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AROUSAL FROM SLEEP BY NOISES FROM AIRCRAFT WITH AND WITHOUT ACOUSTICALLY TREATED NACELLES

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16. Abstract

The electroencephalographic and behavioral responses during sleep of four subjects, aged 46 to 58 years, to three types of noises were tested over 14 consecutive nights. The stimuli were two DC-8 jet landing noises (each 30 seconds in duration and coming from DC-8 aircraft with and without acoustical treatment on the engine nacelles) and a 4-second burst of pink noise. Each of the noises was tested at nominal intensities of 61 and 79 dBA. Other physical descriptors of the noises were measured or computed.

The results indicate that for an equivalent degree of sleep disruption, noise from the jet aircraft with untreated nacelles must be about 6 dBA less intense than the jet with acoustically treated nacelles.

Predictions of the effects of noise on sleep appear, tentatively, to attain the highest accuracy when the physical descriptor of noise intensity includes information about the "impulsive" characteristics of that noise as well as its long-term spectral content.

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AROUSAL FROM SLEEP BY NOISES FROM AIRCRAFT WITH AND WITHOUT ACOUSTICALLY TREATED NACELLES

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I INTRODUCTION

In recent years the National Aeronautics and Space Administration and some aircraft manufacturers have developed techniques for modifying jet engine nacelles to reduce the relative intensity of certain frequencies in the noise generated by those engines. These frequencies, near 2000 Hz, have been found to be particularly annoying, as is implicit in the calculation of phons[1*] and PNdB.[2] Studies[3,4] have demonstrated that the reduction of the intensities of those frequencies as the result of acoustical treatment of aircraft engine nacelles did, in fact, result in a reduction in subjective annoyance as experienced by awake persons.

One of the major complaints about aircraft noise is that it interferes with sleep. It is of some importance, therefore, to determine whether the noise from aircraft with treated nacelles, in addition to being judged more acceptable by the awake listener, has less disruptive effect on human sleep than that from aircraft without treated nacelles. In addition, it is also important to determine which of several general physical measures now available permit accurate prediction of the effects of noise of different spectra on sleep.

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*References are listed at the end of this report.

II OBJECTIVES

The study reported herein had two objectives: (1) to assess the relative sleep-arousal effects of noise from jet aircraft with and without acoustically treated engine nacelles, and (2) to make an estimate as to which of several physical measures of the noise may best predict those effects.

III METHODS

A. Subjects

Four males, ranging in age between 46 and 58 years, were tested. Three of the four had been subjects in a similar study about two years previously, and thus were familiar with the general laboratory procedures.[5] All the subjects had normal hearing. They did not indicate any strong biases for or against jet aircraft or the noise they produce. None of the subjects lived in or near the flight paths to the local airports. All thought themselves to be reasonably normal sleepers, and their sleep during the accommodation nights and the nights without noise was consistent with the self-assessment.

B. Stimuli

Two aircraft noises and a burst of pink noise were the stimuli. The aircraft noises were those generated by two DC-8s while landing. One aircraft had standard engine nacelles, while the other had acoustically treated nacelles.[3]

Both noises were recorded outdoors while the aircraft were overhead and approaching the runway threshold with about 22,241 N (5000 pounds) of thrust per engine. The outdoor aircraft noises were passed through specially designed filters in order to produce noises as would be heard indoors. These simulated indoor noises were used as stimuli in this study.

Initial calibration of the stimuli was accomplished using a sound level meter set at dBA, slow. The three stimuli (untreated and treated aircraft noises and a burst of pink noise) were set to attain peak levels of 79 dBA in the test chambers. These signals as heard near the location of the subjects' ears then underwent one-third octave band analysis (using a General Radio Real Time Analyzer, Type 1921, with a one-half second integration time), and various physical parameters were calculated by digital computer. (See Ref. 2 for the details of these calculations.)

Presented in Table 1 are various physical measures of the three stimuli. The numbers presented are averages over several measures in each room, thereby accounting for slight differences in level due to the subjects' locations with respect to the loudspeaker centered about 1.7 m (5-1/2 feet) above their prone heads. Relatively direct measures of intensity, such as dBA and dBC were found to be within 0.5 dB of their mean values; however, measures that take into account energy levels in particular frequency bands, such as PNdB or PNdB with tone corrections, showed greater variability because of the standing wave patterns present in the rooms or at certain locations within the rooms. These were found to vary a maximum of about 3 dB about the mean, particularly in the case of the untreated noise with its relatively intense pure-tone components; the average variability was about 1 dB, however.

Of particular importance in Table 1 is the divergence between values such as nominal, peak, and maximum dBA that were the same or similar, and values such as EPNdB, EPNdBT, and EPNdBTM that spread the stimuli 4 or 5 dB but also maintained the untreated jet as being the most intense and the pink noise as being least intense. Note, however, that if the impulsiveness of the pink noise burst is taken into account, the pink noise is about 7 dB <u>more</u> intense than the untreated jet noise. A brief discussion of the rationale underlying application of the impulse correction[2,6] to the burst of pink noise is warranted therefore.

The high intensity pink noise used in this study rose from a background noise level of about 32 dBA (52 dBC) to about 64 dBA within the first 0.5 s, an additional 9 dBA in the second 0.5 s, and about 3.5 dBA

Table 1

PHYSICAL DESCRIPTIONS OF THE STIMULI

Stimulus	Nominal Overall Duration (s)	Rise Time to Peak (s)	Duration to 10 dB Down Points from Max dBA	Nominal Level dBA	Max* dBA	Peak dBA	Max dBD_2	Max PNdB	EPNdb (1)	EPNdB FAA (2)	EPNdBT (3)	EPNdBT FAA (4)	EPNdBTM (5)	EPNdBTM FAA (6)	EPNdBTM-ic (7)	EPNdBTM-ic FAA (8)
DC-8 with untreated nacelles	30	16.5	7.5	79	78.9	79.8	83.8	91.5	85.0	88.4	87.5	95.6	88.6	96.4	88.6	96.4
	30	16.0	7.5	61	61.1	62.0	66.2	73.8	66.7	70.3	69.3	77.5	70.2	78.2	70.2	78.2
DC-8 with treated nacelles	30	19.0	9.0	79	78.4	79.5	82.6	90.0	84.8	88.3	85.6	92.0	87.2	92.8	87.2	92.8
	30	18.0	10.5	61	60.4	61.5	64.6	71.5	66.3	69.8	67.1	73.5	68.7	74.4	68.7	74.4
Pink noise	4	1.0	3.5	79	78.0	78.3	81.9	89.7	81.3	82.9	81.7	90.3	83.1	91.8	95.1	103.8
	4	1.0	3.25	61	59.9	60.3	63.7	71.9	63.5	65.1	63.8	72.5	65.4	74.0	70.4	79.0

*Definitions and techniques for calculating the various physical units may be found in Refs. 2, 6, and 7.

(1) Calculated using 15 s as a reference duration.

(2) Calculated using the Sperry (Ref. 7), or Federal Aviation Administration approximation, for duration correction.

(3) Tone correction recommended by Kryter (Refs. 2 and 6).

(4) Tone correction recommended by Sperry (Ref. 7).

(5) Modified to account for the critical bandwidth of the ear at frequencies below 355 Hz (Refs. 2 and 6).

(6) The Kryter technique accounting for critical bandwidths applied to the FAA's procedure, Col. 4.

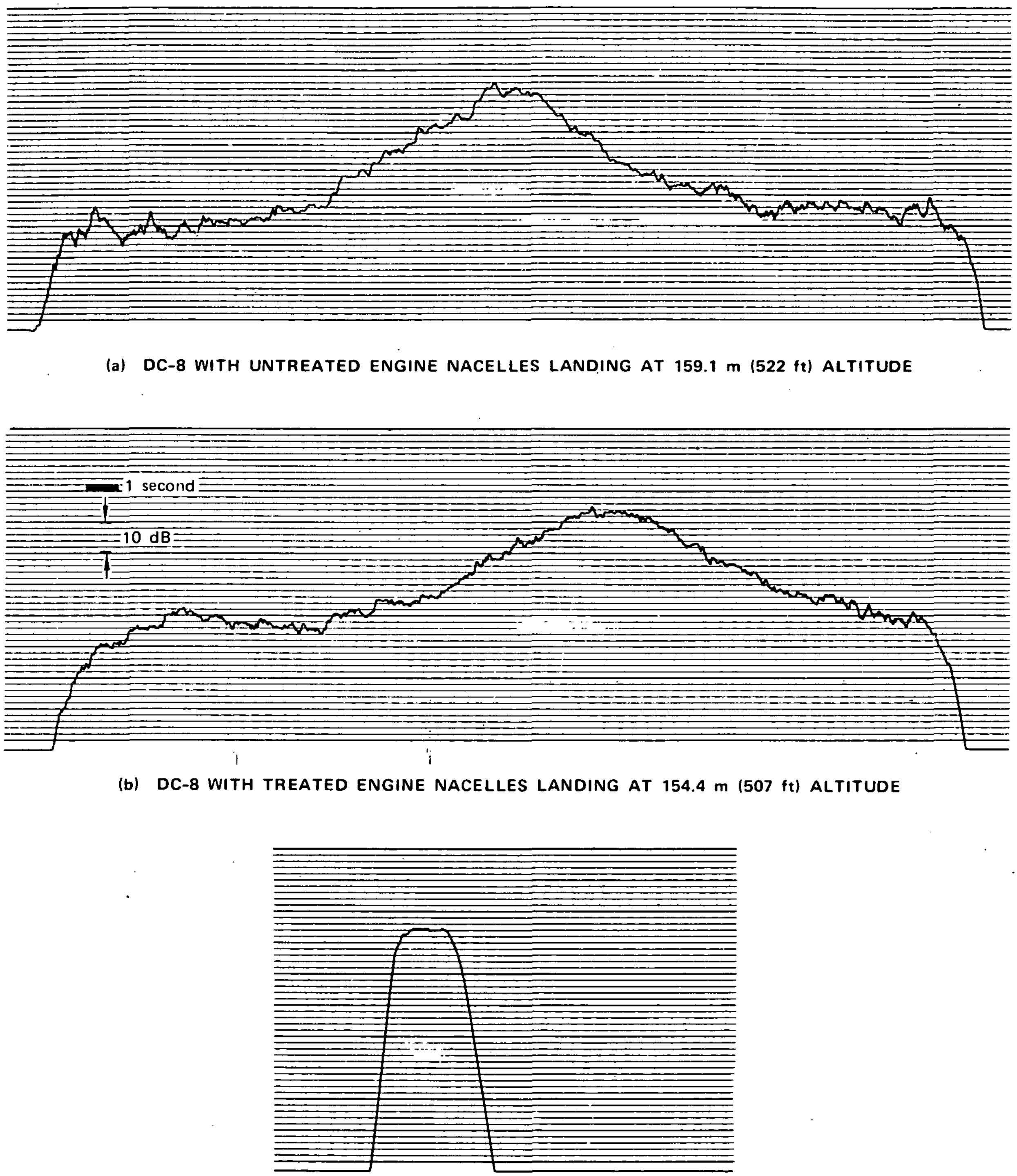
(7) An impulse correction applied to Col. 5 to account for a rise of some 32 dB above background noise level (about 32 dBA) in the first 0.5 s of the "high" intensity pink noise burst, and a rise of some 14 dB above background level in 0.5 second by the "low" intensity pink noise burst.

(8) The corrections described in Col. 7 applied to the pink noise values of Col. 6.

in fractions of a second thereafter to a level of 79 dBA maximum. The low intensity pink noise increased at an equivalent rate, but the maximum level attained was 18 dB less. Kryter, on the basis of subjective judgments made of sonic booms (Ref. 6, Figure 174, p. 301) suggests that the impulse correction be proportional to the difference, in PNL, between the impulse noise and the higher of the background noise level or the threshold of perceived noisiness. This absolute threshold at night, defined by Kryter, is set at 17 dBA; the background level in our laboratory is higher, i.e., 32 dBA.

The growth in level of the pink noise did not meet the definition of an impulsive stimulus first proposed by Kryter (a rise of 40 dB or more within 0.5 s) (Ref. 6, p. 472). However, Kryter (personal communication) indicates that a more general and proper definition of "impulse" would have been a "change in rms level at a rate greater than 40 dB per 0.5 s," rather than the "40 dB or more per 0.5 s" he originally specified. By this new definition our pink noise would be considered as "impulsive." (See the time history of the pink noise burst in Figure 1 where it is seen that the pink noise burst goes from 0 to 50 dB in 0.5 s.) Since the intensity increase was 32 dBA above the background ambient in the first 0.5 s (with a rate of increase during the first part of the 0.5-s interval greater than 40 dBA/0.5 s), an impulse correction of 12 was added to EPNdBTM in accordance with Figure 174 of Ref. 6. With respect to the low intensity pink noise, a correction of 5 was used to account for an intensity increase of 14 dB above background level in the first 0.5 s.

Both aircraft noises increased relatively smoothly to peaks in 14 or 16 s, maintained that level briefly, and decreased to background levels in 12 to 16 s. Time courses of the stimuli are illustrated in Figure 1, where the slight differences in duration between the jet aircraft noises can be seen. The noise from the jet with untreated nacelles attained its peak about 2 s before the jet with treated nacelles, and



(a) DC-8 WITH UNTREATED ENGINE NACELLES LANDING AT 159.1 m (522 ft) ALTITUDE

(b) DC-8 WITH TREATED ENGINE NACELLES LANDING AT 154.4 m (507 ft) ALTITUDE

(c) PINK NOISE BURST

FIGURE 1 TIME HISTORIES OF THE THREE TEST STIMULI MEASURED IN A TEST ROOM NEAR THE SUBJECTS' EARS extended about 4 s longer after the peak than did the treated jet noise. In general, the untreated noise was about 1-1/2 s longer than was the treated noise, that had a duration of about 25 s. The rapid rise and decay of the pink noise is also illustrated in Figure 1.

C. Procedure

Two days and nights separated the initial three accommodation nights and the 14 consecutive control and test nights (see Ref. 7 for a diagram and description of this sequence). Although three of the four subjects were relatively familiar with sleeping in the laboratory, it was thought advisable to accommodate all the subjects, thereby precluding the possibility of invalidating the results obtained in the first several nights of tests.

The first two nights of the 14 were considered control nights, as were the 9th, 10th, and 14th. During these nights the subjects were permitted to sleep without interruption by noise.

During the test nights (nights 3 to 8 and 11 to 13, inclusively), each of the three noises was presented at two intensities, and the intensity for any trial was determined at random. The random presentation of stimuli had one restriction: that each stimulus at each of the two intensities be presented at least once a night. Stimuli were presented on a different schedule each night.

Our laboratory consists of two identical test rooms, and each contains two beds. Each subject was assigned a bed at the beginning of the study, and slept in that bed throughout. On the first night in the laboratory, the purpose of the study was explained briefly, and after they were in bed, the subjects were told to use the "awake"* switch if

*The awake switches were affixed to the headboards of each bed, within easy reach of the subjects.

they should awaken for any reason. This instruction was repeated on the first of the 14 consecutive nights in the laboratory. In addition, each night after the subjects were in bed, the electroencephalograph was calibrated, and a general check made of the system, the subjects were asked to push their awake switches as if to test the operation of the switches. With the exception of a general admonition to sleep well, the subjects were given no further instructions. They were not told when or how many noises would be or had been presented. Any questions in this regard were answered vaguely.

The first stimulus in either room occurred only after both subjects in a particular room had attained sleep stage 2, at least. Neither pair of subjects consistently attained sleep stage 2 sooner or later than the other pair. Generally, the subjects were in bed by 10:30 p.m., and the first stimulus was presented about an hour later. Stimuli subsequent to the first occurred once every 40 minutes, on the average, but not more frequently than once every 20 minutes. Twelve stimulus presentations were scheduled each night, but because of differences in responses to noise and the sleep characteristics of the subjects, only 8 to 11 stimuli could be presented. The average number of stimuli each night was about 9.

D. Scoring the Electroencephalogram

In addition to behavioral awakening (use of the awake switch) electroencephalographic responses were obtained. The electroencephalograms (EEG) from standard electrode placements recommended by Rechtschaffen and Kales[8] and as used in earlier studies[5,9] were monitored continuously throughout the night (from about 10:30 p.m. until about 5:30 a.m.) in order to determine the stage of sleep and the effects of noise thereon.

Electrode placements were:

- An EEG from a right or left (C_3 or C_4) central electrode monopolar with respect to the contralateral mastoid (A_1 or A_2).
- Two electrodes proximal to the outer canthi of each eye, and both monopolar with respect to a single reference electrode just above the nasion. These electrodes are used to record the eye movements required to indicate sleep stage REM (rapid eye movements).
- Bipolar electrodes on the lower chin, one to two cm to the right and left of the midline. The myographic activity recorded is used to assist in scoring sleep stage REM.

Four categories were used to score the responses of subjects to the stimuli. The first three categories are scores obtained by examination of the EEG; the fourth category was used only if the subject pressed his awake switch. The criteria used to assign these scores are shown in Table 2.

E. Control Trials

As previously noted, the laboratory in which the study was conducted consists of two identical test rooms, each with its own loudspeaker system, electroencephalograph, and other electronic and mechanical hardware. In addition, the rooms are acoustically isolated so that a stimulus presented in one room is not easily detectable in the other. With this laboratory arrangement, test trials can alternate with control trials in any given room. For example, if the first stimulus for the night were presented to Room 1, then that period (during stimulation in Room 1) was considered a control trial for subjects in Room 2. The next stimulus, which was usually identical to that just presented in Room 1, was presented in Room 2, and the period during which the stimulus was present in Room 2 was considered a control trial for the subjects of Room 1. This process of alternating test and control trials in any given room

Table 2

CRITERIA FOR VISUALLY SCORING THE ELECTROENCEPHALOGRAMS

Score	Response Required
0	No change in EEG. This category also includes "K complexes," brief bursts of Alpha (about 10 Hz activity), spindles, and eye movements, as appropriate for the subject's sleep stage.*
1	Sleep stage change of one or two steps, but without arousal. The change must occur within 30 s of stimulation and continue for at least an additional 40 s.
2	Arousal of at least 10 s duration, but without use of the "awake" switch. Typically such a record shows brief bursts of Alpha, 10 or more s of low-amplitude Beta (20-40 Hz) activity, and gross body movements.
3	Awake response, in which the subject, after arousal, will move about and use the "awake" switch. Usually the response occurs within one minute of stimulus termination.

*"K complexes," Alpha, spindles, and eye movements occur normally in the EEG in some sleep stages. If such activity were scored as a response, the subjects in those stages would appear to be overly sensitive to stimulation as compared to stages in which the activity does not normally occur.

was continued throughout the night and resulted in an approximately equal number of test and control trials for each subject on any given night during which stimuli were presented.

As can be seen in Table 3, the subjects changed sleep stage in only nine instances (about three percent of the 320 control trials). A single subject was aroused (a score of two) once during his control trials, and none of the subjects were behaviorally awakened. It may be concluded, therefore, that the results described below are primarily responses to the stimuli and do not reflect spontaneous or normally occurring changes during sleep.

Table 3

RESPONSE FREQUENCIES DURING CONTROL TRIALS
(Numbers in parentheses are percentages)

Test Room Number	Number of Control Trials	0	1	2	3	Number of Test Trials
1	158	152 (96.2)	5 (3.2)	1 (.6)	0	166*
2	162	158 (97.5)	4 (2.5)	0	0	159

*During some test trials the control subjects may have been still awake from their previous test trial or were moving before and during stimulus occurrence. Such instances were not counted as control trials. Hence, the numbers of test and control trials are not equal.

IV RESULTS

Our previous study[9] indicated that the subjects' responses typically were distributed within normal limits. Since three of the four subjects were those used in a previous study,[5] it is assumed that the responses of the subjects in this study would be similarly distributed, although their small number precludes a reasonable statistical test of the assumption. In light of this assumption and the small number of test trials for some subjects in REM and Delta sleep stages, the responses are summed across subjects.

A. Effects of Stimulus Intensity

A comparison of the response frequencies to the three stimuli at each of the nominal intensities is presented in Table 4. With respect to the frequency of behavioral awakening (response score of 3) it is of some importance to observe that an increase of 18 dBA in the intensity of the stimuli resulted in very different changes in the response frequencies. For example, the untreated jet noise at 61 dBA elicited an awakening in about 24 percent of the trials, but when that noise was increased to 79 dBA about 49 percent of the trials resulted in awakenings. For the treated jet noise, an 18 dBA increase of intensity resulted in a smaller increase in the frequency of awakening, from about 17% for 61 dBA to 26.5% for the noise at 79 dBA. However, the most pronounced change was observed in response to the pink noise, in which case the 18 dBA change in intensity increased the frequency of behavioral awakening about eight times, that is from 6.3 to 50 percent.

Table 4

RESPONSE FREQUENCIES TO THREE STIMULI
AT TWO INTENSITIES EACH
(Numbers in parentheses are percentages)

Stimulus	Nominal Intensity (dBA)	Responses 0	1	2	3	X^2
Untreated Jet	79	16 (29.1)	3 (5.5)	9 (16.4)	27 (49.0)	16.37*
	61	30 (65.2)	4 (8.7)	1 (2.2)	11 (23.9)	
Treated Jet	79	15 (44.0)	6 (17.6)	4 (11.7)	9 (26.5)	7.56†
	61	51 (70.8)	6 (8.3)	3 (4.2)	12 (16.7)	
Pink Noise	79	11 (15.7)	7 (10.0)	17 (24.3)	35 (50.0)	35.36‡
	61	30 (62.5)	6 (12.5)	9 (18.7)	3 (6.3)	

*3 df (degrees of freedom); $p < 0.001$.

†3 df, $0.10 > p > 0.05$, not significant.

‡3 df, $p < 0.001$.

The lack of a statistically significant difference (at the $p = 0.05$ level) in the case of the treated jet noise is attributed to some lack of power in the chi-square test, since it will be noted that the responses to the treated jet noise changed in the same direction as they did to the other stimuli. Namely, the frequency of behavioral awakenings and arousals (Response 2) increased, while the frequency of 0 responses decreased as a result of an 18-dBA increase in stimulus intensity. It is suggested therefore, that the changes in response frequencies resulting from changes in intensity of the treated jet noise may be functionally significant.

In Table 5 the responses of the subjects to the three stimuli when all had equivalent nominal intensities are compared. It is clear that the subjects responded differently to the three stimuli despite their dBA intensity equivalence. It may be of practical significance to observe that at an intensity of 79 dBA, the treated jet noise resulted in significantly fewer awakening and arousal responses than did the

Table 5

COMPARISON OF THE RESPONSE FREQUENCIES
TO STIMULI OF NOMINALLY EQUIVALENT INTENSITY
(Numbers in parentheses are percentages)

Nominal Intensity (dBA)	Stimulus	Response 0	Response 1	Response 2	Response 3	X^2
79	Untreated Jet	16 (29.1)	3 (5.5)	9 (16.4)	27 (49.0)	15.71^*
	Treated Jet	15 (44.0)	6 (17.6)	4 (11.7)	9 (26.5)	
	Pink Noise	11 (15.7)	7 (10.0)	17 (24.3)	35 (50.0)	
61	Untreated Jet	30 (65.2)	4 (8.7)	1 (2.2)	11 (23.9)	$16.08^\dagger$
	Treated Jet	51 (70.8)	6 (8.3)	3 (4.2)	12 (16.7)	
	Pink Noise	30 (62.5)	6 (12.5)	9 (18.7)	3 (6.3)	

*6 df, $0.02 > p > 0.01$.

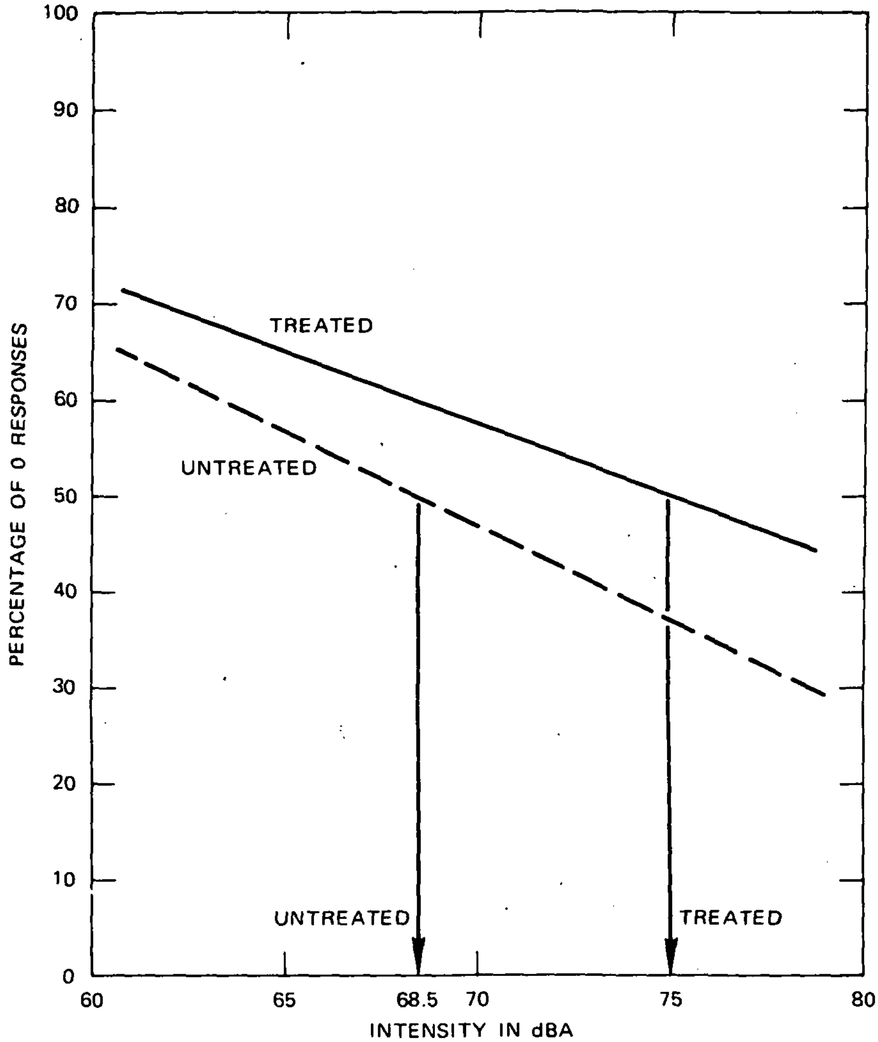
†6 df, $0.02 > p > 0.01$.

untreated jet noise and the burst of pink noise. At low intensity (61 dBA), the treated jet again resulted in fewer awakening responses than did the untreated jet, although the frequency of arousal (Response 2) was somewhat greater for the treated jet noise.

Estimating the extent to which nacelle treatment may ameliorate the disruptive effects of aircraft noise on sleep is of practical importance. Since the functional significance of more frequent than normal changes in sleep stage (Response 1) or arousals (Response 2) and awakenings (Response 3) is not known, it is not unreasonable to describe that disruption conservatively. Consistent with this reasoning, the frequency of zero responses (i.e., no disruption) is plotted in Figure 2 against the nominal intensities of the treated and untreated jet aircraft noise. In Figure 2 it will be seen that the treated jet noise at an intensity of 75 dBA disrupted sleep to about the same degree as did the untreated jet at about 68.5 dBA. In other words, at equivalent dBA intensities the treated jet has less of a disruptive effect on sleep than does the jet aircraft without acoustically treated nacelles. Parenthetically, it should be noted that whereas the treated jet noise disrupted sleep less than did the untreated jet by an amount equivalent to about 6.5 dBA, in another study[3] the treated jet was judged by awake people as being about "4 dBA" less annoying than was the untreated jet noise.

B. Responses During the Different Sleep Stages

Earlier studies suggest that there is little difference between sleep stages 2 and REM in responsiveness for meaningful stimuli. In addition, the subjects were behaviorally awakened more frequently or were awakened at lower stimulus intensities during sleep stages 2 and REM than they were during sleep stage Delta (a combination of stages 3 and 4), and particularly during sleep stage 4.[10,11]



NOTE: Intensities for equivalent sleep disruption by the two stimuli are indicated on the abscissa.

FIGURE 2 FREQUENCY OF NO SLEEP DISRUPTION RESPONSES TO DC-8 JET AIRCRAFT WITH AND WITHOUT ACOUSTICALLY TREATED ENGINE NACELLES

The results of the present study appear to be in partial agreement with those reported earlier. In Table 6 the response frequencies obtained during sleep stage REM are combined with those obtained during sleep stage 2. It will be seen, therein, that in five of the six comparisons, awakening was more frequent during sleep stages 2 and REM than it was during sleep stages 3 and 4. The only exception was in response to the high intensity treated jet noise. Since that particular instance is atypical, and there is no a priori reason to expect greater responsiveness, particularly to treated jet noise during stages 3 and 4, it is suggested that the exceptional result may be spurious. Thus, it may be concluded that generally there will be fewer awakening responses to stimuli of comparable intensities during sleep stages 3 and 4 than during stages 2 and REM, although the differences may not attain statistical significance.

C. Adaptation to the Noises

Because of the small number of certain categories of responses to the stimuli at the two intensities studied (see Table 6, for example), the responses for a given stimulus were summed across the two intensities to develop the response frequencies shown in Table 7. Although it is possible that if a relatively large number of low intensity stimuli were presented in the later test nights, a bias toward showing adaptation would exist (a large number of high intensity stimuli in later nights would reverse the bias), the schedule for stimulus presentation used in this study precluded such biases.

It will be seen in Table 7 that a trend indicating adaptation--defined as a reduction in the frequency of three responses and an increase in the frequency of 0 responses--was found in the case of the treated jet noises and the pink noise, but not in the case of the untreated jet noise. It may be of some interest to note that for the

Table 6

RESPONSE FREQUENCIES TO THREE STIMULI
DURING THE SLEEP STAGES
(Numbers in parentheses are percentages)

Stimulus and Nominal Intensity (in dBA)	Sleep Stage	Response 0	Response 1	Response 2	Response 3	X^2
Untreated Jet 79	2 and REM	14 (29.1)	3 (6.3)	7 (14.6)	24 (50.0)	1.23
	3 and 4	2 (28.6)	0	2 (28.6)	3 (42.8)	
Treated Jet 79	2 and REM	12 (60.0)	1 (5.0)	3 (15.0)	4 (20.0)	8.38*
	3 and 4	3 (21.4)	5 (35.7)	1 (7.1)	5 (35.7)	
Pink Noise 79	2 and REM	8 (14.5)	6 (10.9)	12 (21.8)	29 (52.7)	1.46
	3 and 4	3 (20.0)	1 (6.7)	5 (33.3)	6 (40.0)	
Untreated Jet 61	2 and REM	22 (62.9)	2 (5.7)	1 (2.9)	10 (28.6)	3.22†
	3 and 4	8 (72.7)	2 (18.2)	0	1 (9.1)	
Treated Jet 61	2 and REM	41 (70.7)	3 (5.2)	3 (5.2)	11 (19.0)	5.25
	3 and 4	10 (71.4)	3 (21.4)	0	1 (7.1)	
Pink Noise 61	2 and REM	28 (65.1)	4 (9.3)	8 (18.6)	3 (7.0)	3.88†
	3 and 4	2 (40.0)	2 (40.0)	1 (20.0)	0	

*3 df, $0.05 > p > 0.025$, all other chi-squares are not significant.

†Because the expected frequencies in 20 percent of the cells were less than one, Responses 2 and 3 were combined to calculate the chi-square.[12]

Table 7

RESPONSE FREQUENCIES TO THREE STIMULI
DURING COMBINATIONS OF TEST NIGHTS INDICATING ADAPTATION
(Numbers in parentheses are percentages)

Stimulus	Test Nights	Responses 0	1	2	3
Untreated Jet	1, 2, 3	14 (42.4)	5 (15.2)	3 (9.1)	11 (33.3)
	4, 5, 6	19 (54.3)	0	3 (8.6)	13 (37.1)
	7, 8, 9	12 (36.4)	2 (6.1)	4 (12.1)	15 (45.5)

Nights 1, 2, 3 versus 4, 5, 6 - $X^2 = 5.870$, 3 df, not significant.
Nights 1, 2, 3 versus 7, 8, 9 - $X^2 = 2.199$, 3 df, not significant.

Treated Jet	1, 2, 3	14 (60.9)	2 (8.7)	1 (4.3)	6 (26.1)
	4, 5, 6	25 (80.6)	3 (9.7)	0	3 (9.7)
	7, 8, 9	18 (48.6)	7 (18.9)	6 (16.2)	6 (16.2)

Nights 1, 2, 3 versus 4, 5, 6 - $X^2 = 3.799$, 2 df (Responses 2 and 3 combined), not significant.
Nights 1, 2, 3 versus 7, 8, 9 - $X^2 = 3.789$, 3 df, not significant.

Pink Noise	1, 2, 3	12 (28.6)	2 (4.8)	12 (28.6)	16 (38.1)
	4, 5, 6	15 (38.5)	6 (15.4)	5 (12.8)	13 (33.3)
	7, 8, 9	13 (36.1)	6 (16.7)	7 (19.4)	10 (27.8)

Nights 1, 2, 3 versus 4, 5, 6 - $X^2 = 5.422$, 3 df, not significant.
Nights 1, 2, 3 versus 7, 8, 9 - $X^2 = 4.304$, 3 df, not significant.

treated jet noise, the degree of adaptation shown when test nights 4, 5, and 6 were compared with test nights 1, 2, and 3 was reduced after sleeping two nights in the quiet. Such was not the case with respect to the pink noise. With respect to the untreated jet noise, the results suggest an increasing degree of responsiveness to the stimuli. However, the differences observed were not statistically significant.

D. Predictive Power of the Different Physical Measures

There were essentially no differences in the EEG that permit discrimination between behavioral awakening (Response 3) and arousal (Response 2), as will be shown in a subsequent section. Indeed, some of the subjects stated that at times they were awakened by some particular stimulus but did not have enough "ambition" or "the energy" to turn over and push the awake switch. Consequently, the frequency of Responses 2 and 3 is combined in the second row of Table 8 and in the third row, for purposes of comparison, the frequency of behavioral awakening (Response 3) alone was used to calculate the correlations.

Presented in Table 8 are the correlations between the different response frequencies (summed across subjects as shown in Tables 4 and 5) obtained at each of the six levels of the various physical measures. Before describing these results, it is advisable to consider the meaning or functional significance of these correlations. Plotted in Figure 3, as an example, are the data points used to calculate the correlations using EPNdBTM and EPNdBTM-ic as the physical measures. It will be seen that when the impulse correction is included in the measure of the pink noise, those data points (indicated by a dot enclosed in a circle) are shifted beyond (that is, to the right of) the points corresponding to the untreated jet noise, and are more nearly consistent with their relative frequency as compared to the frequency of responses to the

Table 8

CORRELATIONS BETWEEN DIFFERENT PHYSICAL MEASURES OF THE STIMULI AND VARIOUS MEASURES OF RESPONSES TO THE STIMULI

Response or Response Grouping	Physical Measure of Stimuli									
	EPNdBTM-ic FAA	EPNdBTM FAA	EPNdBTM-ic	EPNdBTM	EPNdBT FAA	EPNdBT	EPNdB FAA	EPNdB	Max PNdB	Max dBA
No Response (Response 0)	-.99	-.88	-.97	-.82	-.86	-.82	-.79	-.84	-.90	-.90
Arousal and Awakening (Responses 2 and 3)	.95	.84	.93	.78	.83	.78	.75	.79	.85	.85
Behavioral Awakening (Response 3)	.87	.87	.86	.82	.86	.82	.79	.81	.84	.83

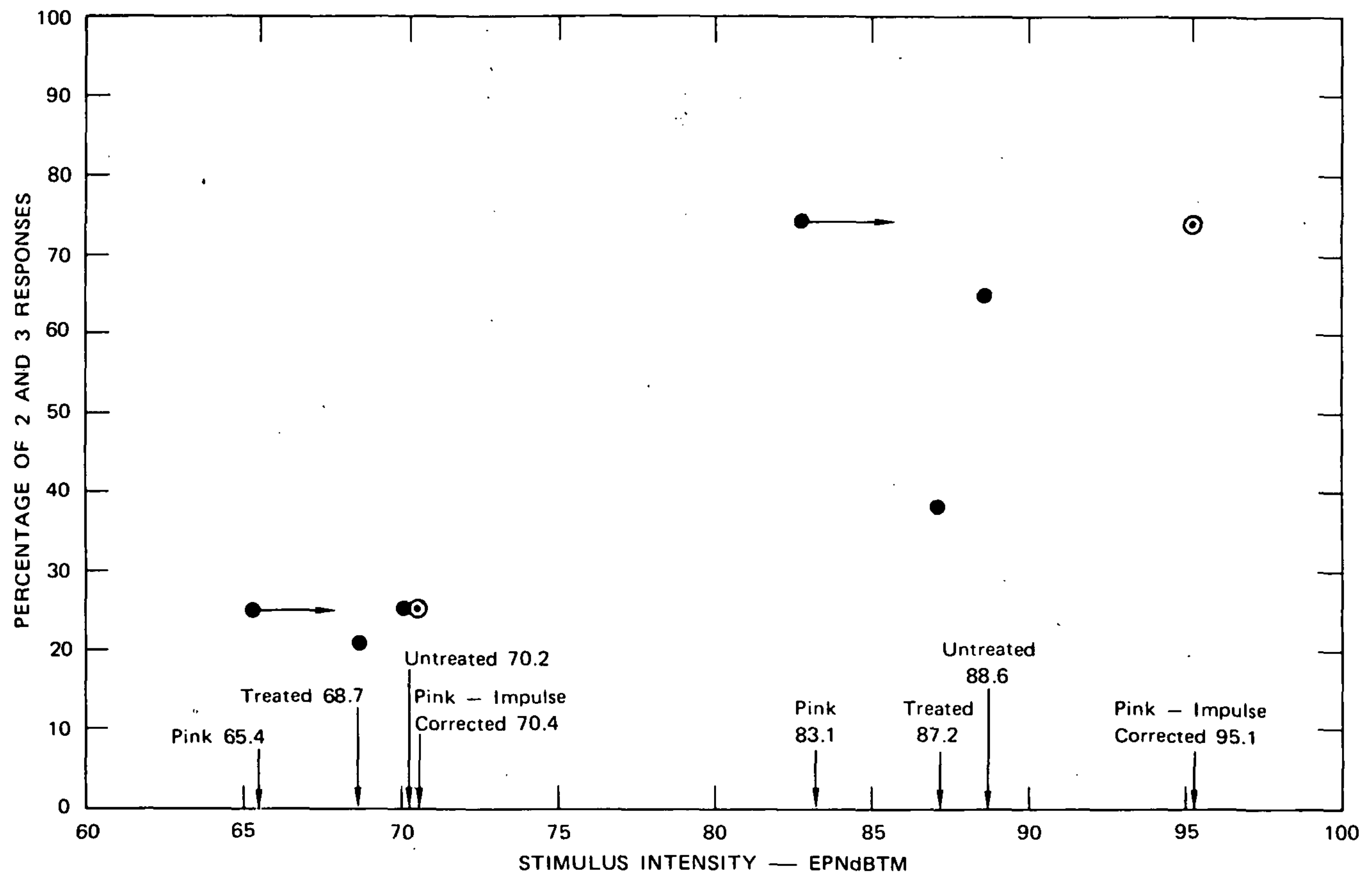


FIGURE 3 DISTRIBUTION OF THE PERCENTAGE OF RESPONSES 2 AND 3 WHEN STIMULUS INTENSITIES ARE CALCULATED IN UNITS OF EPNdBTM, WITH AND WITHOUT AN IMPULSE CORRECTION APPLIED TO THE PINK NOISE

treated and untreated jet noises. Movement of those two points resulted in a change of 0.15 (from 0.78 to 0.93) in the correlation coefficient. The fact that the movement of only two intensity values caused a relatively large shift in the correlation coefficient, indicates the extreme sensitivity of these coefficients due largely to the small number of values used in the calculations. Consequently, these correlations should be interpreted cautiously, and the results should be considered tentative until verified with much larger samples of subjects and varieties of noise.

That the various physical measures are on the average more highly correlated with the frequency of 0 responses than with the frequency of behavioral awakening or the combination of Responses 2 and 3 is demonstrated in Table 8. The magnitude of the coefficients suggests that addition of the impulse correction improved the predictive power of the physical measures whether the response of interest is zero or a combination of Responses 2 and 3. But the improvement is not as apparent when behavioral awakening (Response 3) is considered alone.

Of interest, perhaps, is the seemingly slight loss of predictive power when stimulus duration (EPNdB) or tonal characteristics (EPNdBT) are compared to more simple measures such as Max dBA or Max PNdB. It seems reasonable to expect that as more information is included in the physical descriptor of the stimulus, the predictive power of the descriptor should increase. Thus it would be expected that EPNdB should have a higher correlation than Max PNdB, and that EPNdBT should be more highly correlated with the responses than was EPNdB. Such was not the case although the differences, ranging between 0.01 and 0.11 correlation units, are relatively small; but with certain comparisons the differences are statistically significant.* On the other hand, perhaps it is not unreasonable to suppose that while the duration or tonal qualities of a noise when one is awake will contribute to its annoyance value, disruption of sleep could be solely related to the maximum intensity of the noise or the rate of change of that level.

E. Analysis of the Physiological (EEG) Frequency Components

1. Similarity of EEG Activity During Arousal and Behavioral Awakening

Some evidence suggesting an artificial distinction between the arousal response and behavioral awakening (Responses 2 and 3, respectively) was noted in Part D above. The general similarity of the EEG patterns observed during arousal and behavioral awakening, as illustrated in Figure 4, provides additional evidence that the distinction between those responses may be arbitrary and dependent largely upon the motivation of the particular subject. It is important to note that the responses (and the sleep stages) described in Figure 4 and subsequent figures and tables were obtained by scoring the EEG signals visually (according to the criteria of Table 2) long before the amplitudes in the different frequency bands were measured by computer. Hence, these figures show how closely the visually scored responses correspond to the electrical activity of the brain as measured by computer.

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*For example, the difference of 0.11 units between EPNdB-FAA and Max dBA for the 0 response is significant at $p = 0.05$ (Hotelling's test)[13] as is the difference of 0.06 units between the correlation for Max dBA and EPNdB with Response 0; but a difference of 0.03 between Max PNdB and EPNdB for Response 3 is not statistically significant.

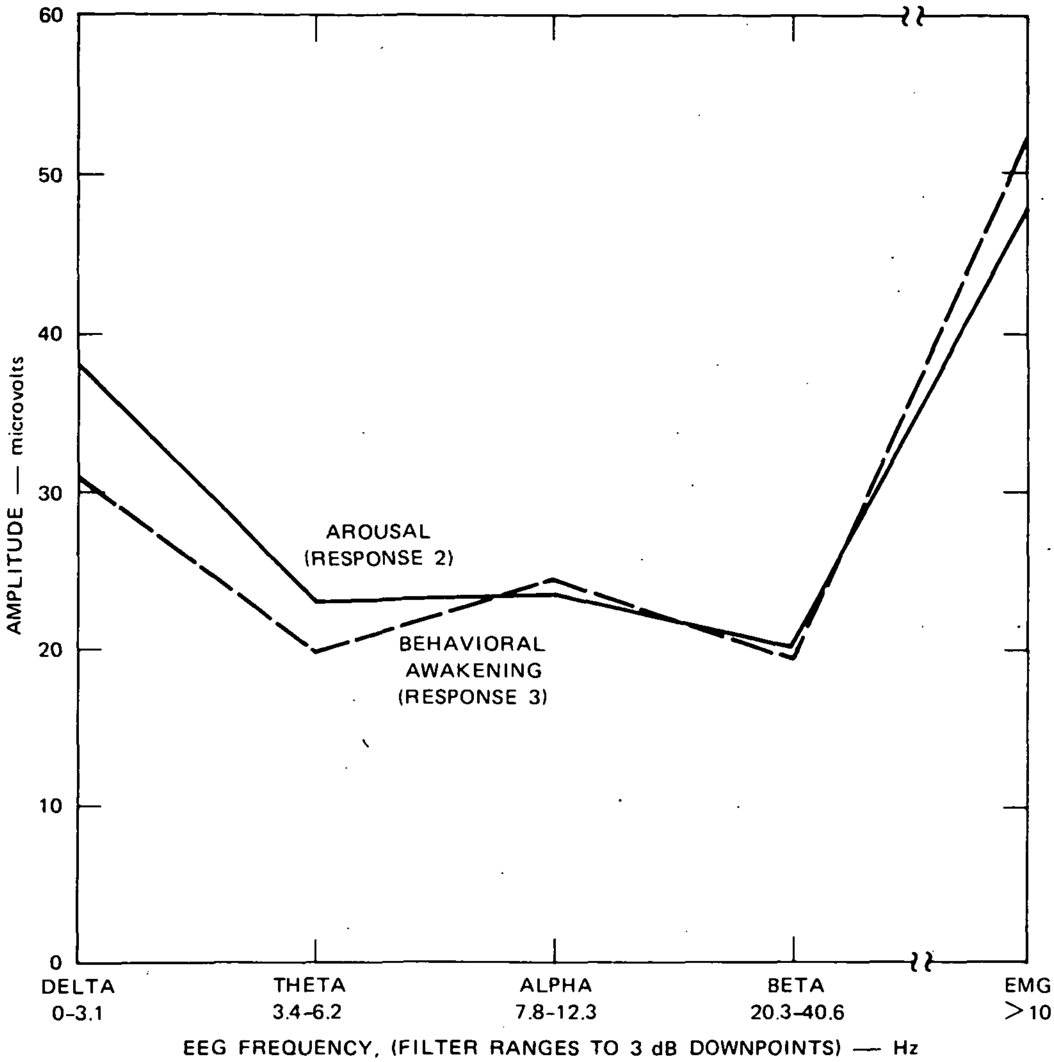

FIGURE 4 SLEEP EEG FREQUENCY AMPLITUDES WITH RESPONSES OF AROUSAL AND BEHAVIORAL AWAKENING TO AUDITORY STIMULI OF DIFFERENT INTENSITIES (EMG LEVEL IS INCLUDED FOR CONVENIENCE)

Statistically, the mean amplitudes* of the signals in each of the four frequency bands during arousal and behavioral awakening were not found to be different. These results are presented in Table 9. For the purposes of subsequent sections of this report, therefore, no distinction will be made between arousal (Response 2) and behavioral awakening (Response 3).

2. Baseline EEG Frequency Levels in the Sleep Stages

Illustrated in Figure 5 are the relative amplitudes of the various EEG frequency components, as well as the submental EMG, obtained during the five sleep stages and while the subject was awake but lying in bed. Each data point in this figure is an average, across subjects, of at least 30 measures (each an average over one minute) selected randomly throughout the control nights; the data points for sleep stage 2 that are more common than the other stages is an average of some 120 measures.

It will be noted in the figure that, as might be expected[8] the EMG level progressively decreased as the subjects shifted from being awake to sleep state REM and, on the average, the EEG levels while awake are higher than they are in the four sleep stages. Delta activity has the highest amplitude in the four sleep stages, while average Alpha

---

*The sleep stage scoring system, described in detail in Ref. 14 was modified for these studies to print out the average amplitude of the signal in each of the four frequency bands as well as the average EMG level every 20 s. During each 20 s epoch, the amplitude of each of the five bands was sampled 400 times; this sampling constitutes the basis of the average amplitude measures presented herein.

Table 9

MEAN AMPLITUDES OF SIGNAL IN DIFFERENT FREQUENCY BANDS DURING THE AROUSAL AND BEHAVIORAL AWAKENING RESPONSES

Frequency Band	Response						t (Response 2 Versus Response 3)
	Arousal (2)			Behavioral Awakening (3)			
	Mean* (in μv)	n†	Standard Deviation	Mean (in μv)	n†	Standard Deviation	
Delta	38.0	17	9.6	31.4	13	7.0	0.514
Theta	23.1	17	4.7	20.3	13	4.2	0.448
Alpha	23.6	17	3.8	24.6	13	3.5	0.191
Beta	19.8	17	6.5	19.7	13	4.9	0.012
EMG	48.4	16	18.7	52.6	12	12.1	0.189

*The measurement epoch of 20-s duration began coincidentally with onset of the stimulus. The aircraft noise had durations of 25 to 27 s, or about 6 s longer than the 20-s measurement epoch. Therefore the two 20-s epochs during which the aircraft noises were present were used in this measurement. Although the pink noise had a 4-s duration, for consistency the same measurement period, i.e., 40 s, was used to assess the effect of pink noise.

†The average amplitude of the responses during each of the three sleep stages (2, Delta and REM) to each of the stimuli was calculated separately, and these averages were used to calculate the averages shown in this table.

levels are slightly higher than those of Delta while the subject is awake but lying in bed. In sleep stage Delta the levels of Delta activity clearly are most prominent. The fact that Theta levels are not higher than Delta levels during sleep stage 1 perhaps may simply reflect its definition as a low amplitude mixed frequency stage during which Theta activity may be more prominent than are the other, interspersed, frequencies. Although a visual EEG signal may be prominent, its relative prominence does not necessarily mean its average amplitude is higher

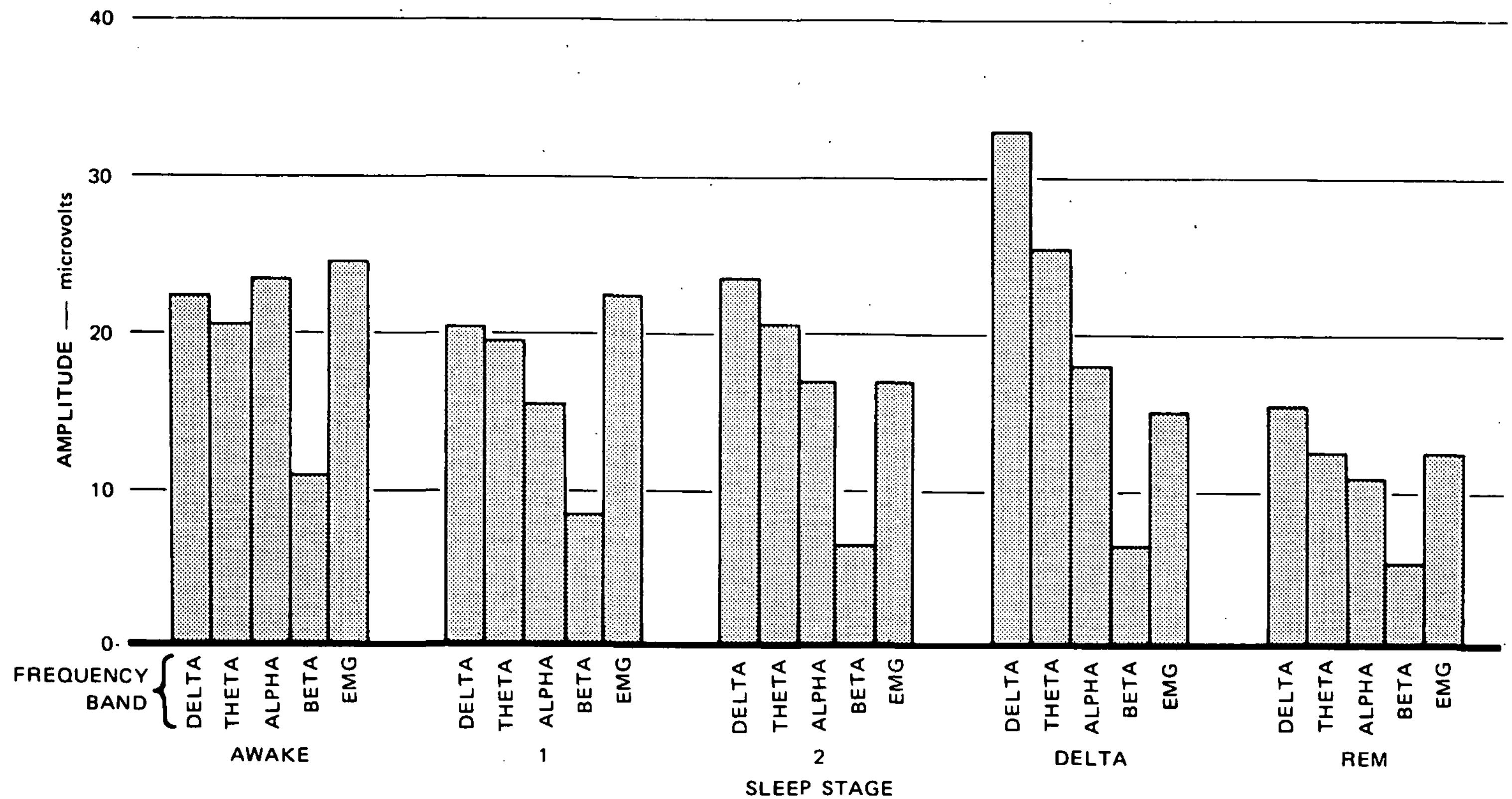

FIGURE 5 BASELINE AMPLITUDE LEVELS IN THE EEG FREQUENCY BANDS DURING THE FIVE STAGES OF SLEEP

than that of other frequencies. During sleep stage Delta, in contrast, the 1/2 to 3 Hz (so-called Delta) activity is not only prominent, but also has relatively high amplitudes.

3. EEG Frequency Levels in Response to the Stimuli

Illustrated in Figures 6, 7, and 8 are the average changes in the different frequency bands as a function of the type of response, i.e., no response (Type 0), a change of stage (Response Type 1), and behavioral awakening and arousal (Responses 2 and 3, combined). Figure 6 illustrates the changes resulting from stimuli during sleep stage 2; Figure 7 shows the changes during sleep stage Delta, and Figure 8 shows the changes during sleep stage REM. These results clearly indicate that with respect to the EEG frequency components only small and unsystematic changes occur if Responses 0 and 1 are compared with prestimulus levels. Only behavioral awakening and arousal are associated with a significant change in the EEG frequency distribution, and that change may be described as a general shift upward in level of all the frequency components, particularly during sleep stages 2 and REM. During sleep stage Delta, Responses 2 and 3 do not appear to be correlated with changes in the Delta or Theta levels, but only with increases in Alpha and Beta.

It is apparent in these figures that the most systematic change is the progressive shift upward of the submental EMG level with each response type. If Figure 4 is referred to, it will be seen that the EMG level during behavioral awakening (Response 3) was slightly higher, but not significantly, than it was during Response 2 (arousal).

It will also be noted in Figures 6, 7, and 8, that during each of the three sleep stages Response Type 0 (no response) was associated with a slight shift upward in all the frequency bands, as well as the EMG, as compared to the average level during the minute just preceding onset of the stimulus.

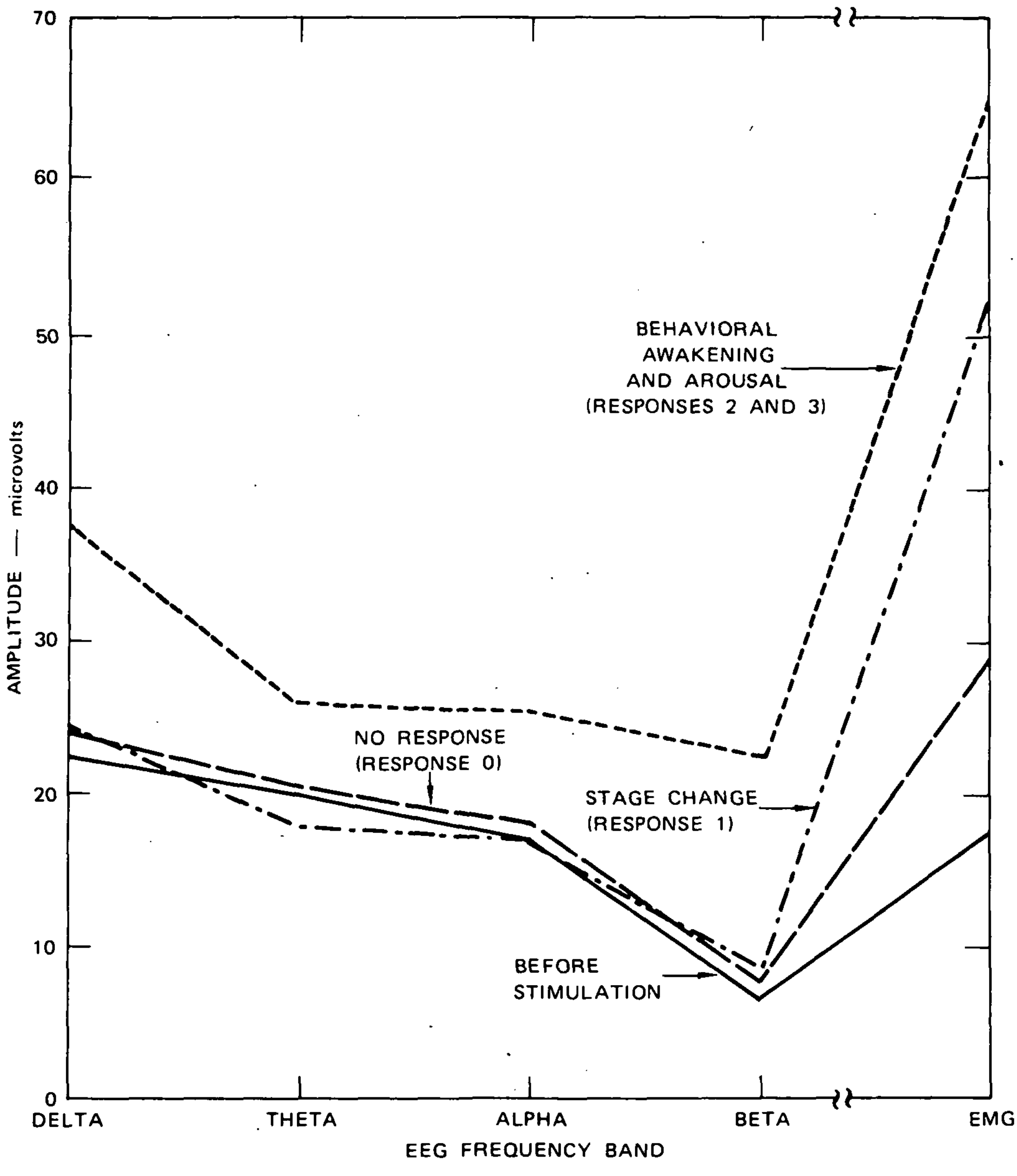

FIGURE 6 EEG FREQUENCY BAND AMPLITUDES DURING THE FOUR RESPONSES TO ACOUSTIC STIMULATION DURING SLEEP STAGE 2

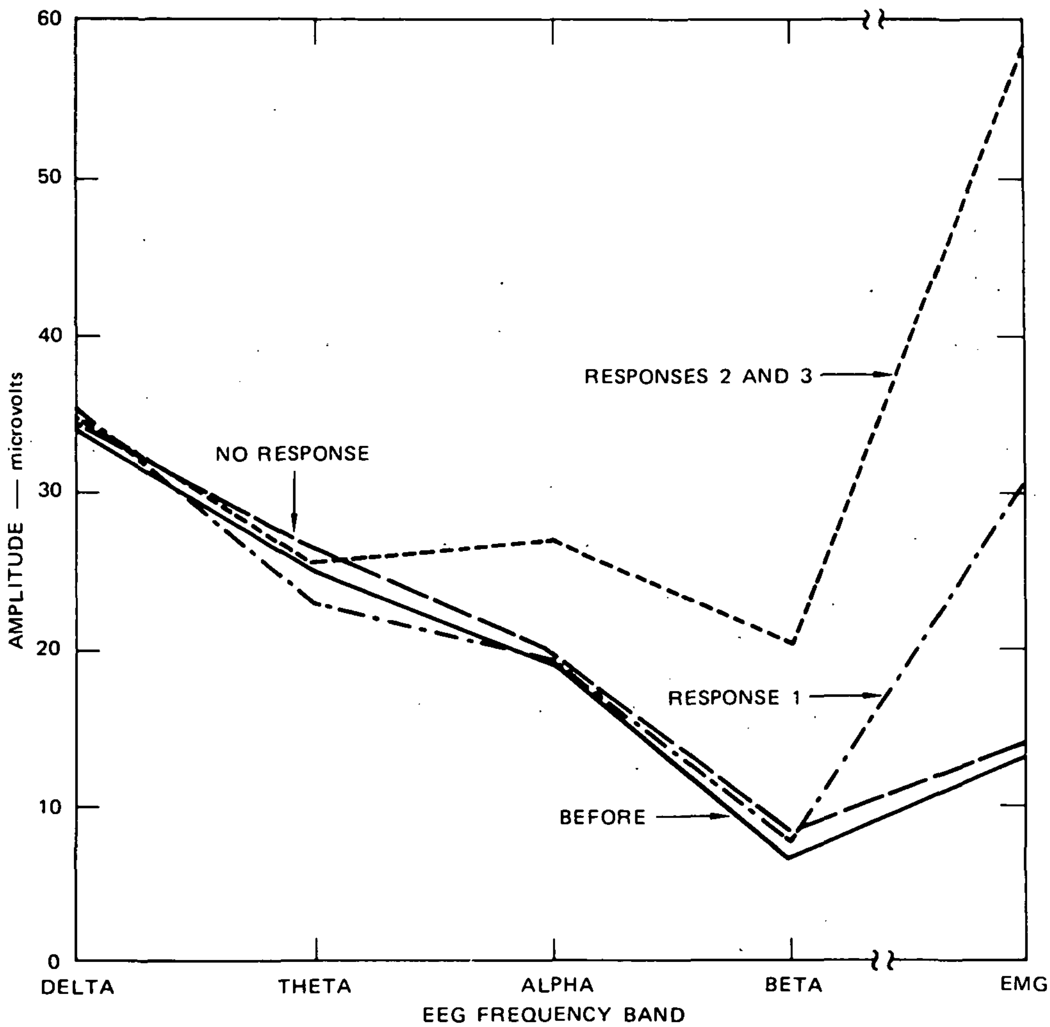

FIGURE 7 SLEEP EEG FREQUENCY BAND AMPLITUDES DURING THE FOUR RESPONSES TO ACOUSTIC STIMULATION DURING SLEEP STAGE DELTA

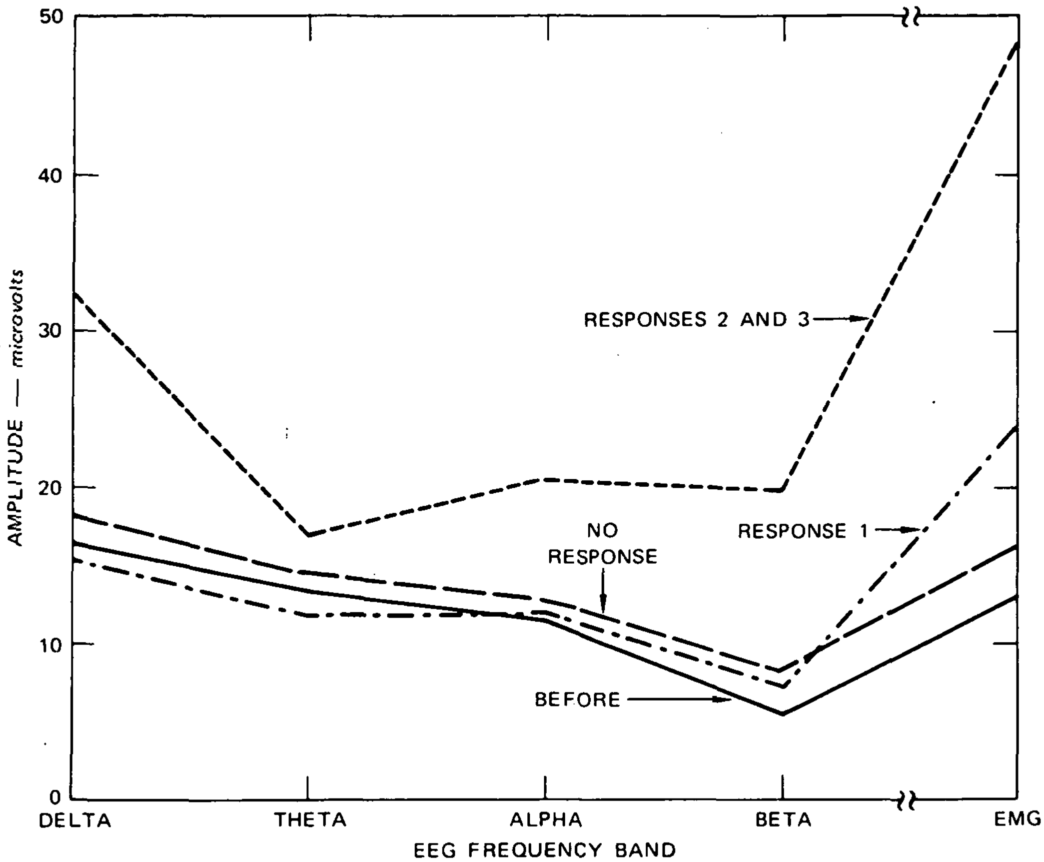

FIGURE 8 SLEEP EEG FREQUENCY BAND AMPLITUDES DURING THE FOUR RESPONSES TO ACOUSTIC STIMULATION DURING SLEEP STAGE REM

4. EEG Frequency Levels in Response to Specific Stimuli

The results presented above suggest that, at least insofar as the EEG frequency data are concerned, there is little reason to distinguish between Responses 0 and 1. In addition, because of the sometimes small number of instances of a particular response occurring to a particular stimulus while the subjects are in a given sleep stage, for the subsequent analysis the EEG frequency levels during Responses 0 and 1 will be combined.

Presented in Table 10 are the mean levels in the EEG frequency bands and the EMG during the three sleep stages observed during the minute just preceding stimulus presentation. It will be noted that these levels are approximately the same as those observed during the control nights (illustrated in Figure 5). That only the Beta frequency band did not show statistically significant mean differences between the three sleep stages should be noted. The mean levels presented in Table 10 are the basis of comparison for the effects of the various stimuli.

In Figures 9, 10, and 11, the average levels of the EEG and EMG responses to the stimuli are compared with the baseline levels obtained during the three sleep stages during which the stimuli occurred. It will be seen that there are few apparent consistent differences between the baseline EEG levels and Responses 0 and 1 regardless of the type of stimulus or its level. The possible exceptions are slight increases in the average level of Beta and increases of slightly greater magnitude in the EMG level.

With respect to the responses of arousal and behavioral awakening, however, the frequency pattern may be characterized by comparatively large increases in the levels of Alpha, Beta, and EMG. If the stimuli occurred while the subjects were in sleep stages 2 or REM (Figures 8

Table 10

MEAN AND STANDARD DEVIATION OF LEVEL IN THE EEG FREQUENCY BANDS AND THE EMG DURING THE MINUTE JUST PRECEDING STIMULATION

Frequency Band	Sleep Stage 2 Mean (in μv)	2 N	2 s.d.	Delta Mean (in μv)	Delta N	Delta s.d.	REM Mean (in μv)	REM N	REM s.d.	F Ratio (Within Mean Square is Error df = 293)
Delta	22.7	160	9.8	33.8	58	3.4	16.4	78	7.4	73.53
Theta	20.3	160	4.4	24.9	58	4.2	13.6	78	4.5	116.41
Alpha	16.9	160	3.8	19.3	58	3.5	11.3	78	2.5	92.89
Beta	6.6	160	2.4	6.6	58	1.0	5.7	78	1.8	0.09*
EMG	17.4	160	12.7	15.3	58	5.3	13.7	78	3.4	3.54

*Not significant; all other F ratios are significant at $p = 0.05$ or less.

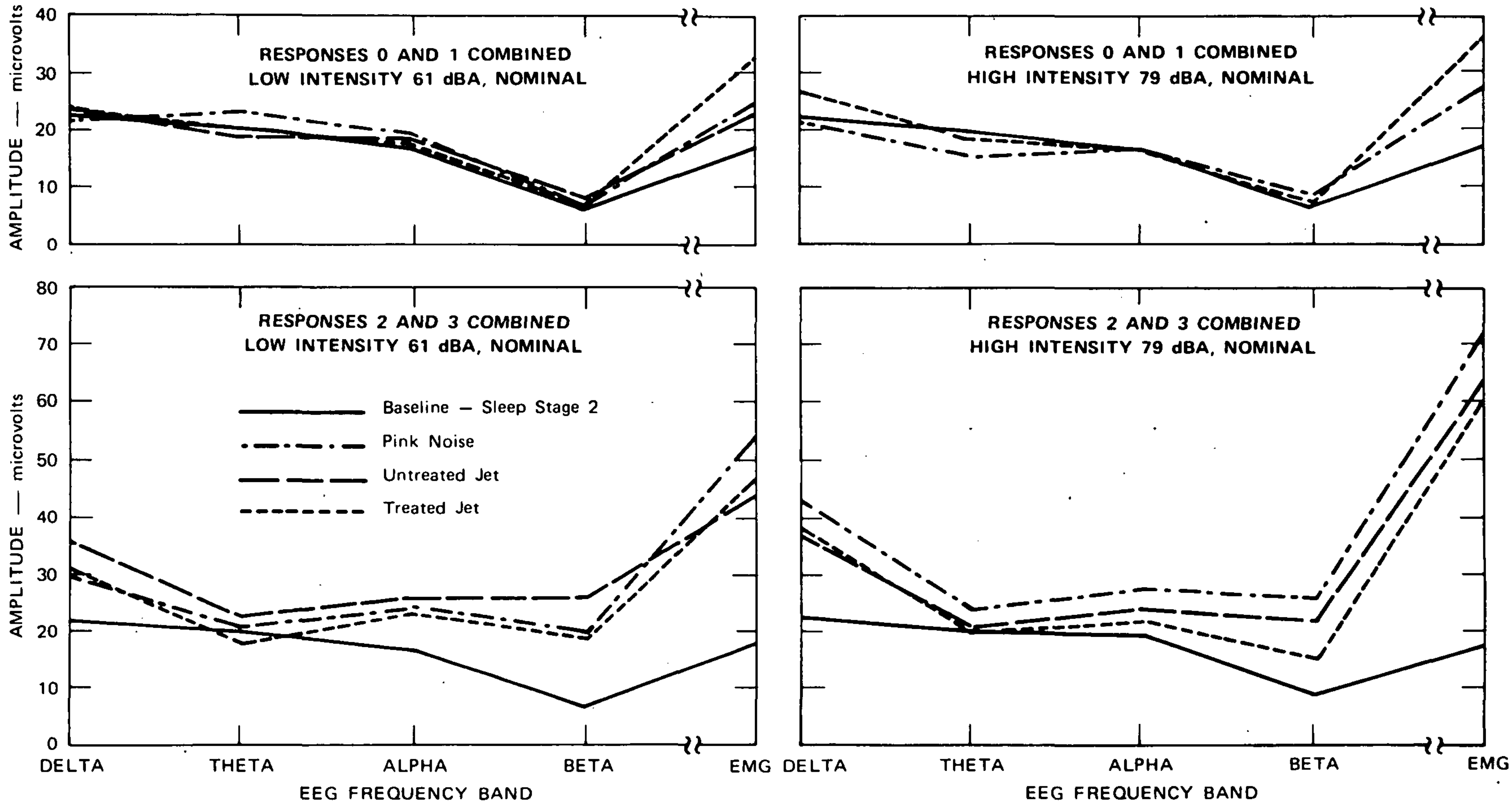

FIGURE 9 SLEEP STAGE 2 EEG FREQUENCY LEVELS IN RESPONSE TO THREE TYPES OF NOISES AT TWO INTENSITIES

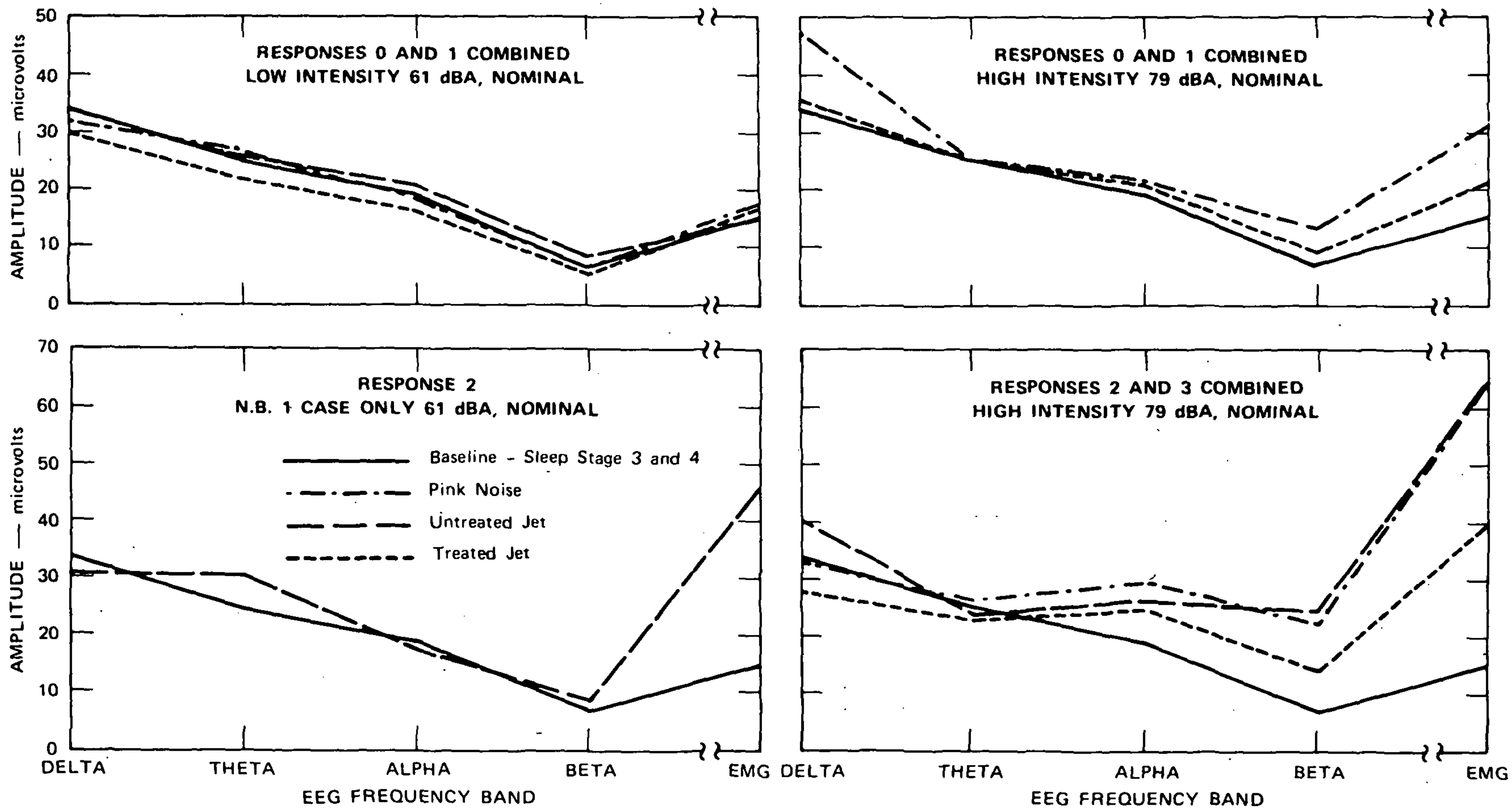

FIGURE 10 SLEEP STAGE DELTA EEG FREQUENCY LEVELS IN RESPONSE TO THREE TYPES OF NOISES AT TWO INTENSITIES

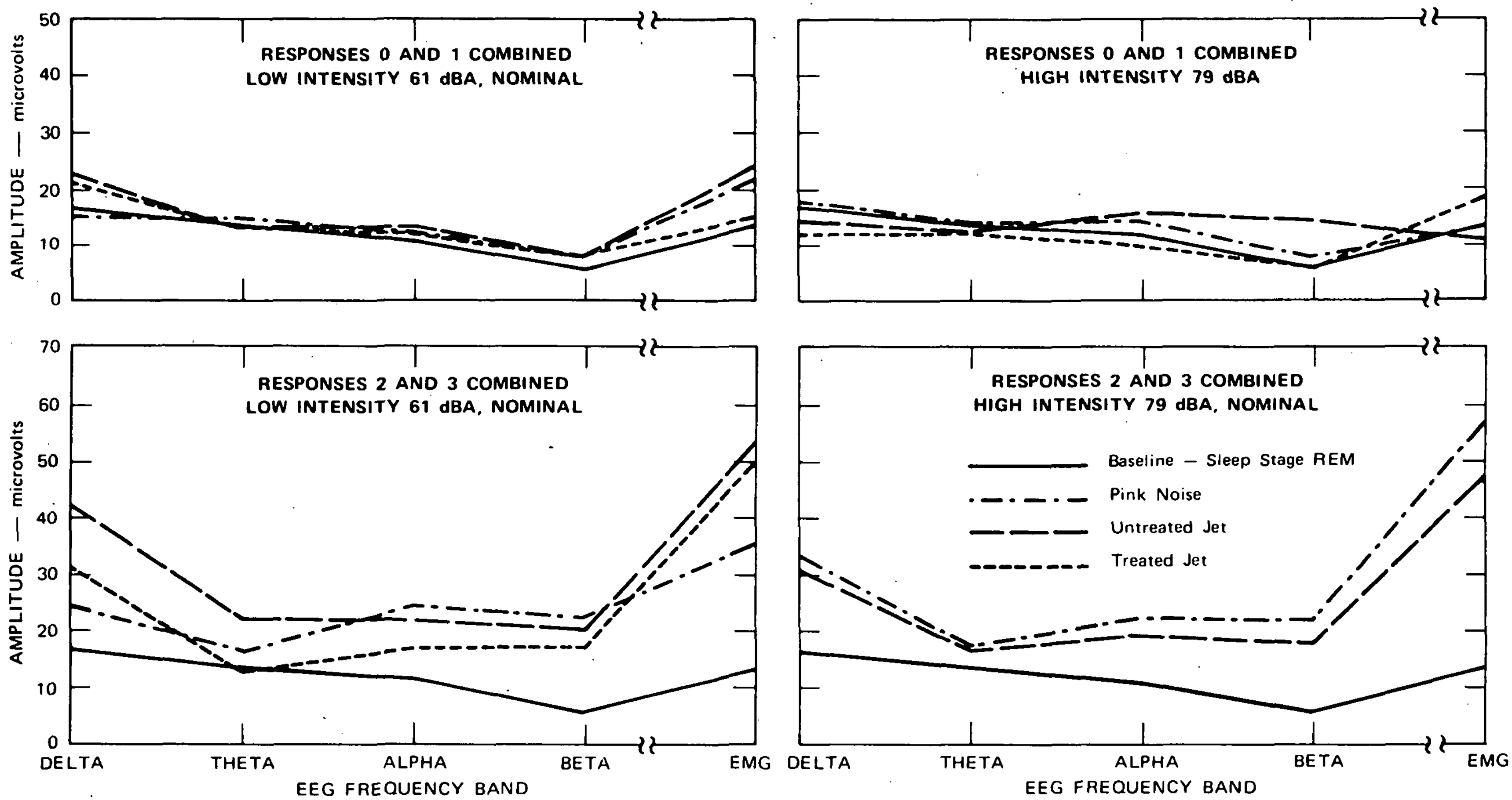

FIGURE 11 SLEEP STAGE REM EEG FREQUENCY LEVELS IN RESPONSE TO THREE TYPES OF NOISES AT TWO INTENSITIES

and 10), there is also an apparent increase in the level of Delta activity. In addition, the combined 2 and 3 responses to the various stimuli appear to be more widely distributed than are the 0 and 1 responses; however, there is no systematic pattern apparent for the three types of stimuli. In general, these results indicate that the EEG changes observed are not dependent upon the type of stimulus (with or without treated nacelles, for example); rather that if a given response occurs, its electrical characteristics are similar regardless of stimulus type.

V DISCUSSION

The results of a previous study[9] were interpreted as indicating the relative importance of behavioral awakening in the assessment of the effects of noise on sleep. The results presented herein indicate the same thing, but on the grounds of absolute voltage changes observed through computer analysis rather than on the grounds of the more common manual (visual) scoring of the EEG record. There appeared to be little difference in the computer averaged voltages between responses scored visually as 0 and 1 (no response and a change of sleep stage, respectively) and the pattern of electrical activity measured by computer just prior to those responses. In contrast, responses scored visually as 2 and 3 (arousal and behavioral awakening, respectively) generally were associated with much larger changes in the computer averages.

One EEG change which tends to be relatively consistent however, even for responses scored 0 and 1 visually, is the slight increase in the level of Beta activity found in the computer output. This increase in Beta activity may account for the small average increases in "cortical desynchronization" reported by LeVere, et al.,[15] although on the basis of their reports it is difficult to discern exactly what electrical parameters may account for the changes they reported. Be that as it may, there is some question about the significance of small changes in Beta level (or of changes of less than one sleep stage as reported by LeVere, et al.) upon the physiological or psychological well-being of humans.

That the physiological or functional significance of the electrical patterns emanating from the brain are only poorly understood is a generally held belief. The results of this study tend to confirm the belief.

Although the responses of the subjects to the noise can be classified by visual inspection of the record, the present data indicate there is little correlation between that visual analysis and its underlying electrical activity, at least in terms of the so-called Delta, Theta, Alpha, and Beta components as they were averaged in this study.

This generally low correlation cannot be accounted for by unreliability in visual scoring since scoring reliability typically ranges from about 75 to 95 percent,[14,16,17] and have been at the upper levels particularly after the standardized scoring manual[8] was introduced.

It may be that the "skirts" (see the 3-dB downpoints shown in Figure 4) of the filters used to distinguish among Delta, Theta, Alpha, and Beta activity, were relatively wide, thus allowing a relatively intense, single frequency in a particular band to stimulate the adjacent bands. However, it is equally true that greatest output will be found in the filter tuned to that frequency (providing, of course, that the frequency of interest is not at the point at which two skirts coincide); and if a particular sleep stage is defined by some electrical activity, in the aggregate that stage should show peaks in the defining frequency band, as illustrated in Figure 5.

Alternatively, the integration times for the filtered outputs used in this study may be inconsistent with the way humans score the EEG. If, for example, while a subject was in sleep stage 2, the response to a noise included (1) an increase in the EMG level, (2) several seconds of Theta activity, and (3) other "mixed frequency" activity, the human scorer may note a stage change of one step, i.e., to sleep stage 1. However, the electronic system used in this study would average that relatively brief change with all of the other activity occurring during 40 seconds. It seems unlikely, at least under the conditions described, that the electronic system would produce an average which reflects the important transitional characteristics of the written EEG record that can be seen by the human eye. In contrast, Responses 2 and 3 (arousal and behavioral awakening), which in the written EEG are characterized by high-amplitude mixed-frequency activity of durations exceeding 40 s, were clearly discernible in the computer output from the baseline levels of any sleep stage. This observation supports the argument that a 40 s integration time is too long to detect the low amplitude and transitory changes that characterize changes of sleep stage.

VI CONCLUDING REMARKS

Because of the small number of subjects and types of noises studied, the conclusions presented below should be considered tentative at this time.

(1) These tests indicate that for equivalent sleep disruption (i.e., no electroencephalographic response) the level of the noise from the untreated jet engine must be about 6 dBA less than the noise from the treated engine. Inasmuch as the landing noise from the treated aircraft is about 10 dBA less (estimated from Ref. 3) than that of the untreated aircraft performing the same operation, the treated aircraft should cause much less (perhaps 1/2) disturbance to sleep under similar landing operations than would the untreated aircraft.

(2) Predictions of the effects of noise on sleep appear to attain the highest accuracy when the physical descriptor of that noise includes information about the "impulsive" characteristics of that noise as well as its more long-term spectral content.

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