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AROUSAL FROM SLEEP: The uniqueness of an individual's response and the problem of noise control

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T. E. LeVere
Neuropsychology Laboratory
Department of Psychology
North Carolina State University
Raleigh, North Carolina 27650

AROUSAL FROM SLEEP: The uniqueness of an individual's response and the problem of noise control.

Chapters

INTRODUCTION

Kryter (1970) reports that Grandgan; Lehmann; Richter; and Jansen and Schulze, among others, conclude that one of the greatest hazards of noise to an individual's physiological and psychological well-being is that associated with sleep disruption. While one may argue the adjective "greatest", it would seem that there is a consensus that noise can disrupt sleep and this, by itself, is certainly not of any benefit. Not withstanding this consensus, a systematic investigation of the sleep disturbing effects of noise, particularly aircraft noise, has only recently begun to command serious interest. For example, at the third annual National Noise and Vibration Control Conference (Atlanta, 1975) nearly 100 papers were presented over a three-day period. Only one of these papers dealt with the annoyance produced by sleep disruption associated with aircraft noise. In this paper, Borsky (1975) suggested, after a rather complicated analytical procedure, that a single nighttime overflight was equivalent in annoyance to two daytime or early evening overflights. While it is possible to question the magnitude of the estimate, it is nonetheless certain that psychological annoyance, as estimated by various rating scales, is at least as great during the nighttime as it is during the daytime and most probably greater.

Laboratory research generally complements this subjective field survey data. For example, consider Figure 1 which summarizes the major results of an early experiment from our laboratory (LeVere, Bartus, & Hart, 1972). This figure quantifies the sleep disruption produced by jet aircraft flyovers as amounts of desynchronization (arousal) occurring in the sleep recorded electroencephalogram along the ordinate and the duration of this sleep disruption in minutes along the abscissa. While the methodology of this experiment was somewhat crude -- the flyovers were not directly determined by the subject's sleep pattern, and all data analysis was off-line -- the results do point out two important facts. First, jet flyovers having a maximum intensity of 80 dB(A) and a duration of no more than 15 seconds are clearly capable of disrupting an individual's sleep. Second, and perhaps more importantly, this disruption far outlasts the actual occurrence of the flyover itself. Thus, the subjective annoyance experienced by individuals living near airports (Borsky, 1975) would appear to be correlated with certain underlying physiological processes.

More recently, Lukas (1975) has reviewed the laboratory research concerned with the disruption of sleep by auditory noise. While much of this review concentrated on the somewhat restricted dependent measure of behavioral awakening and stressed the correlation between other research and the author's own investigations, it is nonetheless extensive, and the overall conclusion commands some validity. This conclusion is that sleep disruption, independent of how it is measured in the laboratory or how it is quantified, represents a real and pressing problem. Since the data supporting this assertion is adequately catalogued by Lukas, an extensive review at this point would be redundant, and we will not further labor the issue.

Figure 1

Average arousal produced by the occurrence of a jet aircraft flyover noise during the 1-minute EEG epoch when the flyover occurred and during the succeeding 5 1-minute EEG epochs (solid line). The broken line represents a control comparison from a series of similar periods randomly selected from nights when the individual's sleep was not disturbed by jet aircraft flyover noise. In this figure, arousal is depicted as a change in cortical desynchronization relative to the 2 1-minute EEG epochs just preceeding a jet flyover noise or a particular 6-minute period selected from a control night. Positive number represents increases in cortical desynchronization (arousal) and a +1.0 would correspond to roughly a shift of one sleep stage. Redrawn from LeVere, Bartus, & Hart, 1972.

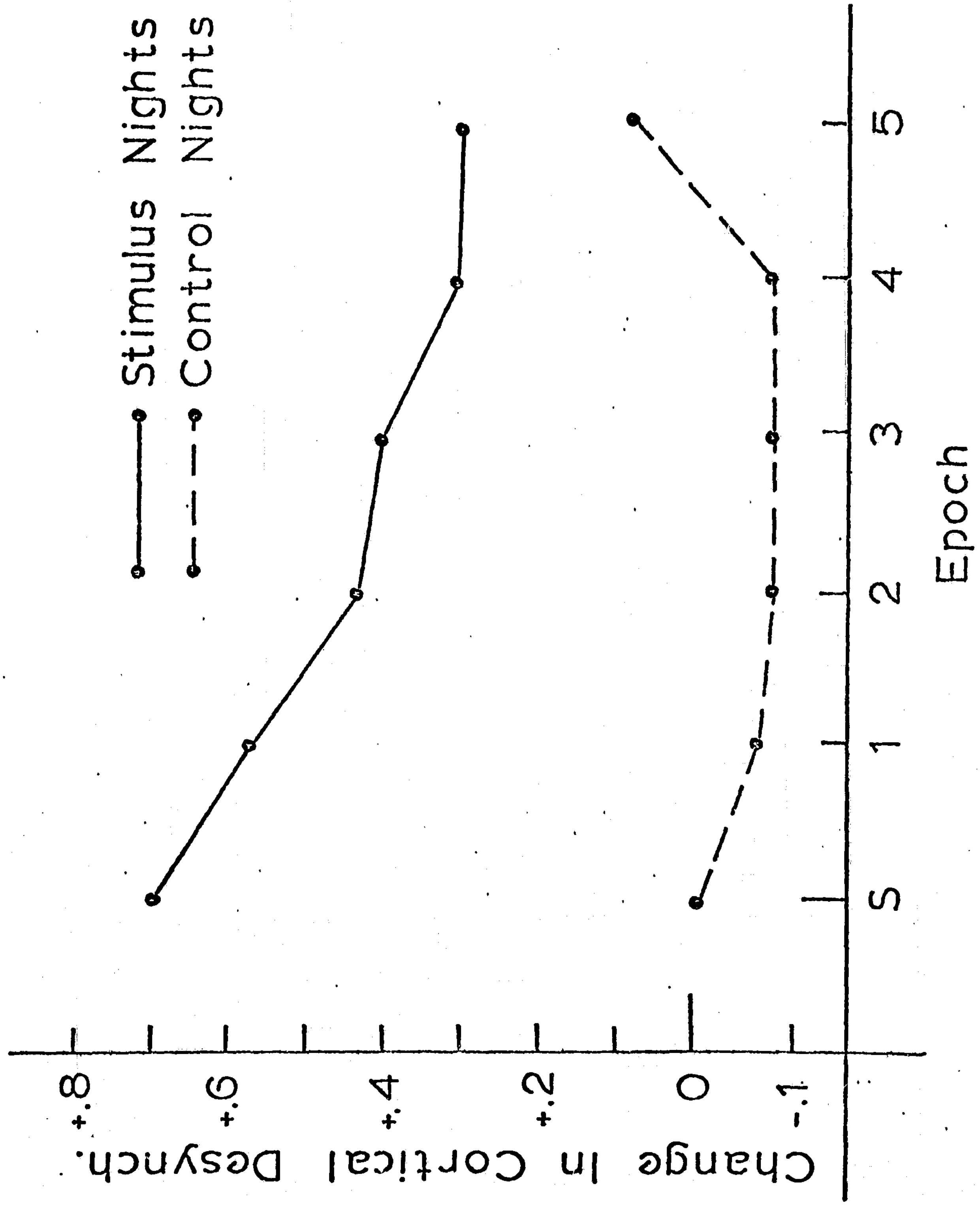

Stimulus Nights
Control Nights
Change in Cortical Desynch.
+.8
+.6
+.4
+.2
0
-.1
S
1
2
3
4
5
Epoch

Figure 1

From both field survey data and laboratory research, it is thus clear that noise can and does disrupt sleep. However, sleep disruption *per se* is only the symptom of the underlying health problem. That is, sleep is not something one does simply because there is nothing else to do. Rather sleep represents a biological process which if interfered with will result in a need state conceptually similar to any other biological need. While this may be a restatement of the obvious to anyone who has missed a night's sleep there is also strong empirical support for the proposition. The data stems from research concerned with the deprivation of certain kinds of physiologically definable sleep states (Johnson, 1969; Webb, 1969; Dement, 1969). The consistent finding of these investigations is that following several nights of deprivation, the individual's sleep pattern will shift to favor the type of sleep just previously deprived. In other words, the individual will attempt to make up for (recover) what has been denied during the previous nights. This is, of course, the classic "rebound effect" and is rather compelling evidence that sleep represents the satisfaction of some biological need. Thus, asserting that sleep disruption is simply an annoyance associated with contemporary living misses the underlying health problem and grossly understates the problem. The disruption of sleep is not only a psychological problem, that is annoyance, but it is also a physiological problem. It creates a biological need. As such, the problem of sleep disruption must be afforded something more than attitude surveys designed to determine whether nocturnal noise is more annoying than daytime noise.

CRITICAL ISSUES ASSOCIATED WITH SLEEP DISRUPTION

At this point, we suggest accepting the proposition that noise is an environmental pollutant which can and does disrupt sleep. Moreover, we believe that this is a significant health problem and that little can be gained from further surveys designed to a) reestablish the proposition that noise disturbs sleep, or b) establish criterion to measure the amount of annoyance associated with such sleep disturbances. On the other hand, we believe that it is just as apparant that the total elimination of all noise may not be the ultimate goal. Indeed, classic sensory deprivation research saliently demonstrates that some amount of extrinsic stimulation is a mandate to the well being of an individual (see Bexton, Heron, and Scott, 1954; Heinemann, 1970; Heron, 1957; Zuckerman, 1962). Thus, the simple and straightforward approach of eliminating all nocturnal noises is not necessarily a viable solution. Rather, one must precisely define what aspects of noise are, in point of fact, detrimental, and what aspects are acceptable. And this is a psychophysical determination which we believe is a prerequisite to any cost effective utilization of engineering technology. However, the majority of researches concerned with the problem of sleep disruption by auditory noise have fallen far short of addressing the basic parameters of the problem.

In this regard, we believe that there are two fundamental issues. First, if an individual's sleep is disturbed by some extrinsic noise, then by definition the individual has responded to the auditory noise. This is just what the majority of survey and laboratory research has established. But the critical issue is not simply whether the individual will respond but rather how the individual responds. Clearly when an individual is asleep, he or she is in a different psychological and physiological condition than when awake. The problem is then whether or not this state is such that the individual reacts differently to auditory sounds when asleep as compared to when the individual is awake. And this is not just an academic question but has far reaching practical implications. For example, should the individual respond similarly when asleep and when awake, then we would be able to realize considerable gains in predicting and controlling the sleep disturbing properties of auditory noise because of the volume of data collected on awake individuals. However, should the individual react differently when asleep, then we will necessarily be forced to discover exactly how an individual responds when asleep before we can even begin to predict and control the sleep disturbing properties of auditory noise.

The second fundamental question is whether or not sleep disruption necessarily involves behavioral awakening. That is, can the sleeping individual respond to an auditory noise without being awakened. In this instance, the concern is whether or not changes in the <u>pattern</u> of an individual's sleep are as detrimental as behavioral awakening. There are two corollary questions involved. First, can an individual subjectively appreciate sleep disturbances (changes in sleep pattern) which do not result in behavioral awakenings? Second, and more importantly, will sleep disruption which does not result in behavioral awakening effect overt waking performance? Clearly, if sleep represents the satisfaction of a biological need state, then one would predict that any sort of disruption of this process should have detrimental effects on waking behavior. However, while this prediction would seem obvious, it has been quite difficult to demonstrate under controlled laboratory conditions.

The goal of the present final report is to address these two fundamental issues. However, before presenting the research concerned with these issues, it is necessary to first gain some appreciation of the sleep process itself. And, of critical importance here, is the realization that sleep is not a unitary or static process but rather is a dynamic process where the effects of a given auditory noise must be viewed vis-à-vis the character of sleep when the noise occurs.

The Dynamic Nature of Sleep

That sleep is a dynamic, constantly varying process is supported by a number of different lines of evidence. The previously noted experiments on selective sleep deprivation are a case in point. These experiments could only be possible if, in fact, there were different and distinct types of sleep which could be deprived. However, somewhat more direct evidence is provided by a number of authors contributing to a book edited by Kales (1969). In the chapter by Webb for example, evidence is presented that wakefulness and sleep are not binary events but rather the overt manifestation of a continually varying circadian rhythm of approximately 24 hours duration.

In the chapter by Kleitman, it is further demonstrated that superimposed upon this 24 hour circadian rhythm there is another rhythm of about 90 minutes duration which Kleitman calls the basic rest-activity cycle (BRA). But perhaps even more to the point is the chapter by Berger where he reviews a number of physiological variables including heart rate, respiration, blood pressure, and temperature which are shown to continually vary during the sleep process. Moreover, in this particular chapter, it is shown that certain of these physiological variables do not covary in synchrony but rather are somewhat at odds given what normally might be expected. Thus, while overt behavior may be drastically reduced during sleep, the myriad of ongoing physiological and psychological processes, for example dreaming, exhibit a degree of complexity rivaling that of the waking state.

However, not withstanding the possible number of variables which may be measured and related to different sleep states and/or processes, most researchers have confined their interest to only three. These are the scalp recorded electroencephlogram (EEG), the electromyogram (EMG), and rapid eye movements (REM). If one includes wakefulness (stage 0) and rapid eye movement sleep (stage REM), then there are six definable and mutually exclusive stages of sleep. A summary of the major characteristics of each stage is presented in Table 1 which summarizes the criterion suggested in A Manual of Standardized Terminology, Techniques and Scoring Systems for Sleep States of Human Subjects (Rechtschaffen and Kales, eds, 1968). Procedurally, an individual's night's sleep is typically divided into successive 20 or 30 second epochs and each epoch is scored as either stage 0, 1, 2, 3, 4, or REM. The sleep stage scored for each successive epoch is then

TABLE 1

CRITERION FOR SLEEP STAGES

	EEG	EOG	EMG
Stage 0	Alpha activity (8-13 Hz) and/or low voltage mixed frequency activity		
Stage 1	Low voltage, mixed frequency activity with occassional vertex sharp waves up to 200 µV	None	
Stage REM	Low voltage, mixed frequency	Episodic REM	Very low amplitude
Stage 2	Sleep spindles (12-14 Hz) and K-complexes on background of low voltage mixed frequency activity		
Stage 3	Moderate amounts (20-50%) of high amplitude slow-wave (2 Hz or less) activity		
Stage 4	Large amounts (greater than 50%) of high amplitude slow-wave activity		

plotted to provide an overall picture of an individual's night's sleep. A typical example of such a plot is shown in Figure 2 and even a brief glance readily attests to the fact that a night's sleep is not a static unvarying process. Clearly, the commonly used phrase "slept like a log" is anything but true.

The Measurement of Sleep Disruption

The problem for the researcher interested in the disruption of sleep by noise is then to understand the effects of noise against the background of a dynamic sleep process. In this regard, the typically employed dependent measure of behavioral awakening is all but inadequate to the task. For example, returning to Figure 2, it can be seen that during the early portions of the night the individual spends considerably more time in Stages 3 and 4. While not altogether accurate, Stages 3 and 4 are commonly considered to be deeper stages of sleep than Stages 1 and 2 in terms of the intensity of a stimulus required to awaken the individual. Thus, if one relies on behavioral awakening, then a given noise which may disrupt sleep (awaken the individual) during the early morning hours may be totally ineffective during the first portion of the night's sleep. However, the auditory noise, while not producing behavioral awakening during the early hours of sleep, may nonetheless produce significant changes in the pattern of the invididual's sleep -- perhaps even deprive the individual of certain types of sleep. But, the dependent measure of behavioral awakening would not detect this sort of sleep disruption. In this regard, it is our position that until it is unequivocally demonstrated that

Figure 2

Eight hour sleep profile showing how sleep stages vary during a night's sleep. Of particular interest is the dominance of sleep stages 3 and 4 during the early evening and the lack of sleep stages 3 and 4 during the latter portions of sleep. Also note the approximate 90-minute character of the individual's cycle through the stages of sleep.

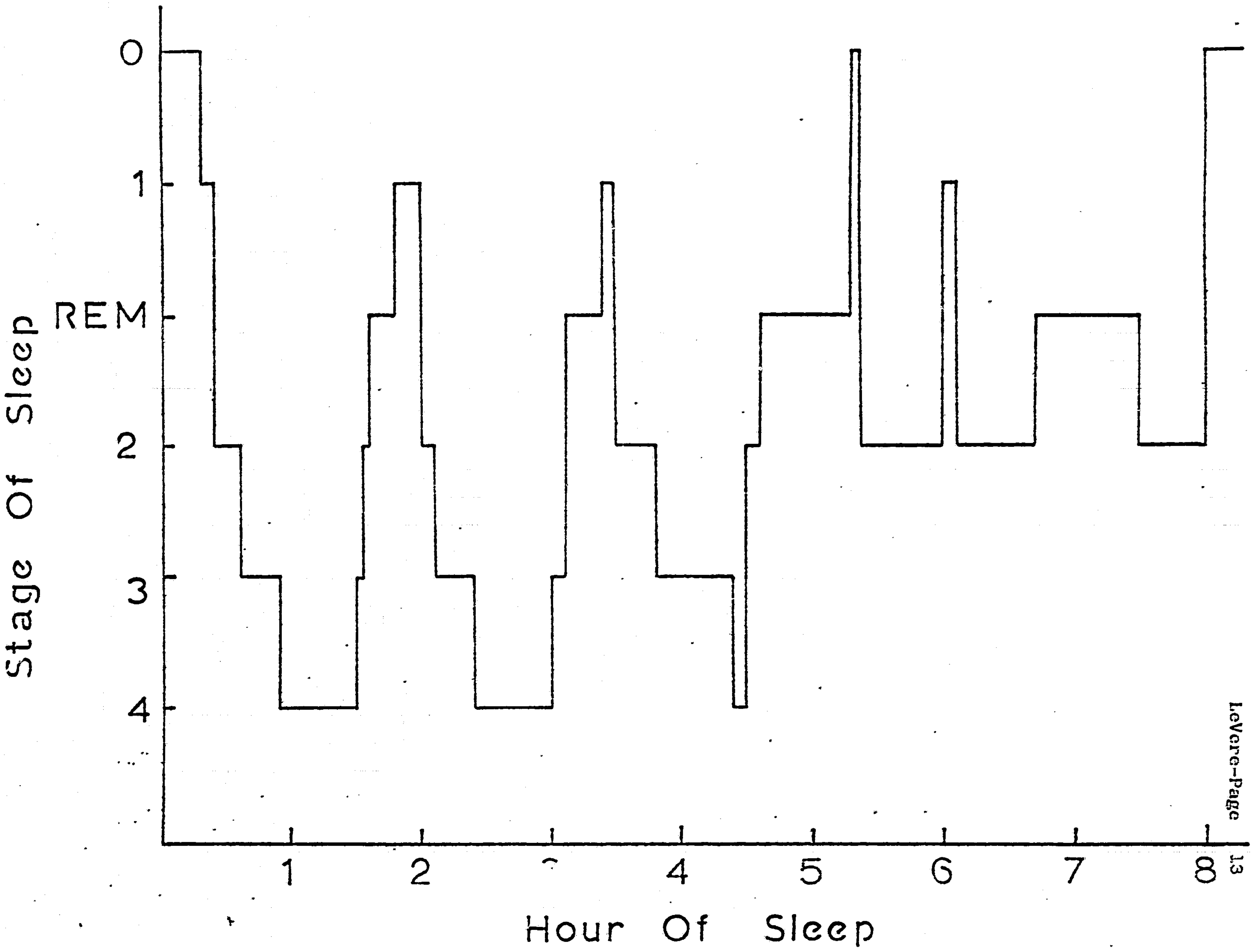


Figure 2

behavioral awakening is the only important measure of sleep disruption, it would appear prudent to attempt to quantify more subtle disturbances of an individual's sleep.

In accord with these arguments, we have over the past years used a computer program which will detect cortical desynchronization (increases in the frequency content) in the ongoing pattern of the individual's EEG to quantify sleep disruption. Our choice of this measure was based principally on three things. First, there is ample evidence that cortical desynchronization is a clear indication of behavioral arousal (Adrian and Matthews, 1934; Moruzzi and Magoun, 1949; Rheinberger and Jasper, 1937; Sokolov, 1960). Second, this measure enables us to assess and quantify sleep disruption independent of the sleep stage when noise occurs and independent of whether the noise produces behavioral awakening. Third, and finally, the frequency content of the ongoing EEG represents a continuous variable and, as such, allows the data to be handled with standard parametric statistical procedures.

THE NATURE AND EFFECTS OF AN INDIVIDUAL'S RESPONSE TO AUDITORY NOISE DURING SLEEP

Before specifically summarizing our research concerned with: a) whether of not an individual responds similarly during sleep and wakefulness, and b) whether sleep disruption may carry over to wakefulness in terms of the individual's estimate of sleep quality and overt performance, we would first like to discuss our general methodology. We have standardized this methodology for all of our experiments to attain some degree of internal consistency within our program.

General Methods

All of our research follows the repeated measures experimental protocal with each subject serving as his own control. Moreover, the treatment conditions are always balanced over subjects to control for sequential biases. Our subjects are male volunteers between the ages of 18 and 35. We require that they are not under a physician's care or taking any medication. Additionally, all subjects must refrain from the use of alcohol or other narcotics, excluding tobacco, during their participation in the experiment.

In terms of the physical hardware, the subjects sleep in an electrically isolated mock-up bedroom within a quiet portion of the laboratory. During each night, the subject's electroencephalographic activity (EEG) and eye movements (EOG) are continuously monitored and passed to our on-line computer system for real-time data analysis. The computer is programmed for a zero-crossing analysis to detect minute to minute changes in the frequency content of the subject's EEG. Principally, we define two types of sleep on the basis of this frequency data: a) sleep characterized by fast-wave EEG activity without rapid eye movements, and b) sleep characterized by slow-wave EEG activity. This corresponds respectively to sleep Stages 1 and 2 and sleep Stages 3 and 4 of the traditional Rechtschaffen and Kales scheme. We have combined these stages because it is our belief that the distinctions between Stages 1 and 2 and between 3 and 4 are principally quantitative in nature. On the other hand, the selective deprivation studies suggest that there is a qualitative distinction between sleep characterized by fast-wave EEG activity and sleep characterized by slow-wave EEG activity. Accordingly, it would seem necessary to investigate how an individual responds to auditory noise during these two types of sleep.

To quantify the subject's response to auditory stimuli, we simply record the total number of wave forms which occur; that is, the amount of cortical desynchronization. Without exception, the subject's response to nocturnal noise is an increase in cortical desynchronization which, it should be remembered, has been classically taken to indicate behavioral arousal. We have, of course, validated our computer procedures and find better than 90 percent agreement between the computer analysis and a visual analysis of a night's polygraph records.

The auditory stimuli with which we disturb sleep all share the common features of being discrete occurrences between 15 and 30 seconds in duration and none ever exceed a maximum intensity of 80dB(A). The stimulus presentations are always randomly distributed over a night's sleep with the usual restriction that an equal number occur during nonREM fast-wave sleep and during slow-wave sleep.

Procedurally, all experiments are totally under computer control. That is, the computer begins the frequency analysis immediately after the subject is settled in bed. After detecting five successive minutes of sleep, the computer switches to a program for the six-hour data run. During this time, the computer continues the frequency analysis but also presents the auditory stimuli in accord with the subject's electroencephalographic activity and the particular demands of the experiment. When an auditory noise is presented, the computer stores the frequency data for the one-minute period just preceeding the noise, for the one-minute period when the noise occurred, and for three to five succeeding one-minute periods.

The Uniqueness of Sleep

Loudness as a Predictor of Sleep Disruption

With these procedures, our first question was whether we might be able to predict sleep disruption from how an individual responds when awake. The initial experiment of this series was concerned with the subjective parameter of loudness (LeVere, Morlock, Thomas & Hart, 1974). We considered the experiment of some interest because of the relationship between loudness and physical intensity or Sound Pressure Level (SPL) as quantified by Robinson and Dadson (1956) and by Pollack (1952). Inspection of the curves presented by these investigators shows that a wide range of intensities are necessary to equate perceived loudness. This is particularly so for frequencies below 1k Hz where considerably higher SPL's are required, and it is here that we concentrated our investigation. The specific question was whether sleep disruption would be similar for different frequency noises which were equal in loudness but necessarily different in physical intensity.

Procedurally, we had our subjects come to the laboratory prior to sleeping and, with the classic psychophysical method of average error, set the physical intensity necessary to equate the loudness of three auditory noises. These auditory noises were 1/3 octave bands centered on the frequencies of 50 Hz, 250 Hz, and 1k Hz with the latter used as the standard and set as 80dB SPL. These three stimuli, at the sound pressure levels set by the subject, were then used to disturb the sleep of this same subject on each of three subsequent nights. The results of this experiment are shown in Figure 3. The left side of the figure shows the arousal produced by the three stimuli during fast-wave sleep while the right side of the figure presents similar data obtained during slow-wave sleep. The plotted points represent the change in cortical desynchronization with respect to the minute just preceding the occurrence of the noise. As can be seen from the figure, each frequency was capable of disturbing sleep as compared to the no sound control condition indicated by the dashed line near the bottom of the figure. Additionally, during fast-wave sleep, the three frequencies produced essentially the same amount of arousal as

Figure 3

Average arousal produced by different 1/3 octave bands of equally loud noise centered on the frequencies of 50 Hz., 250 Hz., and 1k Hz. Arousal here, as in the previous figure, is quantified as a change (increase) in cortical desynchronization relative to the frequency content of the individual's EEG during the 1-minute EEG epoch just preceeding the occurrence of the noise. The arousal produced by these stimuli during sleep characterized by fast-wave EEG activity without rapid eye movements (REM) is shown on the left of the figure while the arousal produced during sleep characterized by slow-wave EEG activity is shown on the right. Redrawn from LeVere, Morlock, Thomas, & Hart, 1974.

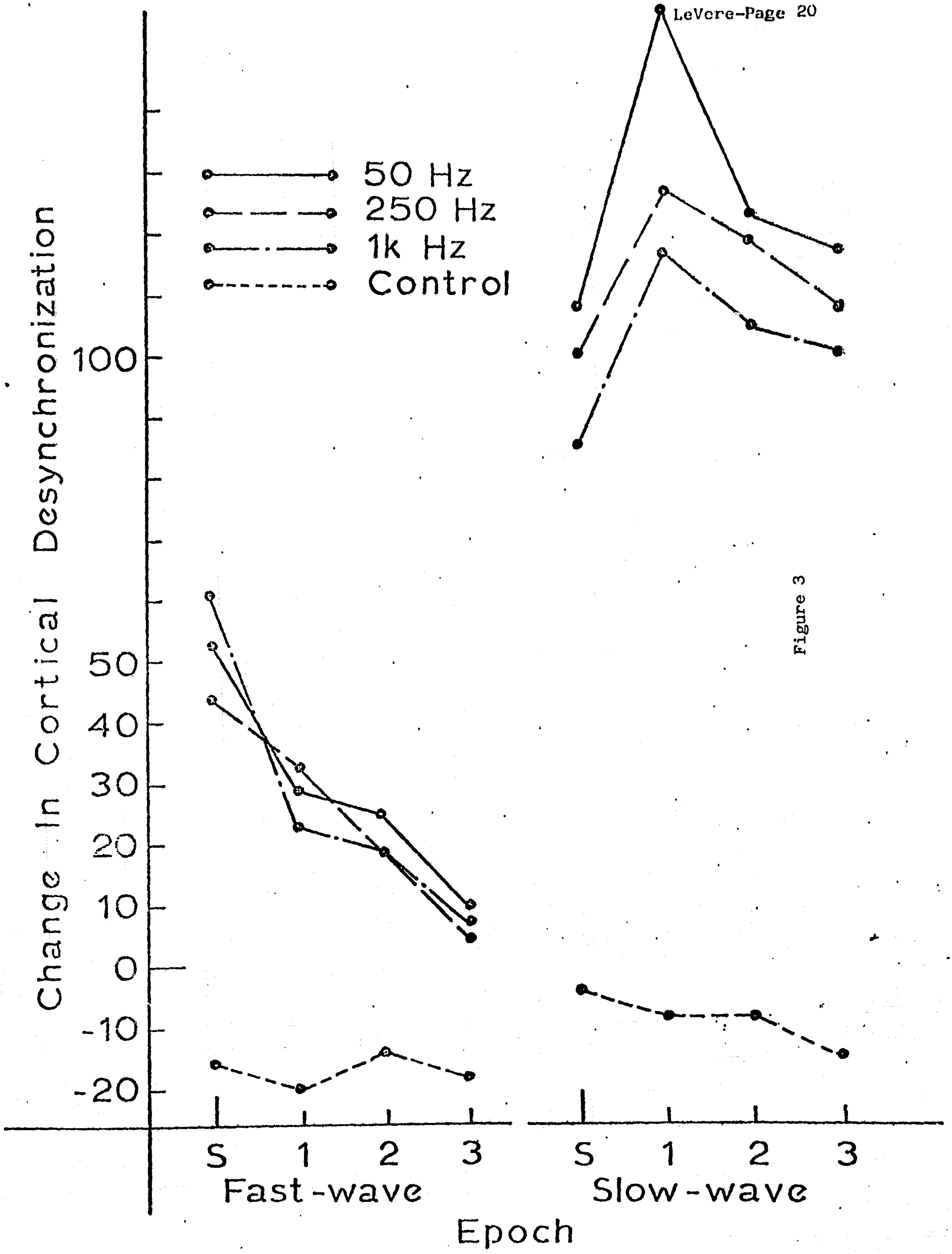

50 Hz
250 Hz
1k Hz
Control
Change In Cortical Desynchronization
100
50
40
30
20
10
0
-10
-20
S
1
2
3
Fast-wave
S
1
2
3
Slow-wave
Epoch

Figure 3

would be predicted on this basis of their loudness. However, and more importantly, this prediction does not hold during sleep characterized by slow-wave EEG activity. In this case, the different frequencies produced different amounts of arousal and the effectiveness of a particular frequency appeared more related to sound pressure level than to subjective loudness. Thus, in this particular case -- but as we shall see it is not unique -- the response of an individual when awake is of little utility in predicting his response to similar stimuli during sleep.

Rise Time as a Predictor of Sleep Disruption

Since subjective loudness did not appear to be a particularly good predictor of sleep disruption, we turned our attention to another psychological parameter -- annoyance (LeVere, Davis, Mills, Berger & Reiter, 1976). Our experiment centered on previous demonstrations that an auditory noise having a gradual onset is judged more annoying by awake individuals than an auditory noise having a sudden onset (Kryter, Johnson & Young, 1969; Nixon, Von Gierke & Rosinger, 1969). Our procedure was simply to disturb sleep with auditory noise having either a gradual onset or a sudden onset. If subjective annoyance transfers to sleep, then one would predict that there should be a greater arousal when an individual's sleep was disturbed by auditory noise having a gradual onset.

Specifically, we again used a 1/3 octave band of auditory noise centered on 125 Hz and with a maximum intensity of 80dB(A). There were two rise times. One, the fast-rise stimulus, reached its maximum intensity instantaneously, remained at this intensity for 15 seconds, and then abruptly terminated. The other, the slow-rise stimulus, approached its maximum in a gradual linear fashion over a period of 7.5 seconds, remained at this maximum intensity for 15 seconds, and then gradually decreased to zero over an additional 7.5 seconds. Each subject slept in our laboratory for three successive nights where on different nights his sleep was disturbed by 24 presentations of either the fast-rise stimulus or the slow-rise stimulus, or left undisturbed. The results of this experiment are shown in Figure 4 which is organized similarly to the previous figure. The data clearly indicate that rise time can be an important perameter in determining sleep disruption. However, and importantly, it would appear that rise time was differentially effective only during sleep characterized by slow-wave EEG activity. And then, the difference is exactly the opposite of what one would predict on the basis of subjective annoyance. That is, noise having a sudden onset is more disruptive of sleep than noises having a gradual onset even though the latter has been judged more annoying by awake individuals. Thus, once again, how an individual responds when awake is not predictive of how his sleep, particularly sleep characterized by slow-wave EEG activity, is disturbed by similar auditory noise. Furthermore, this data suggests that the preponderance of survey data cataloguing the annoyance produced by various types of community noise may be of little utility concerning sleep disruption. And for the simple reason that increased annoyance does not predict increased sleep disruption.

Figure 4

The arousal associated with auditory noise having different rise times. In this figure, the actual amount of cortical desynchronization recorded during the 1-minute EEG epoch just preceeding the occurrence of the noise as well as the actual amount of cortical desynchronization when the noise occurred and during the succeeding 3, 1-minute EEG epochs is shown. Again, as in Figure 2, arousal during fast-wave EEG sleep is shown on the left of the figure, and arousal during slow-wave EEG sleep is shown on the right of the figure. Redrawn from LeVere, Davis, Mills, Berger, & Reiter, 1976.

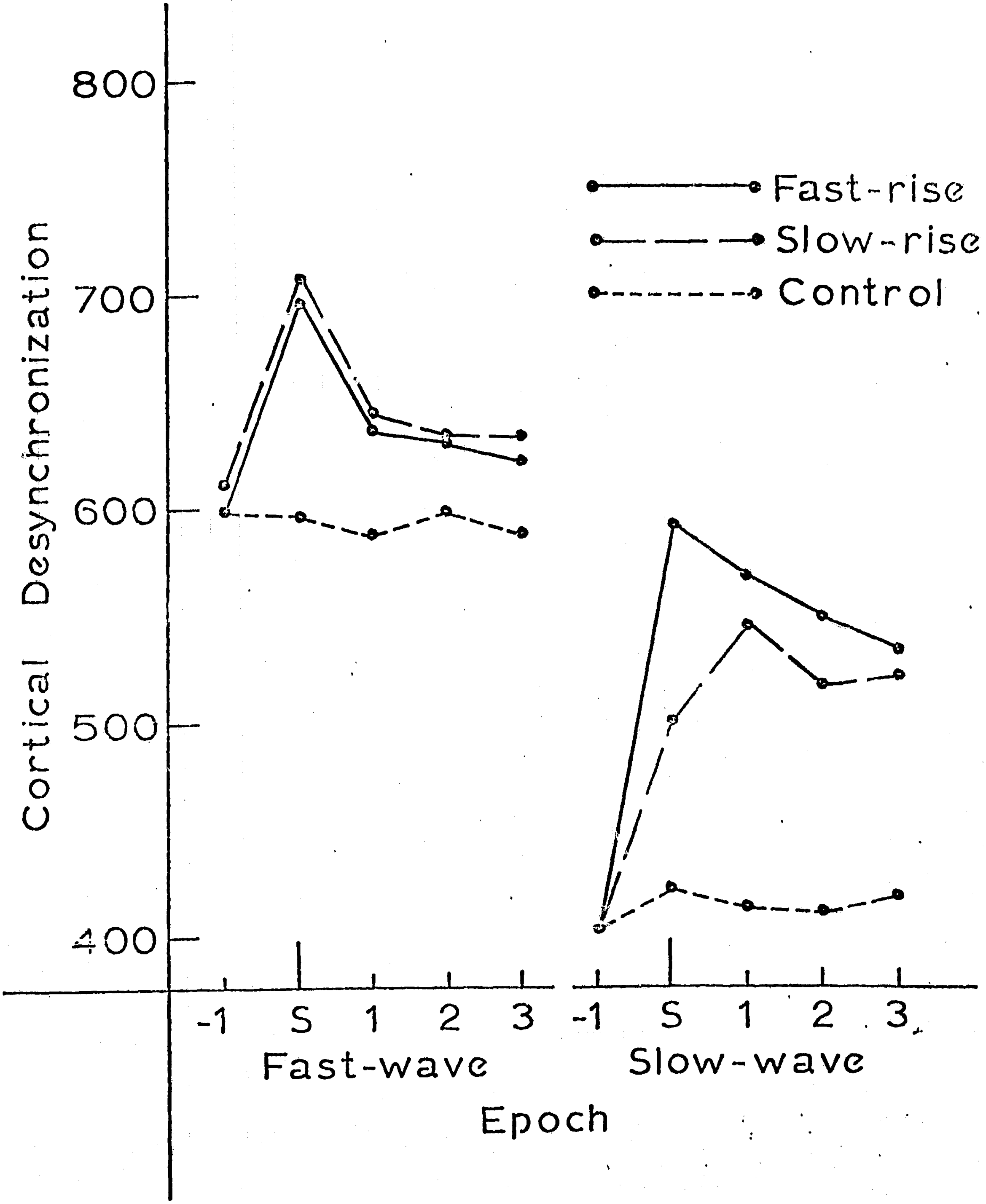

800
700
600
500
400
Cortical Desynchronization
Fast-rise
Slow-rise
Control
-1
S
1
2
3
-1
S
1
2
3
Fast-wave
Slow-wave
Epoch

Figure 4

Cognitive Value as a Predictor of Sleep Disruption

Since the basic, perhaps innate, parameters of loudness and annoyance showed little correlation with sleep disruption, we decided to investigate the properties of a higher level of abstraction (LeVere, Davis, Mills & Berger, 1976). Our question was simply whether the cognitive value associated with an auditory noise might carry over to differentially disrupt sleep. If this was so, then one might be able to predict sleep disruption on the basis of the dictates of traditional learning and attention theory. For example, it is typically believed that stimuli associated with high but inconsistent payoffs are more likely to command an individual's attention than stimuli associated with low but consistent payoffs or no payoff. Given this, one might then predict that those stimuli which are likely more to command the attention of an awake individual, because of a certain reinforcement history, might be also more likely to disrupt sleep.

To test this proposition, we trained our subjects in a situation which differentially rewarded responding to different auditory noises. During these training sessions, the subjects were required to respond, or not respond, to one of three different auditory noises. Responses to one of these noises resulted in high but inconsistent monetary payoffs. Responses to the second noise resulted in lower but consistent monetary payoffs. Responses to the third noise were unrewarded. Following five days of practice, the subjects slept for three successive nights in our laboratory where their sleep was disturbed by the same auditory noises previously used in the performance task. The sleep disruption associated with each of these noises during both fast-wave sleep and slow-wave sleep is shown in Figure 5. As in our previous experiments, all of the auditory noises were capable of producing some amount of arousal. But, again, like the results of our previous research, the auditory noises were only differentially effective during slow-wave sleep. Moreover, and also like our previous results, this differential effectiveness was not what one would predict on the basis of how an individual responds when awake. That is, it was not the inconsistent high payoff noise which produced the greatest amount of arousal but rather the consistent low payoff noise. In point of fact, the arousal produced by the high payoff noise was not significantly different from the arousal associated with the unrewarded noise.

Conclusion

Thus, we believe that we are faced with an inescapable conclusion. That is, that how an individual responds to an auditory stimulus when awake is, at best, only minimally predictive of how he will respond when asleep. And when there is some correlation, it is only for but a single parameter, loudness, and even then only during sleep characterized by fast-wave EEG activity. Apparently sleep is distinct enough that there are a unique set of laws which govern an individual's behavior when asleep. With respect to noise control, this is most unfortunate since much of the data which we might have used, which we had hoped would ease our work, is of relatively little utility.

Figure 5

Arousal produced by three different auditory noises with different cognitive values established through an association with different reinforcement histories. The figure is organized the same as Figure 2. Abbreviations: Hipay = high but inconsistent payoff or reward for responding; Lopay = low but consistent payoff or reward for responding; Nopay = no payoff or reward for responding; Control = cortical desynchronization recorded when a noise stimulus was not presented. Redrawn from LeVere, Davis, Mills, & Berger, 1976.

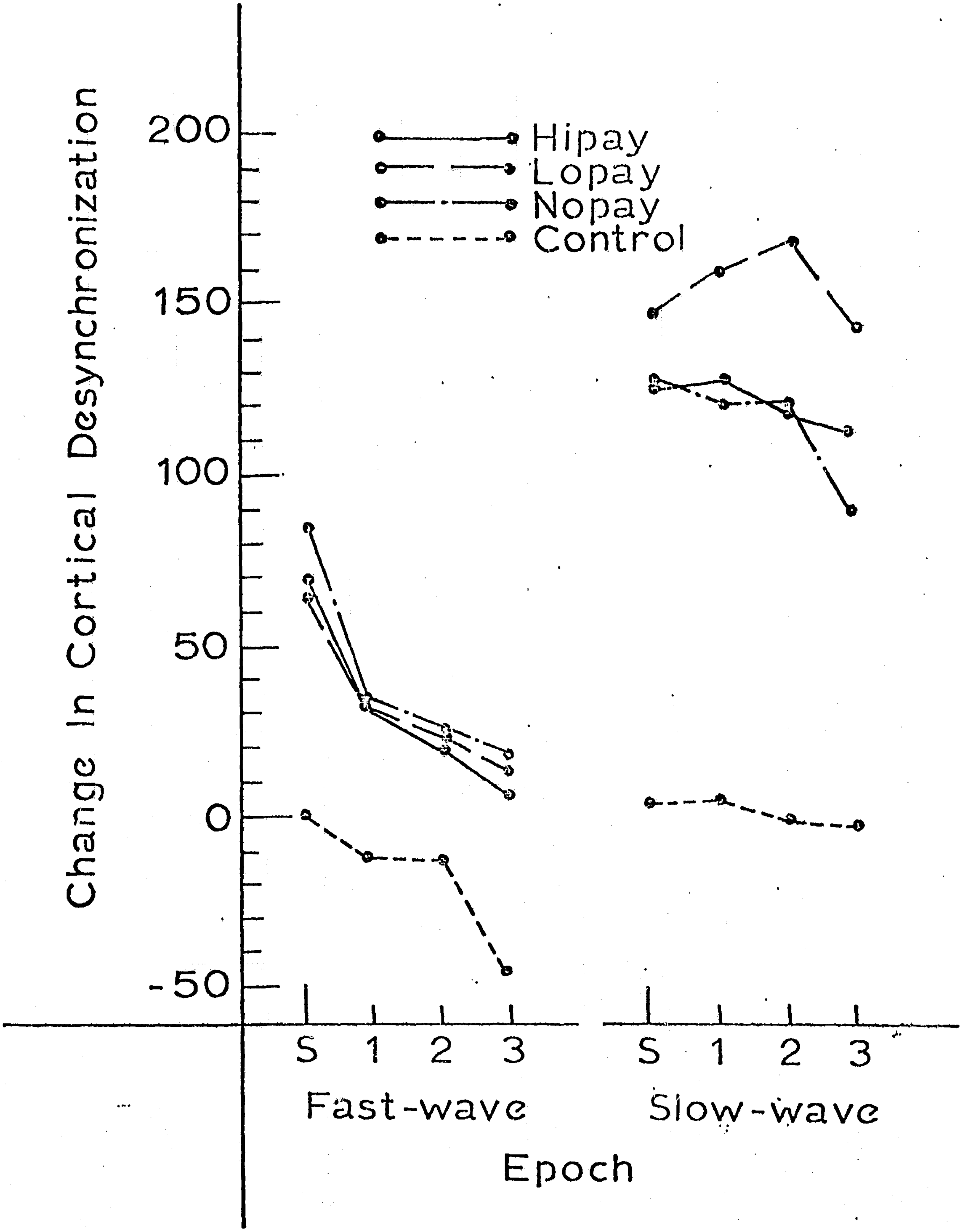

Change In Cortical Desynchronization
200
150
100
50
0
-50
Hipay
Lopay
Nopay
Control
S
1
2
3
S
1
2
3
Fast-wave
Slow-wave
Epoch

Figure 5

The Influence of Sleep Disruption on Waking Behavior

Whether or not it is possible to predict specific amounts of sleep disruption on the basis of an individual's awake behavior, the fact nonetheless remains that various parameters of auditory stimuli do differentially disturb sleep. Given this, we may turn the question over and ask whether differential amounts of sleep disruption may predict waking behavior. The last two experiments which I would like to describe are concerned with this possibility.

The Subjective Appreciation of Sleep Disruption

The first of these experiments was concerned with whether the individual could subjectively appreciate the changes we typically note in his electroencephalographic record (LeVere & Davis, 1977). To give the research a somewhat broader breadth -- and additionally relate it more closely to some of our other work -- we used jet aircraft flyover noise to disrupt the individual's sleep. There were two intensities of these jet aircraft flyovers, 80dB(A) and 65dB(A). We chose the 15dB differential because previous research from another laboratory (Borsky & Leonard, 1973) has indicated that this is sufficient to significantly reduce the annoyance reported by awake individuals.

Each of the subjects of this experiment slept in the laboratory for four successive nights. On different nights they experienced either 15 of the 80dB(A) flyovers or 15 of the 65dB(A) flyovers during either fast-wave EEG sleep or slow-wave EEG sleep. The subjects estimated how tired they felt before retiring at night and how well they thought they slept after awakening in the morning by completing a rating scale.

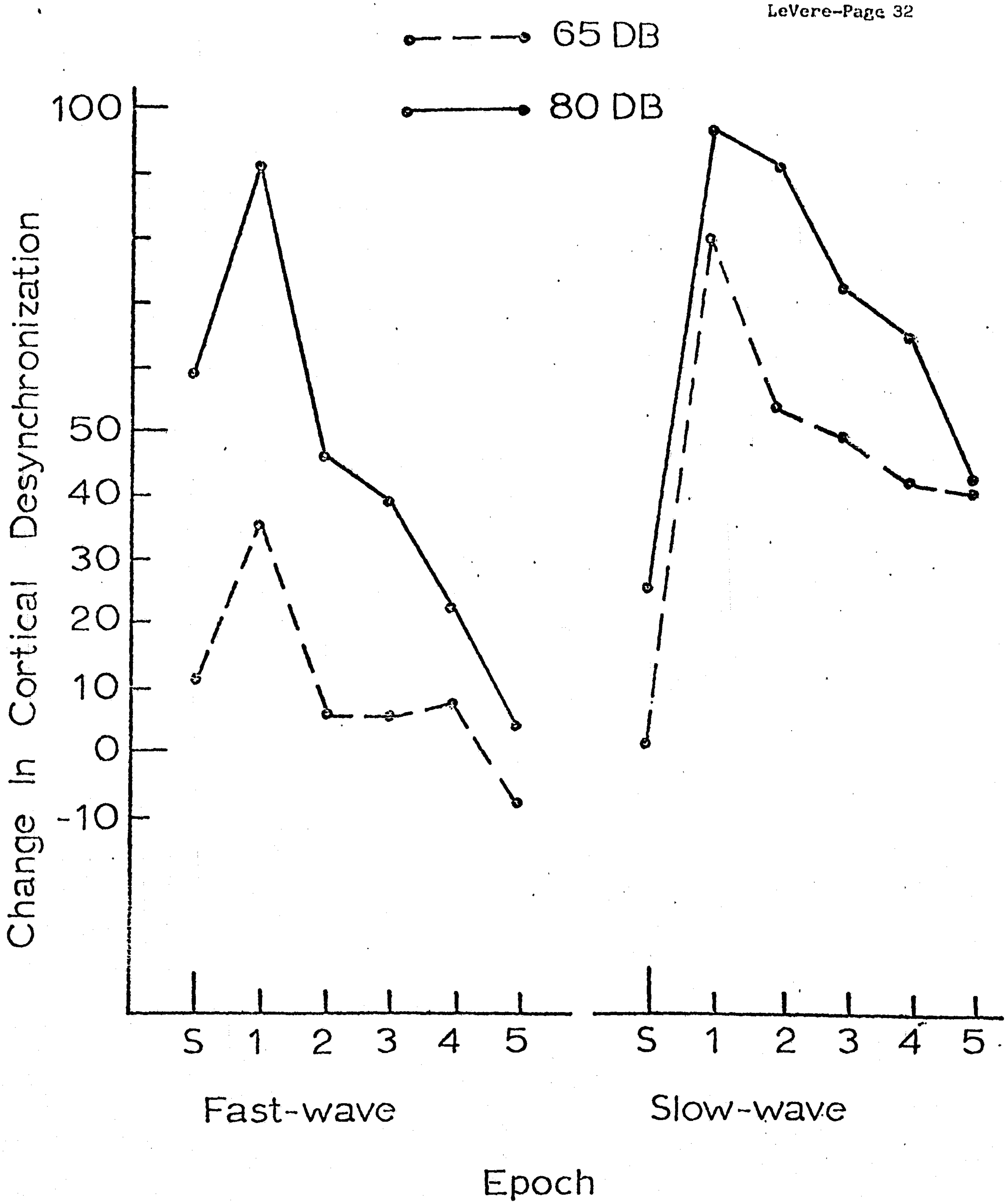
The results of this experiment were somewhat surprising. Firstly, as shown in Figure 6, the 15dB(A) reduction in jet aircraft flyover noise was associated with less sleep disruption only during fast-wave sleep. During slow-wave sleep any differences were statistically unreliable. Secondly, even though there was significantly less sleep disruption during the nights when fast-wave sleep was disturbed, the subjects did not detect this in the estimates of the quality of their sleep. In fact, in no case could we relate the subjects' rating of their sleep to the amount of sleep disruption which we detected. Nor could we relate the amount of sleep disruption which occurred to the estimates of how tired the subject felt before sleeping. Thus, how an individual subjectively felt did not necessarily reflect how easily his sleep would be disturbed or, when his sleep was disturbed, how much it was disturbed. And with regard to the decreased annoyance supposedly experienced by awake individuals when aircraft noise is reduced by 15dB(A), the present results again attest to the uniqueness of sleep.

The Effects of Sleep Disruption on Overt Performance

The proposition that an individual is unaware of the sort of sleep disruptions which typically occur in our experiments was at first somewhat disturbing. The reason being, of course, that this suggests that the sleep interference we have just been discussing is of little consequence

Figure 6

Arousal produced by jet aircraft flyover noise reaching a maximum of 65dB(A), dashed line, and 80dB(A), solid line. Figure is organized as Figure 2. Redrawn from LeVere & Davis, 1977.


65 DB
80 DB
Change In Cortical Desynchronization
100
50
40
30
20
10
0
-10
S
1
2
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Fast-wave
S
1
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Slow-wave
Epoch

Figure 6

to waking behavior. However, we believe that this is not necessarily so; and the final experiment summarizes why.

This final experiment was concerned with whether we might be able to detect the effects of minimal sleep disruptions not in subjective estimates but rather in overt performance (LeVere, Morlock & Hart, 1975). While it is not necessary to detail the reasoning -- which for the most part follows Wilkinson's eloquent analysis (1968) -- we chose to evaluate performance with a reaction time task having a strong short-term memory component. Summarily, the essential features of this task involved three stimulus lights and three response buttons. The subjects were required to press the "correct" response button as soon as possible after one of the stimulus lights was illuminated. The correspondance between the stimulus lights and response buttons was determined by a three-digit code which changed a number of times during the performance session. Moreover, the code was only shown to the subject during the first stimulus light presentation of the series of light presentations during which the particular code was in effect. Thus, after the first stimulus presentation, the subject was required to remember which code was in effect. We believe that this memory component, and the fact that we were concerned with performance and not acquisition, contributed to the sensitivity of our behavioral task.

Procedurally, each subject came to the laboratory and practiced the task for five successive days prior to sleeping. This was to eliminate any learning component when we tested for the effects of sleep disruption although it was not altogether successful. On the following week, the subjects slept in the laboratory for three successive nights. During these nights, the subject was disturbed by either 6 or 24, 15-second bursts of 80dB(A) noise, or left to sleep undisturbed. Additionally, on each night the subject performed the behavioral task both before retiring and upon rising in the morning. It must be emphasized, however, that the subject performed the task in the morning only after he had decided that he was fully awake and ready.

Figure 7 summarizes the sleep disturbance caused by the noise presentations. As can be seen from the figure, the subjects' average response to a noise occurrence was significantly greater when there were only six noise presentations as compared to when there were 24 noise presentations. And this was so for both fast-wave sleep and slow-wave sleep. We attribute this differential responding to the occurrence of habituation.

Figure 8 shows the subjects' mean reaction time during the five practice days and during the performance of the task on each night prior to sleep. As is evident from the figure, there is a significant improvement over the five days of practice and also during the three pre-sleep performance sessions indicating that the acquisition had not entirely stabilized by the time the subject slept. To control for performance changes due to learning, we thus evaluated morning performance by subtracting the subject's mean response time during the previous night's performance from his mean response time during his morning performance. This data is presented in Figure 9 and clearly indicates that when the subjects' sleep was disturbed by six stimulus presentations, there was virtually no effect on morning performance. On the other hand, when the subjects's sleep was disturbed by 24 stimulus presentations, there was over a fourfold increase in mean reaction time which is, of course, quite significant.

Figure 7

Average arousal produced by auditory noise when 24 presentations occurred during the night (solid line) and when 6 presentations occurred during the night (broken line). The dashed line represents random selections of EEG activity during nights when the individual's sleep was undisturbed. The figure is organized similarly to Figure 3. Redrawn from LeVere, Morlock, & Hart, 1975.

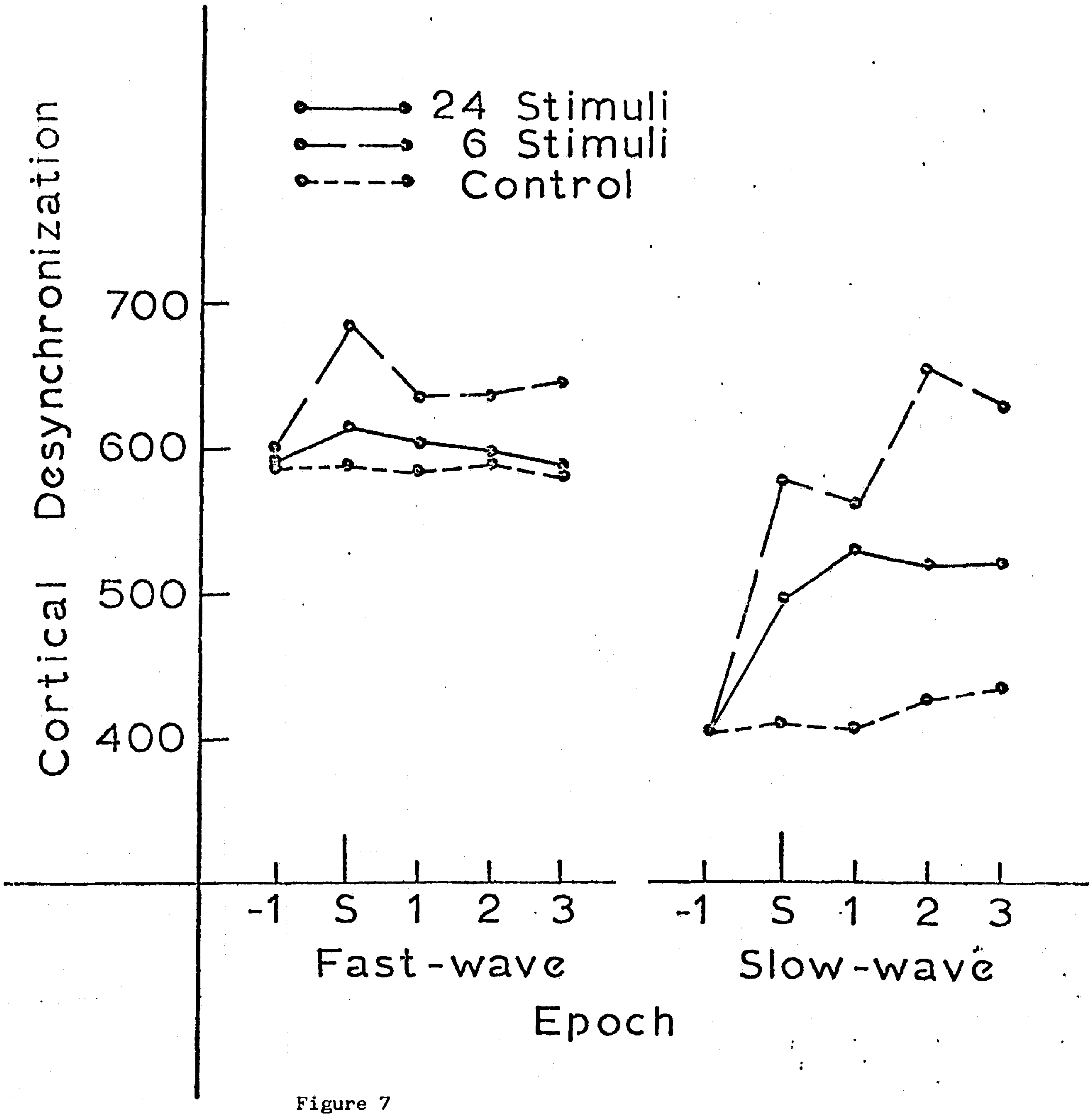
24 Stimuli
6 Stimuli
Control
Cortical Desynchronization
700
600
500
400
-1
S
1
2
3
Fast-wave
-1
S
1
2
3
Slow-wave
Epoch

Figure 7

Figure 8

Decrease in response latency over the five practice sessions before the subject slept in the laboratory and during the presleep performance sessions when the subject slept in the laboratory. Note that performance had not stabilized during the practice sessions so that morning performance following different amounts of sleep disruption was evaluated by determining the difference between the previous night's presleep performance and the following morning's performance. Redrawn from LeVere, Morlock, & Hart, 1975.

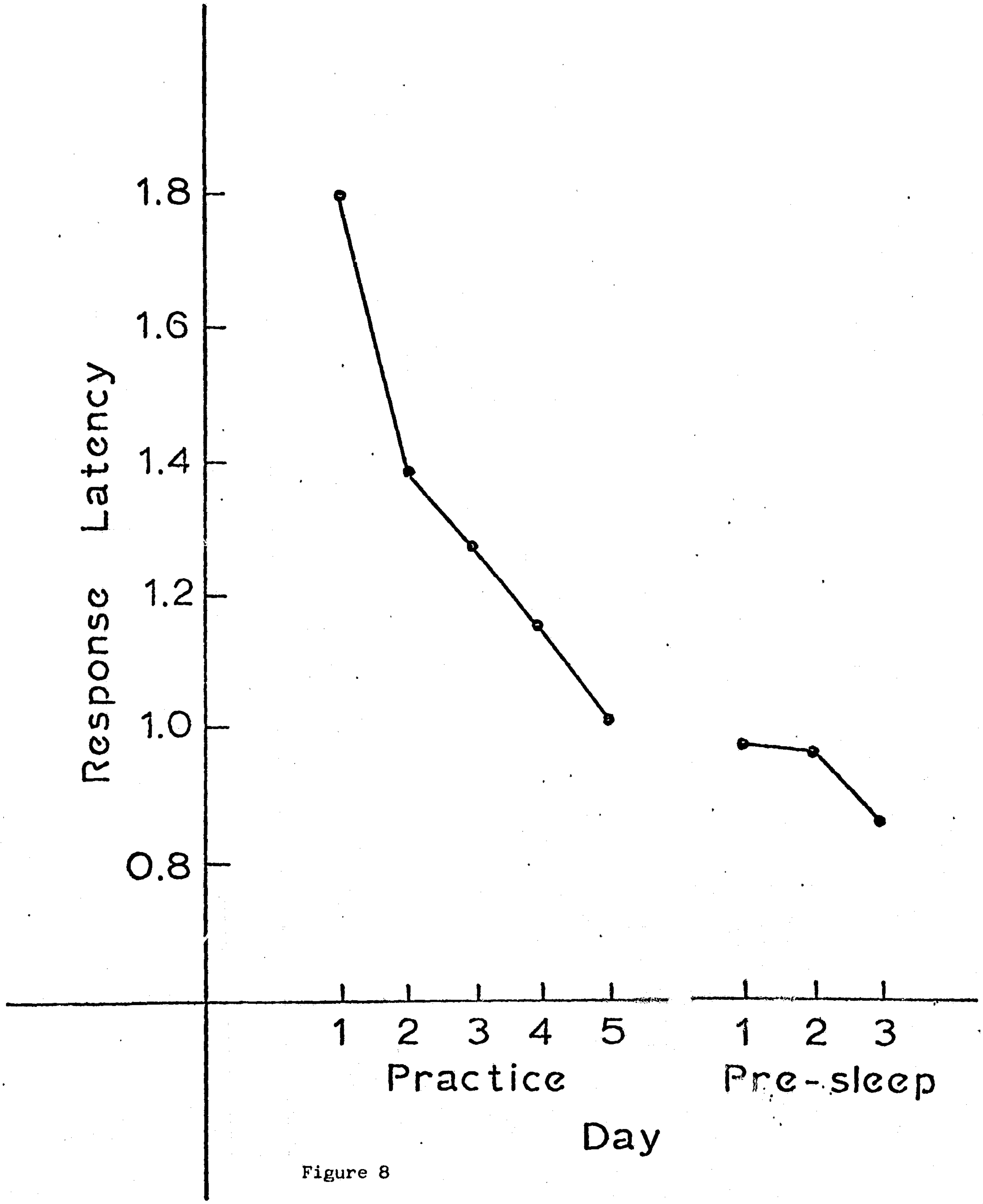
Response Latency
1.8
1.6
1.4
1.2
1.0
0.8
1
2
3
4
5
Practice
1
2
3
Pre-sleep
Day

Figure 8

Figure 9

Difference between the previous night's presleep performance and the morning performance when 6 or 24 stimulus presentations disturbed the individual's sleep or the individual was allowed to sleep undisturbed. Redrawn from LeVere, Morlock, & Hart, 1975.

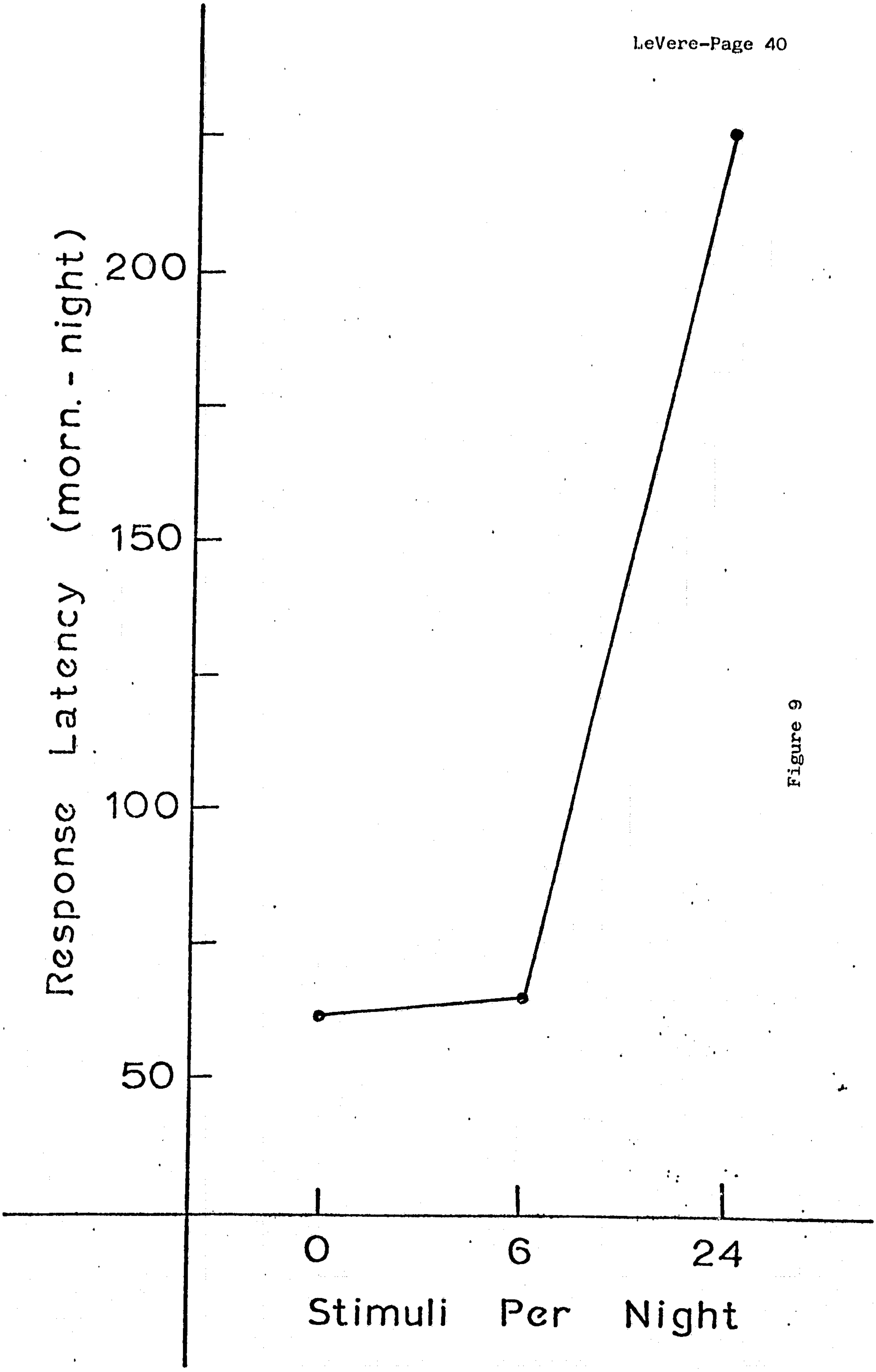
Response Latency (morn. - night)
200
150
100
50
0
6
24
Stimuli Per Night

Figure 9

Thus, although the individual was, on the average, less aroused by each of the 24 noise presentations, these nonetheless produced a greater change in waking performance. Apparently arousal per se is not the controlling factor. What is the controlling factor, we believe, is the total amount of sleep disruption, which, for the 24 presentations was far greater than for the six presentations. Moreover, there was considerably more total slow-wave sleep disruption on the nights when the 24 noise presentations occurred. In fact, the amount of fast-wave sleep disruption was quite similar on both the 6 and 24 noise presentation nights. This then suggests that it is perhaps slow-wave sleep which is more intimately related to waking performance. If this is so, and at present it is just speculation, then our previous data indicating that slow-wave sleep is more sensitive to the various parameters of auditory noise, may gain some considerable significance.

Thus, when one places certain demands on behavior, in the present case memory demands, sleep disruption can have a significant effect on waking performance. Some experts have, however, argued that because these effects are in terms of millisecond changes they are really of trivial consequences. But it is important to remember that we are here dealing with very fast behavioral processes. As such, it is total nonsense to speak in absolute terms. Rather one must consider relative effects and, as we have noted, the sleep disruption reported here produced no less than a four-to fivefold increase in response time -- a deficit which we believe is anything but trivial.

Conclusions

From these data we may draw a number of conclusions. Firstly, sleep is important to the individual. This particular conclusion is not terribly surprising or unique to our research. For example, the well-known "rebound effect" following selective sleep disruption clearly indicates that sleep is a need state (see Kales, 1969). Moreover, the need to sleep is painfully apparent to any parent who has dealt with a small child who has missed a nap. What the present research does is simply provide some initial specification of what waking behavior processes may be most dependent upon adequate sleep. In this regard, we believe that simpler behaviors involving principally motor activity, such as X'ing out zeros, uncomplicated reaction time or tracking tasks, are relatively immune to sleep disruption. Provided, of course, that one ignores what has been called microsleep which may or may not be altogether appropriate. On the other hand, more complex behaviors involving some cognitive component such as learning or memory may be quite dependent upon adequate sleep. And the data is not only what we have reported but additionally a variety of researches including both human and animal subjects (Freeman, 1972; Hartmann, 1973; Williams, Gieseking & Lubin, 1966).

Thus, we believe that as much as it is necessary to accept that auditory noise can disrupt sleep, we also believe that it is just as necessary to accept that waking performance may suffer following sleep disruption. Certainly, there is much to be done in terms of specifying this performance impairment in terms of the behaviors involved, the duration of the effect, and whether the impairment may interact with other behavioral parameters. However, just as certainly there now is little solace in the classic reaction time research which minimized the effects of sleep disruption.

The immediate problem then is one of controlling noise exposure to insure adequate sleep. While at first glance this would seem simple enough, a closer inspection shows this to be far from the truth. And this is particularly so when one considers the numerous and torturous cost-payoff relations which are involved. Some auditory stimulation is most probably acceptable, perhaps necessary, so that the question is one of degree and selective control. But the problem is that we have at present only the most elementary appreciation of how an individual responds to different types of auditory noise during sleep. Moreover, sleep is not a unitary process and an individual's response is clearly different when asleep than when awake. This then makes simply imposing a 5, 10, or 15dB(A) penalty to nighttime noise only the grossest, if at all adequate, corrective measure. Perhaps as a stop-gap solution such a penalty is satisfactory. But, the real solution, we believe, is to determine how an individual responds to noise when asleep because then, and only then, can we be cost effective in our approach to noise control.

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