the intensity of higher frequencies decreased. The sum of power in the midbrain reticular formation followed the cortical progression through the cycle, excepting REM. In REM, the sum of spectral power in the midbrain reticular formation was at a level between LS and MS, where the level of spectral power in concomitant cortical activity decreased to a level lower than LS.

Consistently high coherences were found between the midbrain reticular formation and the cortex in the Aw stage at 8 to 9, and 31 to 32 Hz; in LS at 5 to 6 and 13 Hz; in MS at 1 to 4, 8 to 11, and 15 to 16 Hz; in DS at 5 to 7, and 11 to 12 Hz, and in REM at 3 to 7 Hz.

In general, coherences were higher during sleep than in the Aw stage.

vii) Red nucleus: Spectral intensity values of the left red nucleus and concomitant values of the right occipito-parietal cortex along with the shared activity of these two brain areas are mapped in B of Fig. 7. The intensity concentration of the spectra in the red nucleus was in the delta frequencies below 2 cps, peaking at either 0 or 1 cps throughout the cycle. Moderate intensity levels were found up to 5 or 6 Hz and to a lesser degree through the alpha range. The summed spectral power for the five epochs of each stage increased greatly from the Aw stage through DS, then decreased in REM to a level similar to that of LS. The cortex showed a similar progression of total sum of spectral power through DS, but dropping below that of LS in REM.

The coherences of shared activity between the red nucleus and the cortex were consistently high in the alpha and beta frequencies in Aw, LS and MS, especially at 15 to 20 and 25 to 27 Hz in Aw, at 10 and 16 Hz in LS, and at 9, 17 and 20 to 21 Hz in MS. In DS and REM there is some decrease in the abundance of shared activity and high coherences are not as consistent from epoch to epoch within a particular frequency band.

Discussion

The overall sleep patterns of the unrestrained chimpanzee were found to be more congruent with its phylogenetic position that those reported earlier on the restrained chimpanzees. The young chimpanzees in the present study, excluding the first night, averaged approximately 20% of their nocturnal sleep time in stage REM compared with 15% in REM for the monkey (Kripke et al, 1969) and 24% for preadolescent children (Ross et al, 1968). In the nonREM stages, the young chimpanzees spent about 6% of sleep time in LS, 54% in MS and 20% in DS. This compares favorably with what Ross et al (1968) found for preadolescent children. Their subjects spent about 7% of total sleep time in stage 0 and 1, 50% in stages 2 and 3, and 18% in stage 4.

Excluding the first nightly sleep cycle, in which the duration was extremely sensitive to the stress of the experimental situation (see below), the mean duration of the chimpanzees' sleep cycle was 86 min. This compares with a cycle of 51 min for the monkey and about 90 min for man (Kripke et al, 1969).

Our chimpanzees also occupied a position between monkey and man in the distribution of interrupted interREM intervals and interREM intervals. The interREM intervals of interrupted REM epochs were 17 min or less, while the interREM intervals for uninterrupted REM epochs were 25 min or more. Kripke et al (1969) reported that for monkeys, the interrupted intervals were 8 min or less and uninterrupted interREM intervals were 10 min or more. He also noted from personal communication with Dement (Kripke et al, 1969) that interrupted REM intervals for man were 25 min or less while uninterrupted intervals were 30 min or more.

The slight stress or novelty associated with the recording sessions of this study, as in the investigations of sleep in man, had their effects on the chimpanzees' sleep patterns. Even with extensive adaptation procedures prior to the first recording session for each animal, the "first night effect" was evident. On their first night the animals averaged a lower percentage of REM, a higher percentage of LS, and more time in the Aw stage than on subsequent nights. In addition, longer latencies from the beginning of sleep to the onset of both DS and REM were found.

Inspection of Tables I and II suggested that adaptation was not complete after the first night but continued to some extent throughout the 7 consecutive recording nights. This was evidenced in the gradual reduction of the percentage of LS and the shortening of the latencies to the onset of DS and REM of the initial sleep cycle of the nightly sessions.

Changes in spectral density of the EEG during the sleep wake cycle depicted in the autospectral maps clearly indicate in cortical and most subcortical leads that highest spectral density in all stages of sleep was concentrated in the lower (delta) frequencies. Similar results have been reported in the restrained chimpanzee (Rhodes _et al_, 1965) and in man (French _et al_, 1966). As sleep deepened, the spectral power generally increased. In stage REM and Aw, the power was relatively low. A notable exception to these findings was the hippocampus. First, the spectral intensity during sleep was concentrated in the 2 to 6 Hz band rather than between 0 and 3 Hz. Secondly, spectral power changes in the hippocampus neither consistently paralleled neocortical slowing nor did they consistently display the reciprocal relationship described in other mammals (Adey _et al_, 1963).

These findings are in general agreement with an earlier report by Freemon _et al_ (1969). They observed that low voltage fast activity could occur in the Aw, nonREM and REM stages of the cycle; that the slower 2 to 3 Hz was usually apparent in REM and nonREM stages and 4 to 6 Hz irregular activity could occur in either the nonREM or Aw stages. Computer analysis of the EEG in the present study showed that in addition to the above, intensity peaking of the slower 2 to 3 Hz activity may also occur in the Aw Stage.

Subcortical structures also showed some deviation from the progression of cortical spectral density patterns through the sleep-wake cycle. Areas that mirrored the cortex most were the ventral anterior thalamic nucleus of the thalamus and the reticular formation. To a lesser degree this was found for the amygdala, red nucleus and the caudate, while the centre median and hippocampus mirrored the cortex least. Each area had its own characteristic patterns during REM, nonREM and the Aw stages and, in conjunction with the cortex, could aid in assessing the different stages of the sleep cycle.

Coherence between the various brain regions have also been associated with differentiating the stages of the sleep cycle. In this study, as has typically been reported for man (French _et al_, 1966) and monkey (Hoshizaki _et al_, 1969), coherences are generally higher during sleep than awake, suggesting that a different or more permissive organization of nervous transmission occurs between brain regions during sleep (French _et al_, 1966). Higher coherences during sleep were especially clear between the centre median and cortex, and the midbrain reticular formation and cortex.

Coherent activity between the ventral anterior thalamic nucleus and cortex and the red nucleus and cortex showed yet another pattern. In the thalamo-cortical relationship, the general increase in coherence was seen only in LS and less shared activity in MS, DS and REM. In the rubro-cortical case, generally lower coherences were also noted in DS and REM. This suggests that among these areas, the organization of transmission in MS, DS and REM lacks the moderate relationships present when awake. A similar picture of lower coherences during sleep has been reported between another thalamic area (the dorsal medial nucleus) and the cortex in man (Brazier, 1969).

Still a third picture of cortical-subcortical relationships during the sleep-wake cycle is reflected by coherences between the hippocampus and cortex. A scarcity of shared activity between these structures was found during all stages of the cycle. This, too, is consistent with the findings in man (Brazier, 1969).

The powerful and sensitive computing techniques in this study have proven useful in the description of the cortical-subcortical EEG relationships during the various stages of the sleep-wake cycle. They have been employed similarly in describing the EEG correlates of decision-making in man (Walter _et al_, 1967), chimpanzee (Hanley _et al_, 1968), monkey (Berkhout _et al_, 1969) and cat (Elazar and Adey, 1967).

In the unrestrained chimpanzee the sleep cycle, as well as the animal's cortical-subcortical EEG relationships during the stages of the cycle, compare favorably with that found for man. The results are congruent with the relative phylogenic position of the chimpanzee with respect to man (Wilson and Sarich, 1969) and suggest that the chimpanzee may serve as a good experimental model for human sleep.

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REFERENCES

Adey, W.R., Kado, R.T. and Rhodes, J.M. Sleep: cortical and subcortical recordings in the chimpanzee. Science, 1963, 141: 932-933.

Agnew, H.W. Jr., Webb, W.B. and Williams, R.L. The first night effect: an EEG study of sleep. Psychophysiol., 1966, 2: 263-266.

Berkhout, J., Adey, W.R. and Campeau, E. Simian EEG activity related to problem solving during simulated space flight. Brain Res., 1969, 13: 140-145.

Brazier, M.A.B. Electrical activity recorded simultaneously from the scalp and deep structures of the human brain. A computer study of their relationships. J. nerv. ment. dis., 1968, 147: 31-39.

DeLucchi, M.R., Dennis, B.J. and Adey, W.R. A stereotaxic atlas of the chimpanzee brain. University of California Press, Los Angeles, 1965.

Elazar, Z. and Adey, W.R. Electroencephalographic correlates of learning in subcortical and cortical structures. Electroenceph. clin. Neurophysiol., 1967, 23: 306-319.

Freemon, F.R., McNew, J.J. and Adey, W.R. Sleep of unrestrained chimpanzee: cortical and subcortical recordings. Exp. Neurol. 1969, 25: 129-137.

French, J.D., Adey, W.R. and Walter D.O. Computer analysis of EEG data for a normative library. Final report to National Aeronautics and Space Administration on Research Contract NAS 9-1970, 1966, 187p.

Hanley, J., Walter, D.O., Rhodes, J. and Adey, W.R. Chimpanzee performance data: computer analysis of electroencephalograms, Nature

(Lond.), 1968, 220: 879-881.

Hoshizaki, T., Adey, W.R., Meehan, J.P., Walter, D.O., Berkhout, J., and Campeau, E. Central nervous, cardiovascular and metabolic data of Macaca nemestrina during a 30-day experiment. In F.H. Rohles (Ed.), Circadian rhythms in nonhuman primates. S. Karger-Basel, New York, 1969, 8-38.

Kripke, D.F., Reite, M.L., Pegram G.V., Stephens, L.M. and Lewis, O.F. Nocturnal sleep in rhesus monkeys. In Primate electrophysiology particularly related to sleep. Aeromedical Res. Lab. Technol. Rept., Holloman Air Force Base, New Mexico, 1969, No. 69-5: 5-17.

McNew, J.J., Kado, R.T., Howe, R.C., Zweizig, J.R. and Adey, W.R. Telemetry studies of sleep in the unrestrained chimpanzee. IEEE Nat. Telem. Conf. Record, 1968, 374-379.

Rhodes, J.M., Reite, M.R., Brown, D. and Adey, W.R. Cortical-subcortical relationships of the chimpanzee during different phases of sleep. In Aspects anatomal-fonctionnels de la physiologie du sommeil. Colloques internationalux du CNRS, 1965, No. 127: 451-473.

Rickles, W.H. Jr. A study of EEG and somatovegetative physiology of the immature chimpanzee during sleep. Aeromedical Res. Lab. Tech. Rept. Holloman Air Force Base, New Mexico, 1965, No. 65-19.

Ross, J.J., Agnew, H.W. Jr., Williams, R.L. and Webb, W.B. Sleep patterns in pre-adolescent children: an EEG-EOG study. Pediat., 1968, 42: 324-335.

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

Walter, D.O., Kado, R.T., Rhodes, J.M. and Adey, W.R. Establishment of electroencephalographic baselines in astronaut candidates with computed analyses and pattern recognition. Aerospace Med., 1967, 38: 371-379.

Wilson, A.C. and Sarich, V.M. A molecular time scale for human evolution. Proc. Nat. Acad. Sci., 1969, 63: 1088-1093.

FIGURES

Fig. 1: Telemetered EEG data of a chimpanzee in different stages of the sleep cycle.

Fig. 2: The distribution of between-REM intervals compiled from 21 nights of sleep recordings.

Fig. 3: The distribution of sleep stages in unrestrained chimpanzees during two different nights of sleep recording.

Fig. 4: Contour maps of EEG autospectral intensity and crosspectral coherence levels during the stages of the sleep-wake cycle. Total sumsp = total sum of autospectral power (intensity) divided by 100 for the 5 ten sec epochs of each stage. Coherences of .44, .57, .62 represent statistical significance at the .25, .1 and .05 levels of confidence respectively.

A. Autospectral intensity maps of the right hippocampus and left occipito-parietal cortex and a contour map of coherence between the hippocampus and the occipito-parietal cortex.

B. Autospectral intensity maps of the right amygdala and left occipito-parietal cortex and a contour map of coherence between the amygdala and the occipito-parietal cortex.

Fig. 5: Autospectral intensity maps of the left caudate and the right occipito-parietal cortex and a contour map of coherence between the caudate and occipito-parietal cortex.

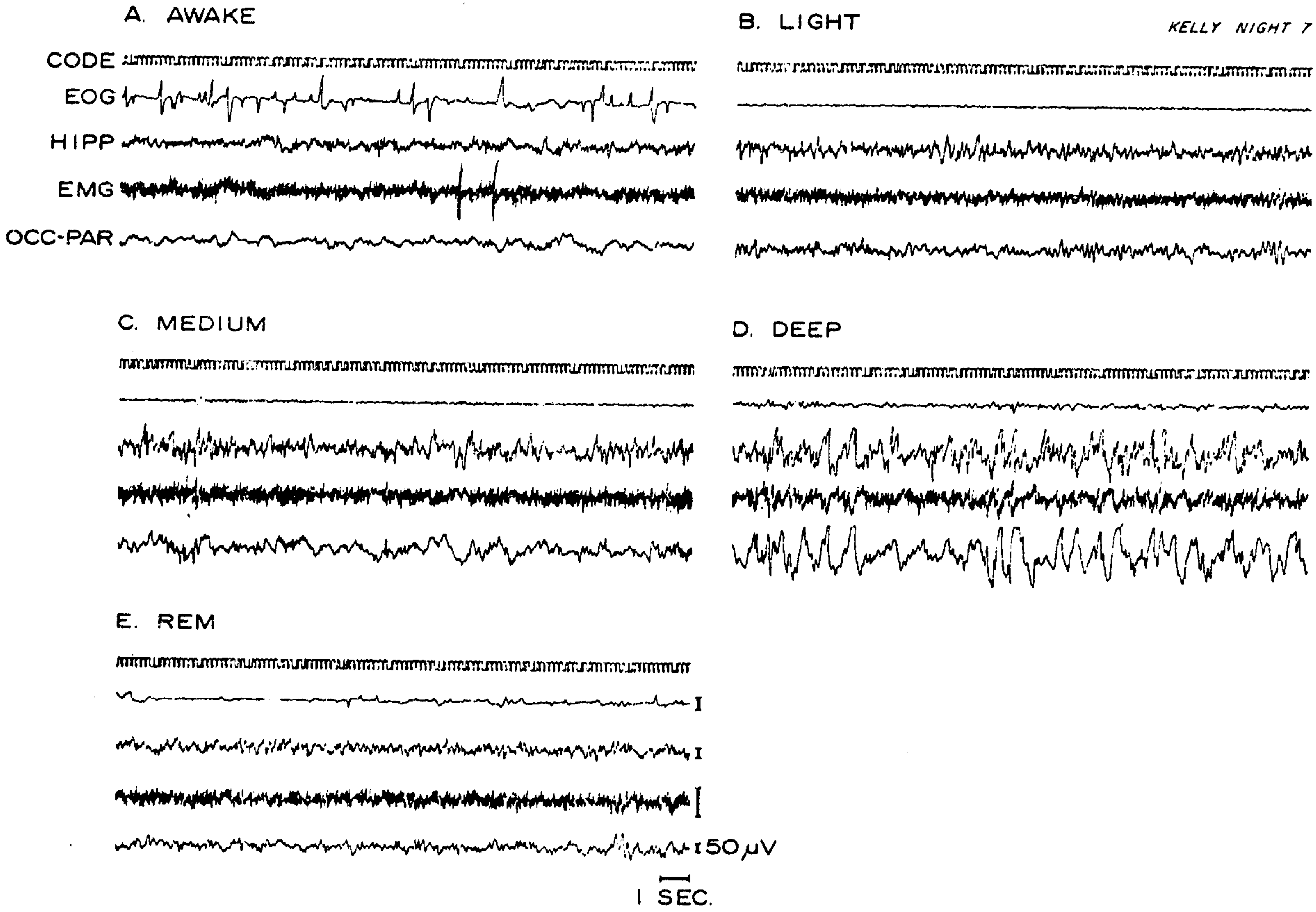
Fig. 6: A. Autospectral intensity maps of the right ventral anterior thalamic nucleus and the left occipito-parietal cortex and a contour map of the coherence between the ventral anterior thalamic nucleus and occipito-parietal cortex.

B. Autospectral intensity maps of the right centre median of the thalamus and the left occipito-parietal cortex and a contour map of coherence between the centre median and occipito-parietal cortex.

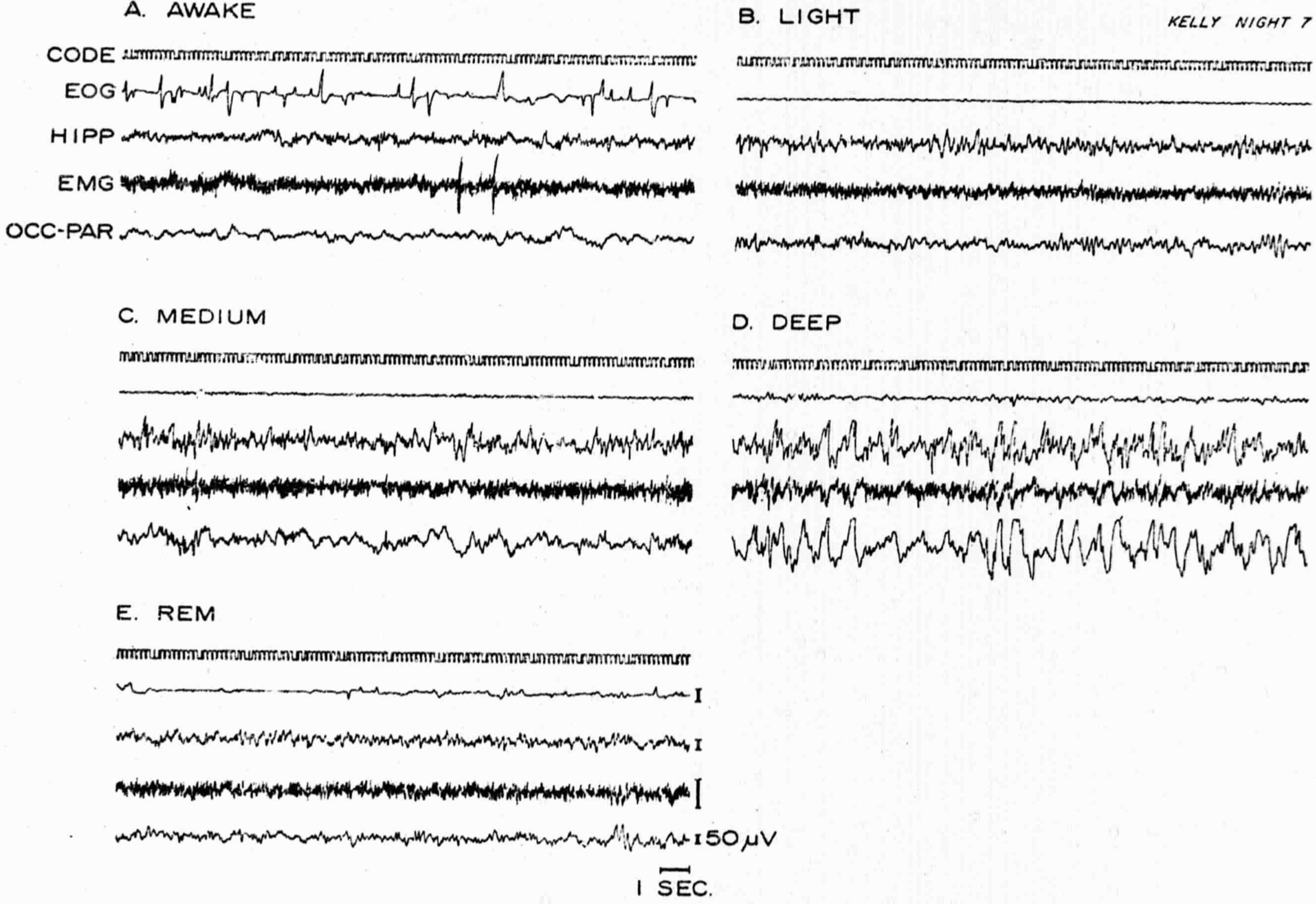
Fig. 7: A. Autospectral intensity maps of the left midbrain reticular formation and the left occipito-parietal cortex and a contour map of coherence between the midbrain reticular formation and occipito-parietal cortex.

B. Autospectral intensity maps of the left red nucleus and right occipito-parietal cortex and a map of coherence between the red nucleus and occipito-parietal cortex.

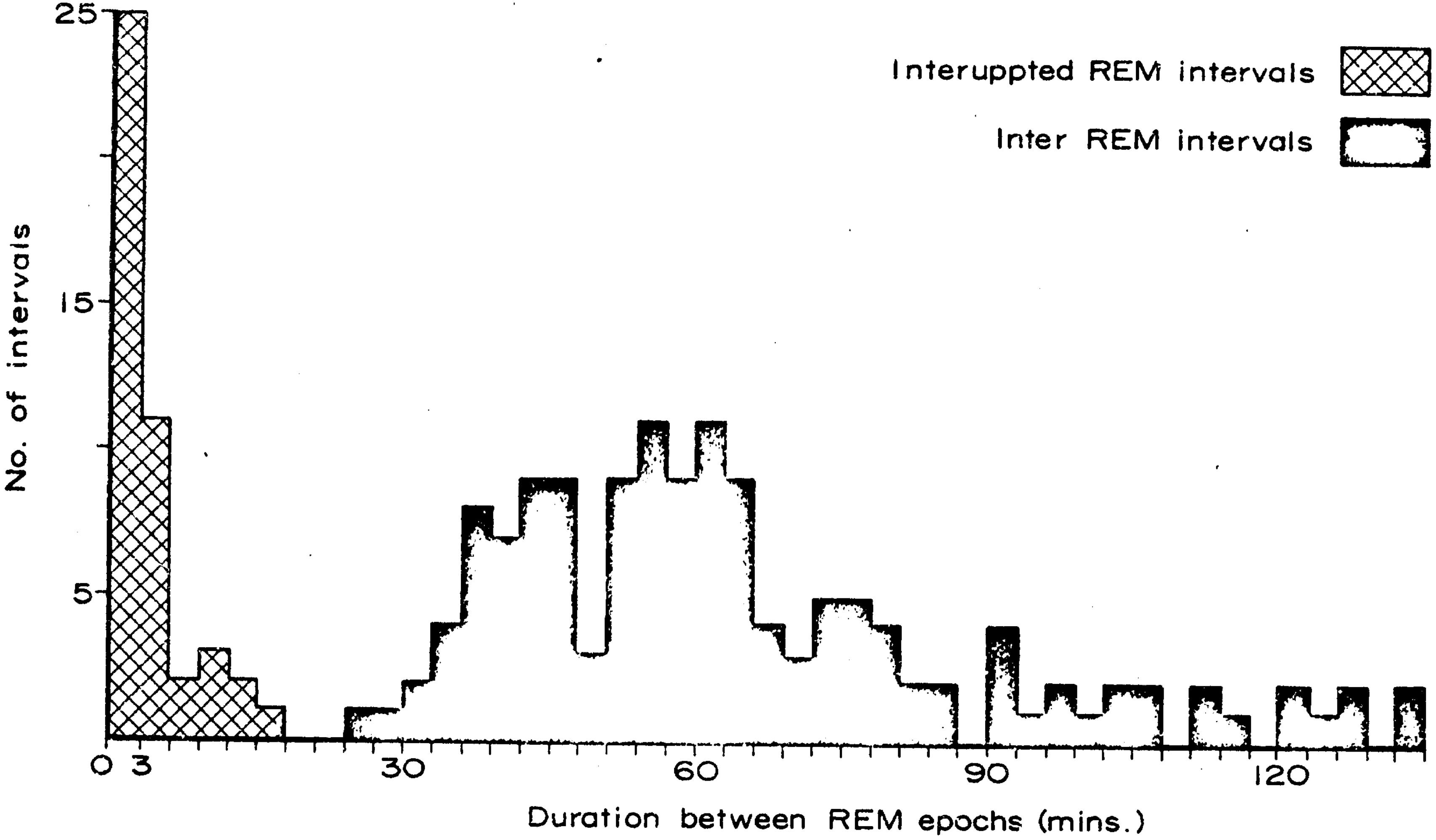
EEG SLEEP STAGES IN CHIMPANZEE



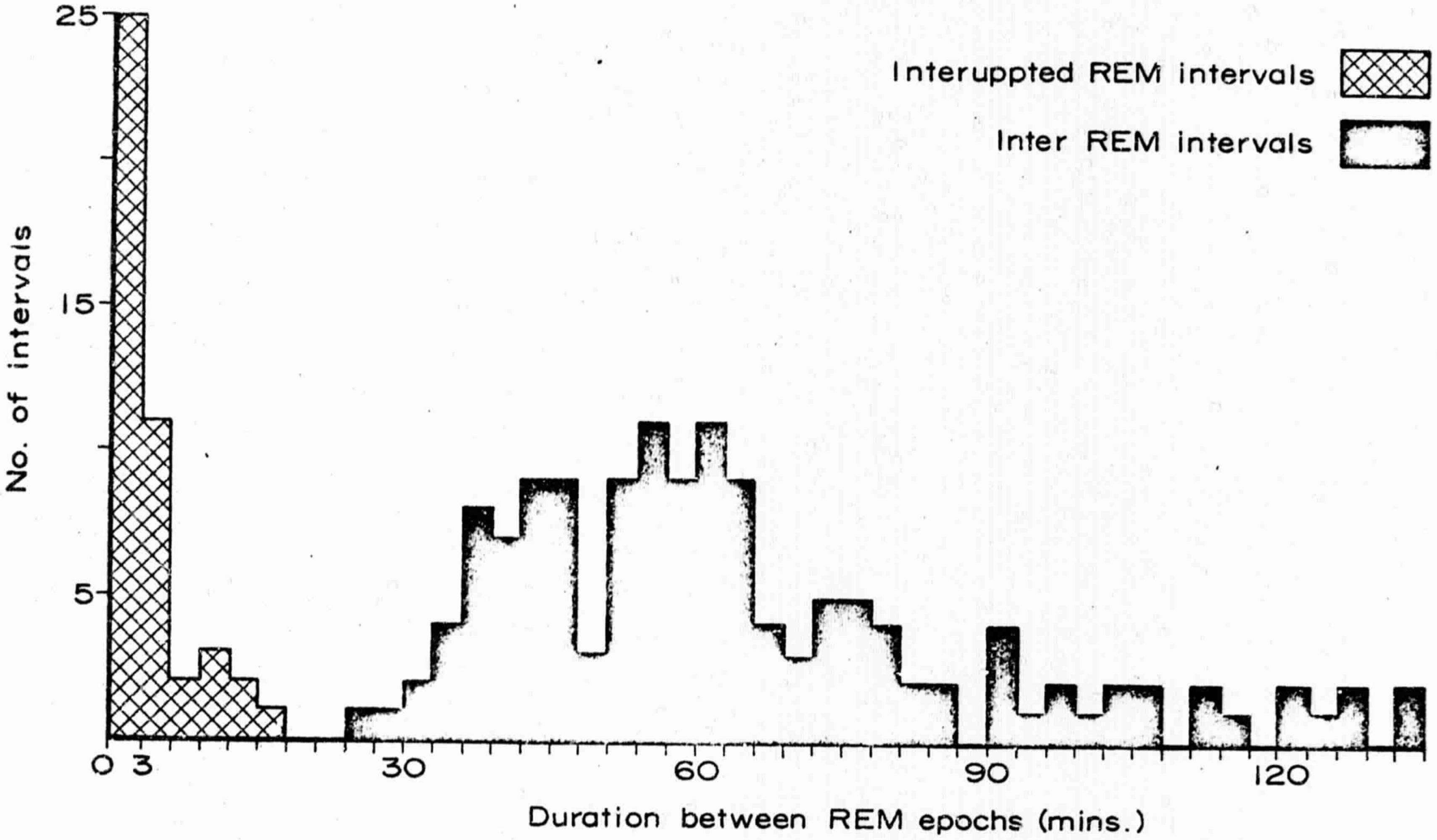
EEG SLEEP STAGES IN CHIMPANZEE



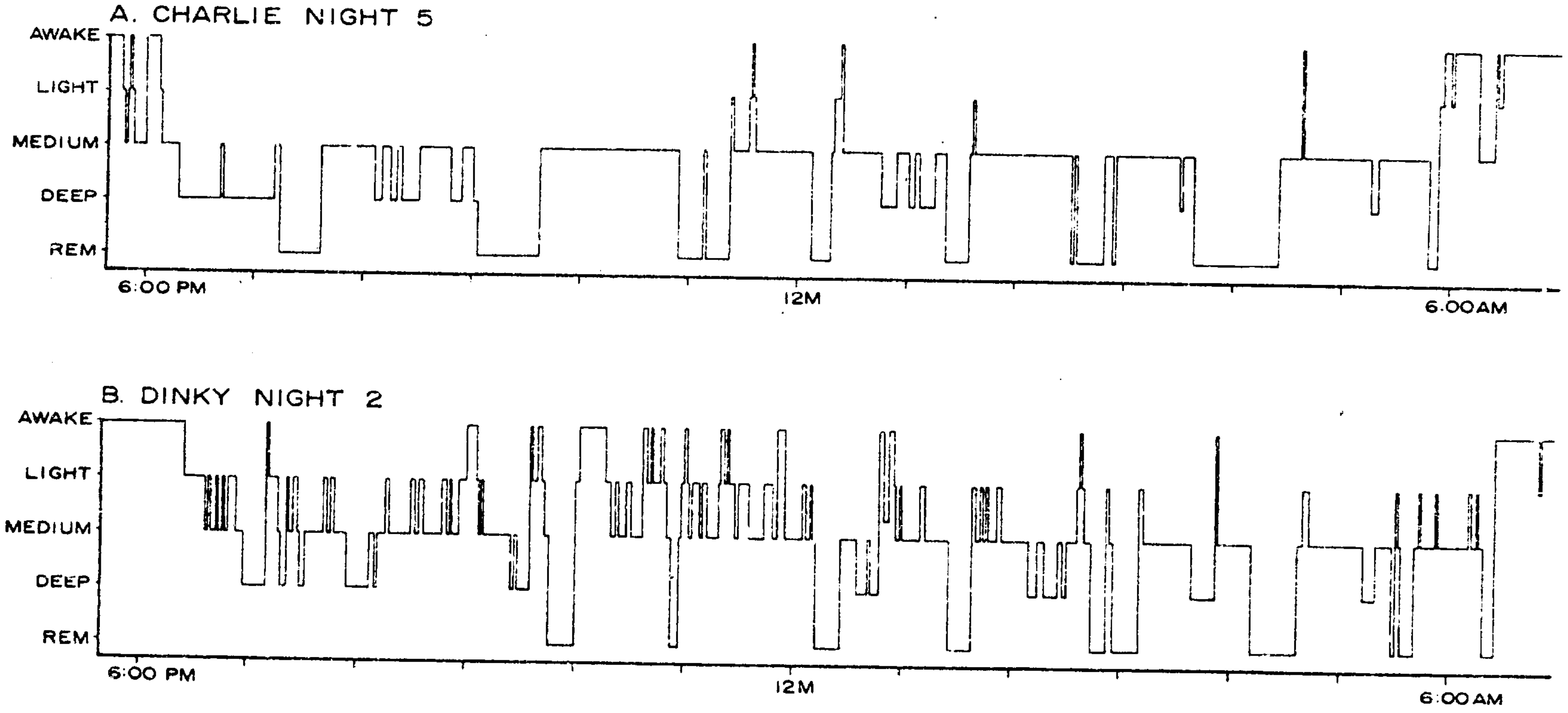
REM INTERVALS IN THE CHIMPANZEE



REM INTERVALS IN THE CHIMPANZEE



SLEEP CYCLES IN THE UNRESTRAINED CHIMPANZEE

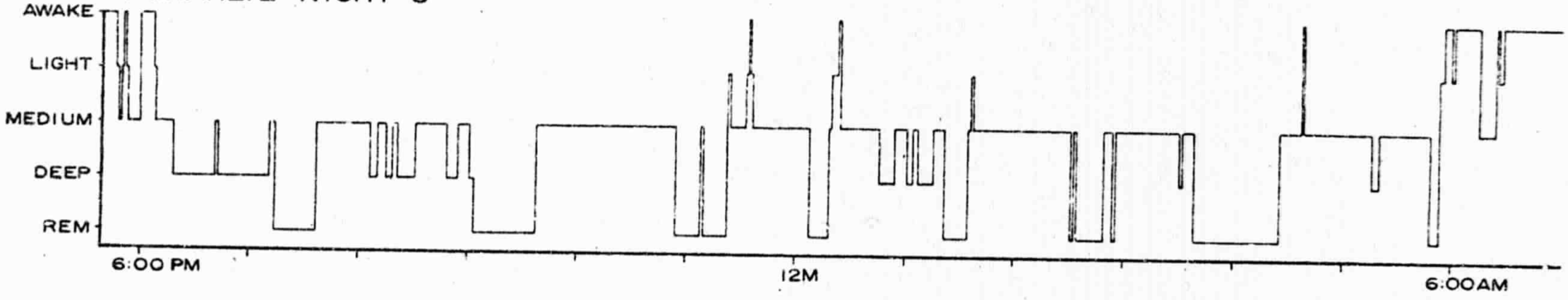


A. CHARLIE NIGHT 5

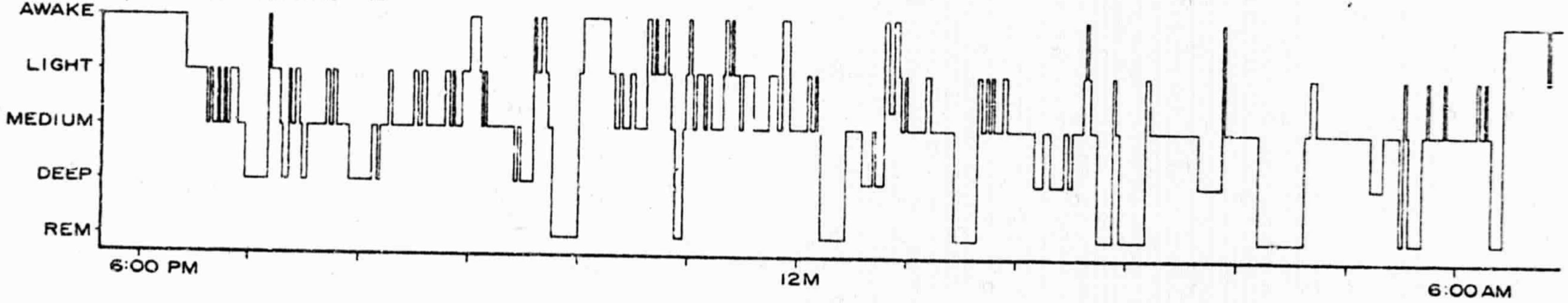
B. DINKY NIGHT 2

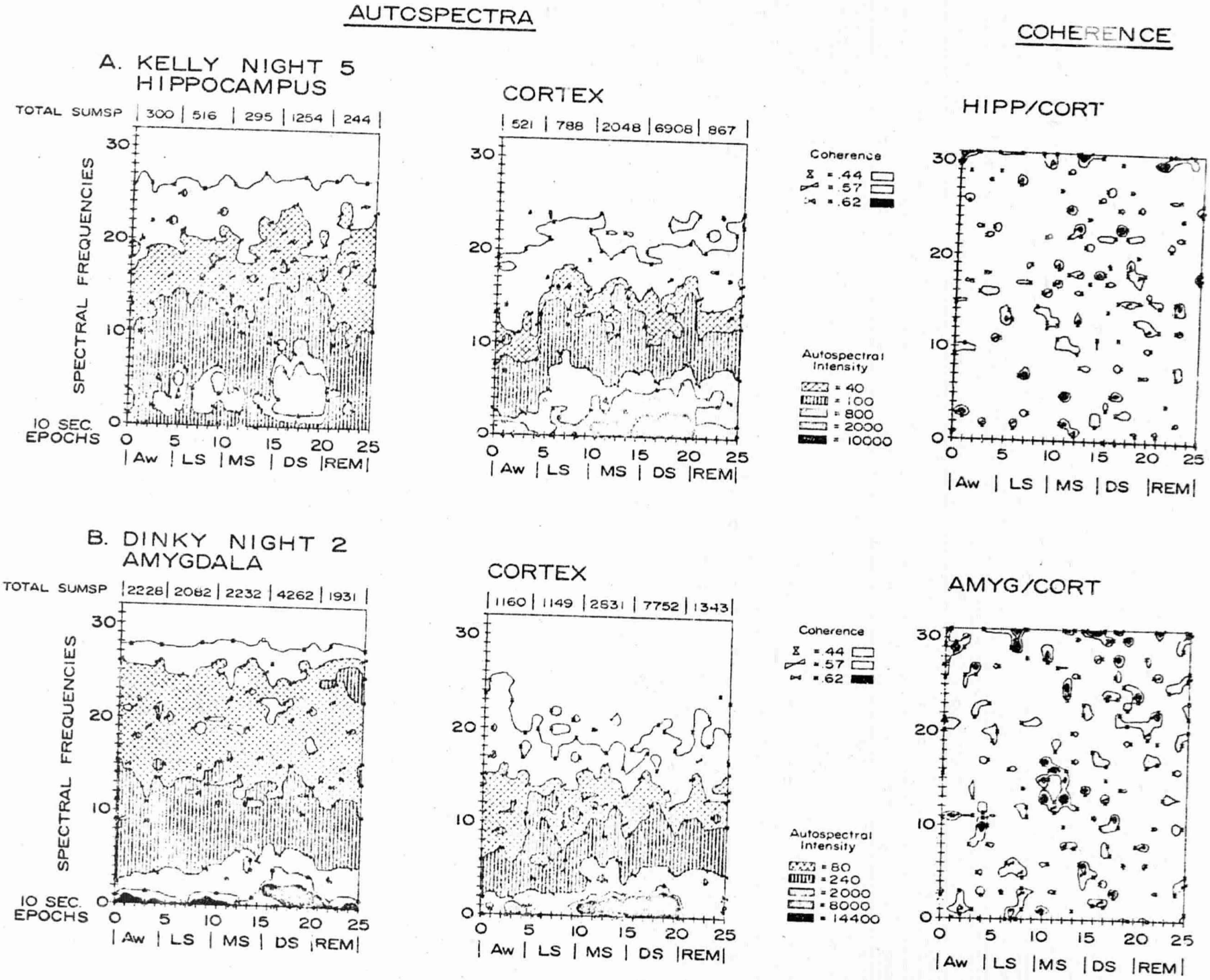
SLEEP CYCLES IN THE UNRESTRAINED CHIMPANZEE

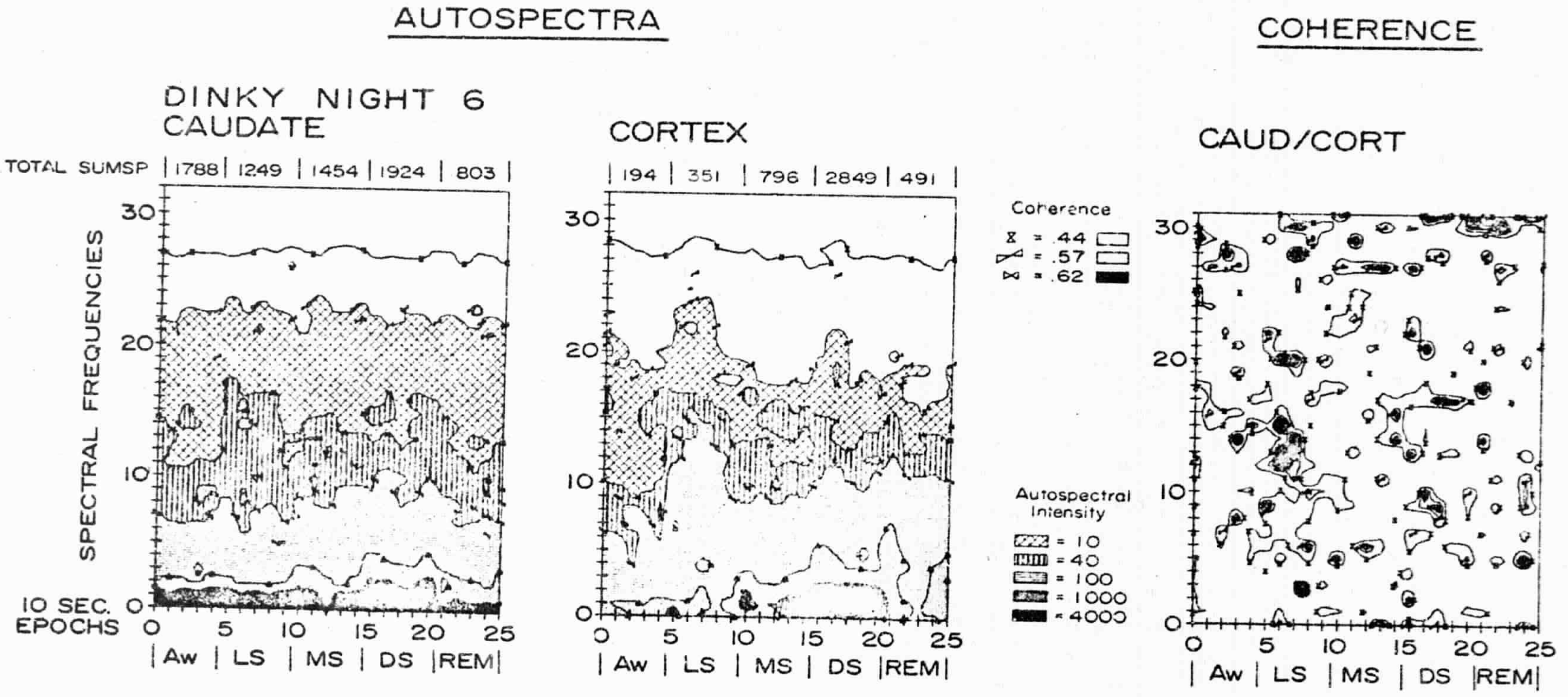
A. CHARLIE NIGHT 5



B. DINKY NIGHT 2




AUTOSPECTRA
COHERENCE
A. KELLY NIGHT 5
HIPPOCAMPUS
TOTAL SUMSP
300 | 516 | 295 | 1254 | 244
CORTEX
521 | 788 | 2048 | 6908 | 867
HIPP/CORT
SPECTRAL FREQUENCIES
30
20
10
0
10 SEC. EPOCHS
0 5 10 15 20 25
Aw | LS | MS | DS | REM
Coherence
.44
.57
.62
Autospectral Intensity
40
100
800
2000
10000
B. DINKY NIGHT 2
AMYGDALA
TOTAL SUMSP
2228 | 2082 | 2232 | 4262 | 1931
CORTEX
1160 | 1149 | 2631 | 7752 | 1343
AMYG/CORT
Coherence
.44
.57
.62
Autospectral Intensity
80
240
2000
8000
14400



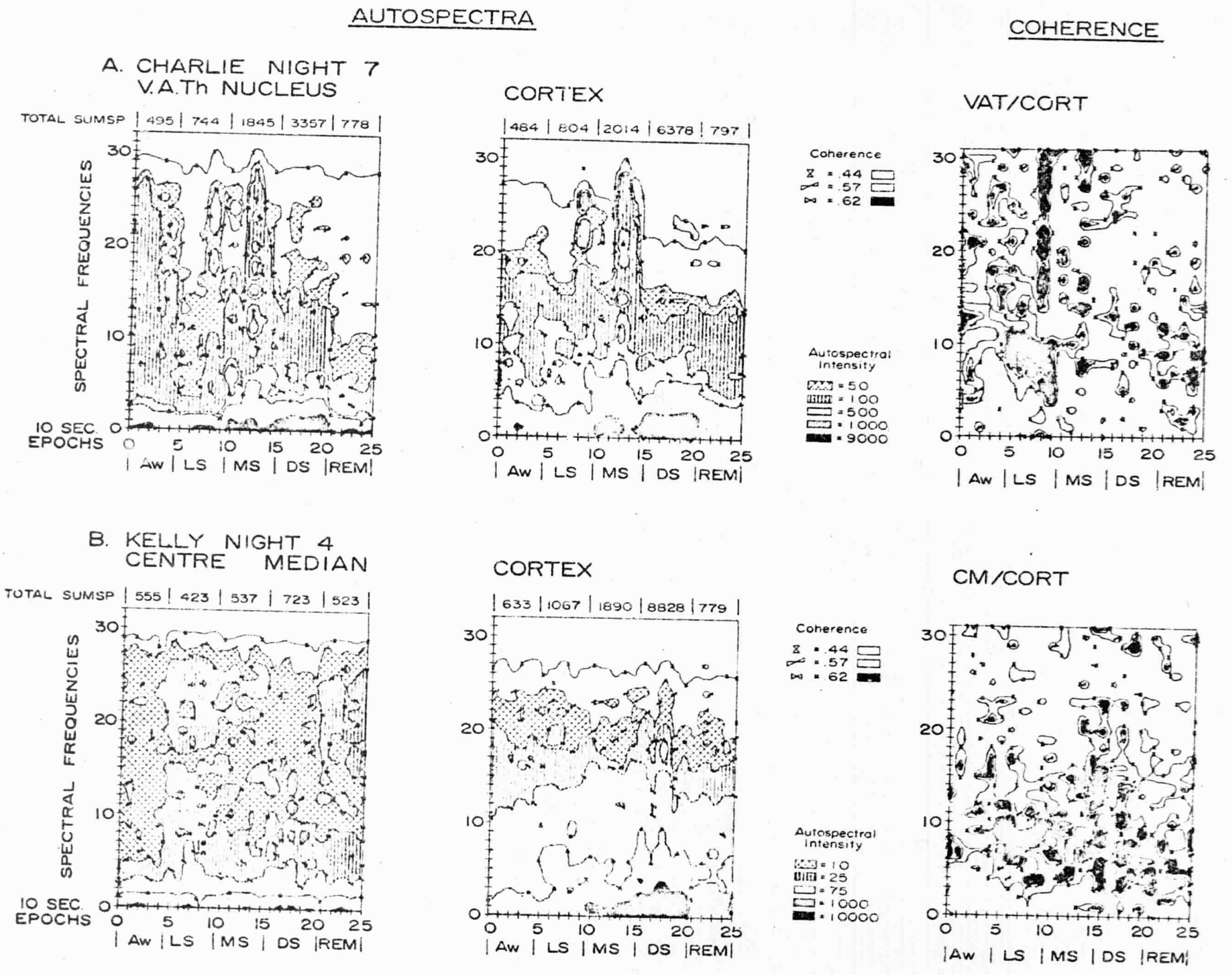
AUTOSPECTRA

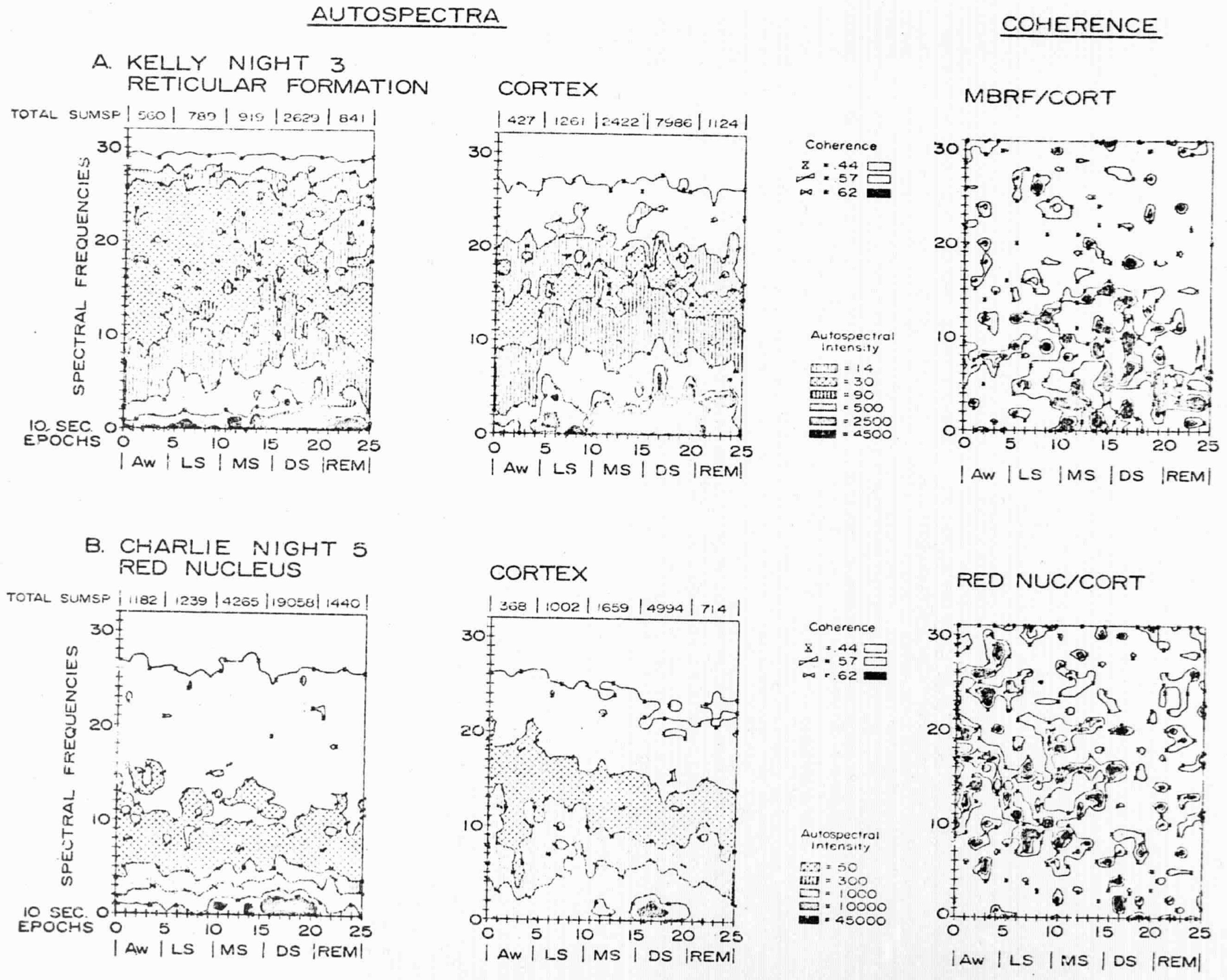
COHERENCE

DINKY NIGHT 6
CAUDATE

CORTEX

CAUD/CORT


AUTOSPECTRA
COHERENCE
A. CHARLIE NIGHT 7
V.A.Th NUCLEUS
CORTEX
VAT/CORT
TOTAL SUMSP
| 495 | 744 | 1845 | 3357 | 778 |
| 484 | 804 | 2014 | 6378 | 797 |
SPECTRAL FREQUENCIES
10 SEC. EPOCHS
0 5 10 15 20 25
| Aw | LS | MS | DS | REM |
0 10 20 30
Coherence
= .44
= .57
= .62
Autospectral Intensity
= 50
= 100
= 500
= 1000
= 9000
B. KELLY NIGHT 4
CENTRE MEDIAN
CORTEX
CM/CORT
TOTAL SUMSP
| 555 | 423 | 537 | 723 | 523 |
| 633 | 1067 | 1890 | 8828 | 779 |
SPECTRAL FREQUENCIES
10 SEC. EPOCHS
0 5 10 15 20 25
| Aw | LS | MS | DS | REM |
0 10 20 30
Coherence
= .44
= .57
= .62
Autospectral Intensity
= 10
= 25
= 75
= 1000
= 10000


AUTOSPECTRA
COHERENCE
A. KELLY NIGHT 3
RETICULAR FORMATION
TOTAL SUMSP | 560 | 789 | 919 | 2629 | 841 |
SPECTRAL FREQUENCIES
10 SEC. EPOCHS
0 5 10 15 20 25
| Aw | LS | MS | DS |REM|
CORTEX
| 427 | 1261 | 2422 | 7986 | 1124 |
MBRF/CORT
Coherence
= .44
= .57
= .62
Autospectral Intensity
= 14
= 30
= 90
= 500
= 2500
= 4500
B. CHARLIE NIGHT 5
RED NUCLEUS
TOTAL SUMSP | 1182 | 1239 | 4265 | 19058 | 1440 |
CORTEX
| 368 | 1002 | 1659 | 4994 | 714 |
RED NUC/CORT
Coherence
= .44
= .57
= .62
Autospectral Intensity
= 50
= 300
= 1000
= 10000
= 45000
0 10 20 30

Stage of Sleep	First Night		Second Night		Third Night		Fourth Night		Fifth Night		Sixth Night		Seventh Night		MEAN	
	Min.	%	Min.	%	Min.	%	Min.	%	Min.	%	Min.	%	Min.	%	Min.	%
LS	67	9.7	63	8.9	39	5.2	51	7.1	42	5.8	33	4.8	26	3.7	46	6.5
MS	381	55.4	367	51.9	410	54.2	376	52.7	393	54.5	375	54.6	384	54.4	384	53.9
DS	137	19.9	145	20.5	147	19.4	151	21.1	127	17.6	143	20.8	162	22.9	145	20.3
REM	103	15.0	132	18.7	161	21.3	136	19.0	159	22.1	136	19.8	134	19.0	137	19.3

TABLE I: Mean Amount and Percentage of Time Spent in the Sleep Stages per Night.

Stages of Sleep	First Night		Second Night		Third Night		Fourth Night		Fifth Night		Sixth Night		Seventh Night		MEAN	
	Lat.	Dur.	Lat.	Dur.	Lat.	Dur.	Lat.	Dur.	Lat.	Dur.	Lat.	Dur.	Lat.	Dur.	Lat.	Dur.
MS	24	9	15	4	9	2	6	6	2	4	11	7	4	7	10	6
DS	37	12	30	42	25	10	26	15	22	32	27	32	20	10	27	22
REM	203	14	183	15	139	11	100	9	93	12	98	8	80	12	128	12

TABLE II: Mean Latencies from Sleep Onset to First Epoch of Medium Sleep (MS), Deep Sleep (DS), and REM Sleep, and Duration of Corresponding Epoch (Time in Minutes).

	First Night	Second Night	Third Night	Fourth Night	Fifth Night	Sixth Night	Seventh Night	MEAN
Mean No. of REMs	6.7	7.0	7.0	8.0	8.7	7.3	8.0	7.6
Mean Duration (Minutes)	15.5	18.7	23.0	17.0	18.4	17.8	16.8	18.1
Range (Minutes)	3-34	5-43	5-48	4-40	4-46	2-36	3-32	2-48

TABLE III: Mean Number and Duration of REM Sleep Stages per Night.