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MEASURES OF NOISE LEVEL: Their Relative Accuracy in Predicting Objective and Subjective Responses to Noise During Sleep

Office of Health and Ecological Effects
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MEASURES OF NOISE LEVEL: THEIR RELATIVE ACCURACY IN PREDICTING OBJECTIVE AND SUBJECTIVE RESPONSES TO NOISE DURING SLEEP

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ABSTRACT

A review of domestic and foreign scientific literature on the effects of noise on human sleep indicates that no sleep disruption can be predicted with good accuracy (correlation coefficients of about 0.80) if the noise descriptor accounts for the frequency-weighted spectrum and the duration of the noise. Units such as EdBA, EPNdB, and SENEL are better predictors than a unit such as maximum dBA. Furthermore, no sleep disruption can be predicted more accurately than arousal or behavioral awakening responses.

Some evidence suggests that questionnaires about subjective sleep quality should contain items dealing with the subject's (a) sense of well being on arising, (b) sense of the general quality of his sleep, and (c) estimates of how long it took to fall asleep. Scores on these items can be summed to develop a Composite Sleep Quality measure. Although the amount of evidence is limited, such Composite Sleep Quality is correlated highly (about 0.90) with Composite Noise Rating (CNR) when units of EPNdB or EdBA are used to calculate CNR. Other techniques for calculating the total nighttime noise environment, such as L_{eq} and NNI, have some shortcomings with respect to their ability to predict Composite Sleep Quality.

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I INTRODUCTION

Sleep disturbance by noise is a common complaint. Despite the prevalence of complaints, however, sleep investigators are not sure what the implications of the complaints are with respect to physiological or psychological health. On one hand, the degree of actual (measurable) sleep disturbance is of minor significance when compared with the effects of much higher noise levels or other stresses experienced daily at work and at home. On the other hand, perhaps sleep disturbance is of major significance if a person feels his sleep has been disturbed severely and, as a consequence, feels lethargic, nervous, and unable to perform or work at his usual level of efficiency. Our inability to provide conclusive answers to the physiological and psychological implications of sleep disturbance stems in part from the fact that investigators have not been able to define and demonstrate the function, or functions, of sleep, and in part from the fact that investigators have neither described the physical characteristics of the stimuli uniformly nor used the same response measures.

Consonant with this analysis, Lukas[1] recently proposed a rationale for and recommended use of a single measure of significant sleep disturbance (a change of the electroencephalographic pattern to at least one "shallower" sleep stage or No Sleep Disruption) and also recommended a metric (in units of EdBA or EPNdB) to describe the physical characteristics of noise.

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[1] J. S. Lukas, "Sleep and Noise: A literature Review and a Proposed Criterion for Assessing Effect," J. Acoustical Soc. Amer. (December 1975), in press. This monograph provides a review of the experimental literature and may be considered a part of this report.

This report is a review of most of the recent experimental sleep and noise literature.[2] It provides some additional points to the earlier scatter plot of the frequency of No Sleep Disruption at various noise levels.[1] In addition, we have developed a tentative composite measure of subjective sleep quality and, in so far as the data permit, show its relationship to composite measures of the nighttime noise environment.

[2] Several reports, particularly those from Eastern European nations, were requested but not received.

II REPORTS REVIEWED

A list of all the papers reviewed is provided in the Bibliography. Those not included or referenced in the body of this report have been omitted for one or several of the following reasons: (a) The papers inadequately (for our purposes) describe the physical characteristics of the stimuli--telephones, bagpipes, doorbells, Chinese gong[3]--or names spoken forward and backward at approximately the same intensity;[4,5] (b) the papers present uncommon techniques for scoring the electroencephalographic (EEG) response to stimuli;[6,7,8] (c) the studies confine

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[3] W. P. Wilson and W.W.K. Zung, "Attention, Discrimination, and Arousal During Sleep," Arch. gen. Psychiat., Vol. 15, pp. 523-528 (1966).

[4] I. Oswald, A. M. Taylor, and M. Treismann, "Discriminative Responses to Stimulation During Sleep," Brain, Vol. 83, pp. 440-453 (1960).

[5] G. W. Langford, R. Meddis, and A.J.D. Pearson, "Awakening Latency from Sleep for Meaningful and Non-Meaningful Stimuli," Psychophysiology, Vol. 11, pp. 1-5 (1974).

[6] T. E. LeVere et al., "Arousal from Sleep: The Differential Effect of Frequencies Equated for Loudness," Physiology and Behavior, Vol. 12, pp. 573-582 (1974).

[7] B. Metz and A. Muzet, "Effets propres et interaction de l'elevation du niveau sonore et de la temperature ambiante sur le sommeil," Centre D'Études Bioclimatiques du CNRS, Strasbourg, France (April 1975).

[8] Y. Osada et al., "Sleep Impairment Caused by Short Time Exposure to Continuous and Intermittent Noise," Bull. Inst. Publ. Health, Vol. 18, pp. 1-9 (1969).

stimulation to only certain sleep stages;[9,10] and (d) the papers are reviews.[11,12,13]

The research studies reviewed in detail, as well as a summary of their major design characteristics, are listed in Table 1. Table 1, particularly the Stimulus Type and PNL (perceived noise level) columns, reveals the diversity of types and levels of stimuli studied in various laboratories. Note, however, that about 75 percent of the test stimuli were transportation noises, and 76 percent of these were from sub- or supersonic jet aircraft. Therefore, it is reasonable to exercise some caution in generalizing the results to situations other than transportation noise; to suggest however, the data presented in this report indicate that similar results were obtained when nontransportation noises were studied. For example, such stimuli as bursts of pink, shaped white noise, and pure tones produced results consistent with those obtained when transportation noises were the test stimuli.

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[9] H. Firth, "Habituation during Sleep," Psychophysiology, Vol. 10, pp. 43-51 (1973).

[10] F. B. Keefe, L. C. Johnson, and E. J. Hunter, "EEG and Autonomic Response Pattern During Waking and Sleep Stages," Psychophysiology, Vol. 8, pp. 198-212 (1971).

[11] M. E. Dobbs, "Behavioral Responses to Auditory Stimulation during Sleep," J. Sound Vibration, Vol. 20, pp. 467-476 (1972).

[12] H. L. Williams, "Effects of Noise on Sleep: A Review," in Proceedings International Congress on Noise as a Public Health Problem, W. D. Ward, ed., pp. 501-511 (U.S. EPA No. 550/9-73-008, 1973).

[13] J. D. Miller, "Effects of Noise on People," pp. 58-78 (U.S. EPA No. NTID 300.7, 1971).

Table 1

DESIGN CHARACTERISTICS OF NOISE STUDIES PROVIDING DATA FOR THIS REPORT

Code Used in Figures	Study	Stimulus Characteristics: Type	dBA-Max	PNL[1]	Duration (seconds)	Number per Night	CNR	NNI	$Leq_{7.5}$	Subjects: Number and Sex	Age (years)	Response Measures	Notes
▲	**Anonymous (Japanese Research Group on the Effect of Noise) (1971)**	Jet aircraft noise	65.0 75.0 85.0	88.8 98.8 108.8	10.3	About 54 in random order	121.8	50.5	63 8	8 males	College age (?)	EEG, several physiological and psychological	1 baseline night, followed by 2 or 3 nights with noise. No indication of background noise level.
×	**Collins and Iampietro (1973)**	Simulated sonic booms	68.0	79.0	0 284	8 at hourly intervals	88 0	12.5	35.7	24 males	8 each, 21-26, 40-45, 60-72	EEG, other physiological, subjective, performance	21 consecutive nights, nights 3-5 were baseline, 6-17 were test nights, 18-21 were recovery nights Estimated background ≈35 dBA.
	Globus et al.[9] (1973)	Jet aircraft, near or far from airport	77.0 (mean)	101.0	8.0	46 0	118.7	49 0	58 3	6 couples	45, average	EEG, subjective	No clear indication of background level, however, a subsequent report by Pearsons et al., suggests 40 dBA.
			57.0 (mean)	81.0	8.0	17.0	96.5	19.5	40.9	5 couples	≈45		
♦	**Herbert and Wilkinson (1973)**	Pairs of clicks, 1 s between clicks (1800 Hz)[4]	65.0 75.0 80.0 90.0	83.0[5] 93.0 98.0 108.0	See footnote 6	1370 in random order	131.5	69.6	46.3	10 males	18 to 35	EEG, performance	1 night of noise, 2 control nights. Average interval between click pairs = 2 s
	Johnson et al. (1973)	Tone-like "pings," 22 s between pings (3500 Hz)	82 0 87.0 92.0	92.8 97.1 102.2	0.66	1113, fixed interval	123.3 127.6 132.7	58.5 62.8 67.9	66.4 71.4 76.4	20 males	18 to 33	EEG, motor, physiological, performance, psychological	55 consecutive nights, with noise during the middle 30 nights, 10 nights at each level. Noise on for 24 hours daily.
●	**Kramer et al. (1971)**	Shaped white noise	n a.	105.5	Continuous	An average of 8	112.5	38.0		2 males	25	EEG, psychological performance	15 consecutive nights. Background noise = 42 dBA.
×		Simulated sonic boom	n.a	106.5 To stage shift	0.2		113.5 112.6	40.0 39.1 See*		2 males 2 males	50 (1 atypical subject excluded) 70		Increased noises until subjects awakened or changed sleep stage, white noise increased 1 dB 6 s, impulse increased 10 dB/min (1 presentation).
◈	**Ludlow et al., 2 studies (1972)**	Simulated sonic boom Morgan and Rice	64.7 67.7 71.1	77.5 80.5 83.9	≈0.5	12/night, fixed intensity, random intervals	86.3 89 3 92.7	13.7 16.7 20.1	37.5 38 0 38.9	8 males	17 to 30	Behavioral awakening, subjective quality	3 adaptation nights followed by 3 test and 1 control night (7 consecutive nights in total), distributed noise and control nights.
◊		Ludlow and Morgan	62.5 72 5 78.0	75 3 85.3 90.8		8/night, fixed intensity, random intervals	82 3 92.3 97.8	8.8 18.8 24.3	37.2 38.8 41.6	8 males	21 to 30		6 adaptation, 6 noise, and 2 control nights (14 consecutive nights in total), distributed noise and control nights. Background noise ≈37 dBA.[7]
	Lukas et al. (1970)	Simulated sonic booms	68.0 73.5 79.0	78.0 83.5 89.0	0.28	20/night 12/night	118.8,124.8, 130.8 116.6,122.6, 128.6		50.8 48.8	2 females 2 males	7 and 8 41 and 54	EEG, behavioral awakening	4 or 5 accommodation nights followed by 16 test nights, nonconsecutive, 2 nights/week, the 2 stimulus types presented at a single intensity on any night, level generally increased in steps over first 6 nights. Background noise ≈35 dBA.
		Jet flyover noise	68.0 74.0 80.0	110.8 116.8 122.8	5.0	6/night	113.6,119.6, 125.6		45.8	2 males	69 and 72		

⊠	Lukas et al. (1971)	Simulated sonic booms	68.0 73.5 79.0 84.0	78.0 83.5 89.0 95.0	0 26 0.29	Usually 16/night, twice at each level, sequence and level at random	105.9	33 9	47.6	2 males and females 4 males	5 to 8 45 to 57	EEG, behavioral awakening, subjective quality	27 nonconsecutive nights, usually 2 nights per week (6 or 7 accommodation nights, followed by 20 noise-test nights). Background noise ≈32 dBA.
⊡		Jet flyover noise	63.0 69 0 75.0 81.0	85.0 91.0 97 0 103.0	4.0					4 males	69 to 75		
⊗	Lukas et al. (1972)	Simulated sonic booms	68.0 79.0 84 0	78.0 89.0 95.0	0.30	Average of 10/night, twice at each level, randomized	108.2	35.6	51.9	8 females	29 to 49	EEG, behavioral awakening, subjective quality	14 consecutive nights and 3 accommodation nights, of the 14, nights 1, 2, 9, 10, and 14 were control nights and the remainder were test nights. Background noise ≈32 dBA.
⊙		Jet flyover noise	68 0 80.0 86.0	90 0 102.0 108 0	4.0								
◎	Lukas et al. (1973)	DC8 on landing, Treated Nacelles	60.4 78 4	84.4 102.4	10.5 9.0	Average of 9/night, twice at each level, randomized	109.0	34.4	50.3	4 males	46 to 58	EEG, behavioral awakening	The same as in Lukas (1972).
○		DC8 on landing, Untreated Nacelles	61.1 78.9	85.3 103.0	7.5 7.5								
▲		Pink noise burst	59 9 78 0	73.8 92.0	3.3 3.5								
◙	Lukas et al. (1975)	Blown-flap STOL sideline noise	64.8 76 8 82.8	92.3 104.3 110.3	25.5	An average of 21/night, 2 at each intensity nightly, in random order	115.0	43.9	54.6	8 males	35 to 56	EEG, behavioral awakening	16 consecutive nights. Nights 1, 2, 3, 4, 11, 12, and 16 were accommodation and control nights, the remainder were test nights. Average background noise ≈33 dBA.
▣		Blown-flap STOL takeoff noise	63.0 75.0 81.0	90.4 102.4 108.4	9.3								
⊠		Turbon fan STOL sideline noise	57.8 69.8 75 8	84.5 96.5 102.5	24.4								
▽		Pink noise burst	59.1 71 1 77 1	77.1 89.1 95 1	2 1								
	Metz and Muzet (1975)	Shaped white noise as simulated truck passage	80.0	106 1	8.0 (see notes)	80	126 9	33 1	86 0	18 males	19 to 27	EEG, subjective, ECG, movements, temperature	Triangular pulses of noise rising and falling at 2.5 dB/s or 5 dB/s, 3 groups, low noise and low temperature, high noise and low temperature, and low noise and high temperature, 2 quiet nights, 2 noise nights, 1 quiet night Background noise 43 dBA.
			65 0	103 1 91 1 88 1	4.0 8 0 4 0	80 80 80	111.9	18 1	83 0 71.0 68.0				
	Muzet et al (1973)	Study by Schneider (1973)											
	Muzet (1974)	A review of research methods and some of the data of Schneider (1973) and Schieber et al (1968)											
	Olivier-Martin (Schneider) et al. (1972)	Study by Schneider (1973)											

*Nights with impulse and continuous, 39 1

		Automobile traffic noise	80.0 81.0	101.9 102.(	4.0 estimated	H B (see notes)	131.8	69.6	70.0 68.2	9 males	Young adults	EEG, EMG heart rate	H = 4.3 (average) noises/min, traffic noise between 1000 and 2400, B = 1.8 (average) noises/min, noise between 2400 and 0400, during 8-hour test night an hour of heavy traffic (H) alternated with an hour of light traffic (B), order of heavy and light counterbalanced, 2 noise and 1 control night. Background noise = 48 dBA.
■	Schneider (1973)	Jet takeoff (90 s) (30 s) (90 s) (30 s)	77 0 80.0 82.0 96.0	109.5 101 0 118.0 119.5	22.0 2 0 30.0 3.0	32 in random order	128.9	58.6	63 7	9 males 9 females	19 to 24 19 to 23	Subjective quality, EEG, performance	1 night of noise between 2 controls. Factor analysis of subjective responses Background noise = 35 dBA (±5).
	Scott (1972)	Continuous white noise	93 0	152.5	8 hours	Continuous	150.5		93.0	8 males	18 to 20	EEG	8 consecutive nights, 5 in quiet and the middle 2 nights in noise. A control group slept during an opposite sequence of nights, but insufficient data reported to incude here. Background (quiet) ≈45 dBA.
▲	Thiessen (1970)	Tractor-trailer (motor freight)	40.0 45.0 50 0 55.0 60.0 65.0 70.0 75.0	63 5 68.7 73.7 78 7 83.7 88.7 93.7 98.7	4 6	7 during first 6.5 hours of sleep, presumably at random in time and order	98.4	24.9	45.0	12 males	Primarily college age	EEG	No indication of number of nights per subject, consecutive or nonconsecutive nights. Background noise = 35 dBA.
◊	Zimmerman (1970)	800 Hz tone	66 5 see *	69.1	1.0	Generally 4 tests night	76.7	-0.1	36.7	32 males (?)	Mean 21 5	Verbal awakening threshold	Tone on for 1 s and off for 8 s, at each step intensity increased 5 dB, tested after 3.5 hours of uninterrupted sleep. No indication of background noise level.

*Averaged overall sleep stages and "Light and Deep" sleeping groups.

[1] Perceived noise level in units of EPNdB calculated using duration between 10-dB downpoints is the effective duration and using 0.5 s as reference duration Units of EdBA can be estimated by subtracting 13 from the given values.

[2] Duration between 10-dB downpoints used to calculate EPNdB.

[3] CNR, Composite Noise Rating, and NNI, Noise Number Index, after Burns, were calculated using EPNdB as the basic unit of noise level. Kryter's Formula 7 (p 484) was used in these calculations. $Leq_{7\ 5}$ after EPA's "Information" document (1974), 7.5 hours considered to be standard duration.

[4] Kryter (p. 236) citing Ward suggests that clicks are about 0 002 s duration

[5] 15 added to dBA levels (Kryter, p 306) to estimate PNdB

[6] Interval between stimuli < 1 s It is assumed the subject perceives a single stimulus of single intensity, therefore, 3 dB added to peak level to obtain EPNdB

[7] Ludlow and Morgan state that the noise pollution level 46 5 dBA in one room, and 44.6 dBA in the other We assume an average value of 45 dBA and - 3 0 dB, Lnp = Leq + 2 56 σ (Robinson)

[8] EPNdB for continuous noise was calculated assuming that it was present for about 160 s before the subjects responded. The rationale when the overall levels of the white and background noises were equivalent (about 69 dB SPL), the white noise showed higher levels (14 5 and 22dB, respectively) in the 1 kHz and 2 kHz bands than did the background noise. (The higher bands show a similar pattern, but differences of lesser magnitude.) Therefore, when the overall levels were equivalent, the subjects probably heard the white noise Because Kramer et al. state that the stimulus "... was initially presented at a predetermined level below the ambient level of the room . ." (p 6), we assume that level was below an audible level to an awake, listening individual Quantitatively, the overall level of the white noise should have been, at most, 47 dB at its onset. For our calculations, we assumed a level of 45 dB SPL

[9] The number of noises per night and CNR levels were estimated using data provided in Pearsons et al that specify noise levels in greater detail.

Table 1 (Concluded)

Code Used in Figures	Study	Stimulus Characteristics: Type	dBA-Max	PNL[1]	Duration (seconds)	Number per Night	CNR[2]	NNI[3]	$Leq_{7.5}$[4]	Subjects: Number and Sex	Subjects: Age (years)	Response Measures	Notes
	Osada et al. (1968)	White noise	40.0	98.0	Noise on continuously for 6 hours	1 6-hour period each night, no data regarding fluctuations	96.0		40.0	5 males	Students	EEG, ECG, G.S.R., biochemical (blood, urine)	Apparently each subject spent 6 nights in lab--the first night was a control--and one night in each of the other noise environments. Background noise ≈30 dBA (from 1975 paper).
		Traffice noise	40.0	87 0			85.0		40.0				
			55 0	102.0			100.0		55.0				
		Factory noise	40.0	87.0			85.0		40.0				
			55.0	102.0			100.0		55.0				
	Osada et al. (1969)	White continuous	40, 60	87.8 / 107.8	Continuous noise = 2.5 min, pulsed - 5 min, 10 s on and 10 s off	1 of each type in random order	106 7	34.1	45.3	5 males	Students	As above	Each subject, spent 3 nights in the lab, exposure on all 3 nights, beginning each half-hour from 12 to 5 30 am. Background noise ≈ 30 dBA.
		White pulsed	40, 60	77.6 / 97 6									
		1/3 octave at 125 Hz, Continuous	40, 60	56 2 / 76.2									
		1/3 octave at 125 Hz, Pulsed	40, 60	55.9 / 75.9									
		1/3 octave at 3150 Hz, Continuous	40, 60	76.0 / 96.0									
		1/3 octave at 3150 Hz, Pulsed	40, 60	75.8 / 95.8									
	Osada et al. (1972)	Pink noise, continuous	40.0	94.0	3 hours	2	97.0	18.5	39.0	5 males	Students	As above	Each subject spent 5 nights in lab, one night for each noise and level, noise on from 12 00 to 2 00 and from 4 00 to 7 00; 21 stimuli during each period. Background noise ≈30 dBA.
		Train noise	50.0	76.3	14	42	90.5	20.6	37.2				
			60.0	86.3			100.5	30.6					
		3 jet aircraft noises	50.0	74.5 / 75.3 / 76.8	12	42	89.9	20.0	32.5				
			60.0	84.5 / 85.3 / 86.8	12	42	99.9	30.0	39.6				
△	Osada et al. (1975)	Train noise, while passing over a bridge	40.0	64.0	8	18 noises/night, once every 20 minutes	76.6	2 8	30.1	6 males	Students	As above	Each subject spent 6 nights in lab, one night at each noise level plus one night in background of 30 dBA.
			50.0	74.0			86.6	12.8	30.9				
			60.0	84 0			96.6	22.8	35 2				
			70.0	94.0			106.6	32.8	43.8				
			80.0	104 0			116.6	42 8	53.7				
	Pearsons et al. (1974)	Jet aircraft termination of night operations, Before	77.0 (mean)	101.0	8.0	46	118.7	49 0	58.3	6 males and females	45	EEG, subjective	Background noise ≈ 40 dBA
		After	51.0 (mean)	75.0	8 0	13	109.6	37.1	40.2				
	Schieber et al (1968)	White noise ramp 0 to 86 dB in 10 s	73.0	89.0	1 0	24, only during last 4 hours of sleep, at intervals of 5, 10, or 15 min	100 8	29.7	43.2	6, sex not given	Age not given	EEG	2 noise and 1 control night. Background noise = 42 dBA.
		Jet, takeoff and flyover	87.0	112 0	16.0	W (see notes)	122 2	54.6	63.3	9, sex not given	Age not given	EEG, EMG	Condition W = 32 stimuli/8 hours (2 of each type of noise hourly), V = 16 noises/8 hours, alternating hours with noise, noises at 15-min intervals, 2 noise, 1 control night. Background noise = 44 dBA.
			72 0	97.0	18 0	V (see notes)	119.1	35.1	60.3				

III RESULTS

Factors Related to Noise Sensitivity

Reviews published in the Journal of Sound and Vibration,[14] and by the Environmental Protection Agency[12] suggest that several factors affect responses to noise during sleep. These responses may be manifested by brief occurrences of certain EEG patterns, a change in sleep stage towards shallower sleep, or behaviorally defined awakening. This reviewer found little reason to delete or add to the factors affecting sensitivity to noise during sleep. The factors are described briefly below.

(1) Age. The older the subject the more likely is he to respond.

(2) Sex. Women tend to be more responsive than men at comparable ages, but there is some indication that college-age women are less responsive than college-age men.

(3) Sleep stage. In general, people are most responsive during sleep stage 1, next during stage 2, and then during stages REM and Delta. To some extent, relative sensitivity to noise during stages Delta and REM depends upon the specific response measure used and the meaning of the noise. In general, noise during stage Delta elicits an EEG response at nearly the same intensity needed to elicit that EEG response during stage REM, but the subjects appear unable to respond behaviorally to stimuli during stage Delta. This lack of behavioral response is not apparent during stages REM or 2. Meaningful noises (such as one's name or identifiable

[14] J. S. Lukas, "Awakening Effects of Simulated Sonic Booms and Aircraft Noise on Men and Women," J. Sound and Vibration, Vol. 20, pp. 457-466 (1972).

aircraft noises) reduce intensity thresholds for behavioral responses during stages 2, Delta, and REM, but the reduction is less in stage Delta than in the other stages. The meaning of the noise appears to have little effect upon thresholds for EEG responses.[1,12,13]

(4) Noise level. An ealier study[15] suggested that prediction of the probability of No Sleep Disruption or behavioral awakening is most accurate when the descriptor of the noise accounts for the frequency weighted spectrum (in terms such as dBA* or PNdB) and for stimulus duration (the term E in units such as EdBA or EPNdB).† Generally, the higher the noise level, the greater the probability of a response, no matter how the response may be defined.

(5) Frequency of noise occurrence. There is some question about the effect of the frequency of noises on the response frequencies. Schieber et al.[16] reported that traffic noises averaging about 1.8 auto and truck passages per minute at 61 dBA disturbed sleep more than traffic noise averaging about 4.3 passages per minute at 70 dBA. They also found that 32 jet takeoff and flyover noises per night caused more sleep disturbance than 16 noises. The jet noises were at comparable levels. They suggested that the greater sleep disturbance by low frequency traffic was due to the difference in level between $L_{50\%}$ and $L_{1\%}$. The difference was 20 dBA for the low frequency traffic but 10 dBA for the high frequency traffic. Schieber et al. assume that

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*The reference level for all noise intensity measures in this report is 0.00002 N/m^2.

†Typically dBA, PNdB, or other similar measures indicate the maximum level of intensity reached during a noise occurrence; EdBA or EPNdB refers to an integration of the dBA or PNdB values present each 0.5 s over the entire occurrence of the noise. See K. D. Kryter, The Effects of Noise on Man, pp. 245-307 (Academic Press, New York, New York, 1970).

15 J. S. Lukas, D. J. Peeler, and J. E. Davis, "Effects on Sleep of Noise from Two Proposed STOL Aircraft," NASA Report No. CR-132564 (January 1975).

16 J. P. Schieber et al., "Étude analytique en laboratoire de l'influence du bruit sur le sommeil," Centre d'Études Bioclimatiques du CNRS, Strasbourg, France (April 1968).

the sleeper somehow adjusts to the average noise level and responds on the basis of the differences between the peak ($L_{1\%}$) and average ($L_{50\%}$) levels. Their explanation fails to account for the background noise levels (about 48 dBA) the sleeper experienced more often and with longer duration under the low frequency traffic condition. Perhaps a more accurate explanation may be that the intensities of the infrequent traffic noises were of a somewhat higher peak level (3-6 dBA; see Ref. 16, Table B) and generally of longer duration than the more frequent traffic noises.

It should be noted, however, that continuous[17] or very frequent[18] noise throughout the night, even at levels as high as 95 dBA,[17] seems to cause little change in the average durations of sleep stage. These results suggest that generally healthy and young people, in one way or another, are able to sleep reasonably well despite adverse conditions. Anecdotal evidence of sleeping habits gathered during wars and natural disasters suggests as much. Thus, there may be cause to doubt that the EEG measures of sleep quality used to date adequately describe both the short and long term effects of continuous sleep disturbance.

(6) Noise quality. There is clear evidence that inherently meaningful sounds, such as one's name, or sounds that acquire meaning, such as by instructions or conditioning, can awaken the sleeper at intensities lower than those required for meaningless or neutral sounds.[3,4,5,19,20] To some extent the amount of change in threshold for awakening is dependent upon

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[17] T. D. Scott, "The Effects of Continuous, High Intensity, White Noise on the Human Sleep Cycle," Psychophysiology, Vol. 9, pp. 227-232 (1972).

[18] L. C. Johnson et al., "Prolonged Exposure to Noise as a Sleep Pattern," in Proceedings International Congress on Noise as a Public Health Problem, W. D. Ward, ed., pp. 559-574 (U.S. EPA No. 550/9-73-008, 1973).

[19] H. L. Williams, "The Problem of Defining Depth of Sleep," in Sleep and Altered States of Consciousness, S. S. Kety, E. V. Evarts, and H. L. Williams, eds., pp. 277-287 (Williams and Wilkins, Baltimore, Maryland, 1967)

[20] W. B. Zimmerman, "Sleep Mentation and Auditory Awakening Thresholds," Psychophysiology, Vol. 6, pp. 540-549 (1970).

the subject's motivation; motivation can be altered by instructions, conditioning, or financial inducements.

(7) Response measures. EEG measures, such as K-complexes or bursts of alpha, have been found most sensitive to acoustic stimuli during sleep. Other autonomic responses are less sensitive but show a consistent hierarchy over the various sleep stages, that is, heart rate and peripheral vasoconstriction are less sensitive than EEG measures; respiration and electrodermal activity are less sensitive than heart rate and peripheral vasoconstriction; and motor responses are least sensitive.[10] Simple motor responses, such as pressing a microswitch taped to the hand, occur at relatively low stimulus levels. Higher stimulus levels are needed to elicit more complex behavior, such as verbal responses that indicate the subject is aware of specific properties of some stimulus,[21] or more complex motor responses, such as reaching for and pressing a switch attached to the headboard of the bed.[14]

(8) Presleep activity. Conventional wisdom suggests that active individuals would sleep "better" or more deeply (more stage Delta and REM) and thus be less sensitive to noise during sleep. Although the question of sensitivity to noise after activity has not been studied directly, Hauri[22] found that six hours of exercise (equivalent to traveling about 50 miles by bike and about 1-1/2 hours of lifting 15-pound weights) had only a small effect on the EEG measures of sleep quality during the first 3-1/2 hours of sleep, that is, when sleep stage Delta is most prevalent. In Hauri's[22] study the same subjects exercised, relaxed, or studied intensively during the six-hour presleep period. Hauri found no significant differences between any of the sleep EEG variables after the subjects performed those activities, but did find that heart rates were

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[21] A. Rechtschaffen, P. Hauri, and M. Zeitlin, "Auditory Awakening Thresholds in Real or NREM Sleep Stages," Perceptual and Motor Skills, Vol. 22, pp. 927-942 (1966).

[22] P. Hauri, "Effects of Evening Activity on Early Night Sleep," Psychophysiology, Vol. 4, pp. 267-277 (1968).

higher after exercising than they were after relaxing or studying and remained higher even after 3-1/2 hours of sleep. Because time in stages Delta or REM did not increase significantly, it is reasonable to suggest that average sensitivity to noise (regardless of sleep stage) did not change.

If presleep activity consists of prolonged periods of sleep loss (204 hours[23] and 64 hours[24]), the amount of time spent in stages Delta and REM increase, and an increase of the arousal and stage change thresholds can be anticipated. Williams et al.[24] found large increases in thresholds for evoked changes in EEG patterns and for behavioral awakening in all of the sleep stages. However, noise found in most environments is unlikely to cause such prolonged losses of sleep.

Noise Intensity Measures

Two criterion responses to nighttime noise are used commonly: arousal or behavioral awakening, and no-change-in-sleep-pattern. Arousal is defined as an EEG pattern having some or all the characteristics of an awake EEG,[25] while behavioral awakening requires a specific motor or verbal response. Typically, arousal occurs prior to or coincidentally with

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[23] P. Naitoh et al., "Interpretation of Non-Sleep EEG and Sleep EEG Pattern in Recovery Nights after 204 Hours of Prolonged Wakefulness," Psychophysiology, Vol. 4, p. 392 (1968).

[24] H. L. Williams et al., "Responses to Auditory Stimulation, Sleep Loss and the EEG Stages of Sleep," EEG Clin. Neurophysiol., Vol. 16, pp. 269-279 (1964).

[25] A. Rechtschaffen and A. Kales, eds., A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects, NIH Publication No. 204 (1968).

behavioral awakening.* For our purposes, we can consider these responses essentially equivalent because, on one hand, if EEG arousal is the response of interest, behavioral awakening follows frequently if it is required; on the other hand, if behavioral awakening is the desired response and it occurs in response to noise, it matters little whether an arousal occurred because the criterion response was obtained. Furthermore, behavioral awakening implicitly indicates a greater degree of cerebral activation and control than does EEG arousal alone.

A rationale for and a definition of a more inclusive criterion response, No Sleep Disruption, has been developed recently.[1] Briefly, No Sleep Disruption specifically includes brief, transient changes in EEG pattern that occur normally in the different sleep stages; examples of such changes are K-complexes during stage 2, brief bursts of alpha during stages 1 or REM, and brief increases in muscular tension levels or brief movements of the body during any of the stages. Thus, a response is any EEG change or behavior indicating the subject has shifted from one sleep stage to some other shallower stage within one minute of stimulus termination. If the effects of noise are described in terms of No Sleep Disruption many other responses (stage changes, arousals, behavioral awakenings) are subsumed. Investigators may wish to study particular

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*There is some controversy on this point (see, for example, Refs. 10, 12, 26). If the motor response requires little conscious effort on the subject's part, the motor response may occur without indication of EEG arousal. If the motor response is relatively complex, such as reaching for a response switch, calling out some prelearned material, or repeating some auditory or visual stimulus pattern, EEG arousal is likely to occur in conjunction with the behavioral response.

[26] H. L. Williams, H. C. Morlock, Jr., and J. V. Morlock, "Instrumental Behavior During Sleep," Psychophysiology, Vol. 2, pp. 208-216 (1966).

responses, for example stage changes, but it is recommended that in addition to the particular responses, results on the frequency of No Sleep Disruption be provided.

Frequencies of arousals or behavioral awakenings and No Sleep Disruption have been correlated with several commonly used measures of noise intensity to discern which intensity measure best predicts the different response frequencies. The results are shown in Table 2. We have distinguished between college-age (about 20-25 years of age) and middle-age (about 30-60 years of age) subjects, because earlier studies indicate that age affects response frequencies. Because women, children, and the old have been studied rarely, there are too few data to establish reliable coefficients for these age and sex groups. Therefore, the response data used to calculate the coefficients include women in the appropriate age groups, but not the very young or old. We have included data provided by Osada et al.;[27] Anon.;[28] Thiessen;[29] Schneider;[30]

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[27] Y. Osada et al., "Experimental Study on the Sleep Interference by Train Noise," Bull. Inst. Publ. Health (1975), in press.

[28] Annon., "Effects of Aircraft Noise on Sleep," Part 4, pp. 45-69, Report of the Effect of Noise, 1970 (March 1971). This report was kindly provided by Dr. Y. Osada of the Japanese Institute of Public Health.

[29] G. J. Thiessen, "Effects of Noise During Sleep," in Physiological Effects of Noise, B. L. Welch and A. S. Welch, eds., pp. 271-275 (Plenum Press, New York, New York, 1970).

[30] N. O-M. Schneider, "Evaluation subjective du sommeil normal ou perturbe par le bruit, relations avec certains indicateurs physiologiques et traits de personnalité," Ph.D. thesis, Université Louis Pasteur, Strasbourg, France (December 1973).

Table 2

COEFFICIENTS OF CORRELATION BETWEEN RESPONSES TO NOISE DURING SLEEP AND SELECTED MEASURES OF NOISE INTENSITY

Age Group	No Sleep Disruption — Intensity Measures: Max dBA	EdBA*	EPNdB*	SENEL+
College (22)‡	-0.769	-0.796	-0.766	-0.754
Middle age (35)‡	-0.699	-0.761	-0.817	-0.717
College and middle age	-0.692	-0.789	-0.812	-0.761
	Arousal or Behavioral Awakening			
College (23)‡	0.460	0.475	0.287	0.404
Middle age (35)‡	0.746	0.795	0.809	0.819
College and middle age	0.581	0.615	0.500	0.518

*EdBA and EPNdB calculated according to technique described by Kryter,[39], pp. 472-484.

+SENEL (Single Event Noise Exposure Level) = $L_{max} + 10 \log_{10} \frac{t}{2}$, where L_{max} is in units of dBA, and t is noise duration measured between the 10 dB downpoint (Ref. 40, p. A-29).

‡Number of data points.

Collins and Iampietro;[31] Lukas et al.;[15,32,33,34,35] Kramer et al.;[36] and Zimmerman.[20] Rather than presenting stimuli at one or several intensities and obtaining response frequencies as did most investigators, Kramer et al.[36] and Zimmerman[20] increased stimulus levels until the desired response (a stage change, arousal, or behavioral awakening) was obtained. Therefore, to incorporate their data it was necessary to assume that the thresholds reported were the mean intensity at which all subjects either changed sleep stages[36] or were aroused or behaviorally awakened.[36,20]

Two conclusions can be drawn from the coefficients shown in Table 2: (1) the frequency of No Sleep Disruption in both age groups is predicted more accurately by the various measures of intensity than is the frequency of behavioral awakening or arousal, and (2) arousal and behavioral awakening can be predicted more accurately in middle-age than in college-age subjects.

Of greater importance than these two conclusions, perhaps, is a statistical comparison of certain pairs of correlations insofar as the

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[31] W. E. Collins and P. F. Iampietro, "Effects on Sleep of Hourly Presentations of Simulated Sonic Booms (50 N/M^2)," in Proceedings International Congress on Noise as a Public Health Problem, W. D. Ward, ed., pp. 541-548 (U.S. EPA No. 550/9-73-008, 1973).

[32] J. S. Lukas and K. D. Kryter, "Awakening Effects of Simulated Sonic Booms and Subsonic Aircraft Noise on Six Subjects, 7 to 72 Years of Age," NASA Report No. CR-1599 (May 1973).

[33] J. S. Lukas, M. E. Dobbs, and K. D. Kryter, "Disturbance of Human Sleep by Subsonic Jet Aircraft Noise and Simulated Sonic Booms," NASA Report No. CR-1780 (July 1971).

[34] J. S. Lukas and M. E. Dobbs, "Effects of Aircraft Noises on the Sleep of Women," NASA Report No. CR-2041 (June 1972).

[35] J. S. Lukas, D. J. Peeler, and M. E. Dobbs, "Arousal from Sleep by Noises from Aircraft with and without Acoustically Treated Nacelles," NASA Report No. CR-2279 (July 1973).

[36] M. Kramer et al., "Noise Disturbance and Sleep," DoT Report No. FAA-NO-70-16 (1971); see also T. Roth, M. Kramer, and J. Trinder, "Noise-Sleep and Post Sleep Behavior," paper presented at the American Psychiatric Association Meeting, Washington, D.C., 1971.

comparison may suggest how noise intensity should be described to best predict human responses to noise. The difference in coefficients (aggregated over the age groups) for maximum dBA (-0.692) versus EdBA (-0.789) indicates the latter to be statistically greater (t = 2.13, p = 0.025; one-tailed test);[37] the coefficient of correlation of noise levels when measured in units of dBA and EdBA is 0.851. The larger difference between the EPNdB and SENEL coefficients (-0.812 versus -0.761) was statistically significant (t = 2.89 with 54 degrees of freedom, with a correlation of 0.974 between levels in units of EPNdB and SENEL; p = 0.005), but the smaller difference (0.023 units) between EdBA and EPNdB is not statistically significant (t = 1.58 with 54 degrees of freedom). The coefficient of correlation between intensity measured in units of EdBA and EPNdB is 0.983. Therefore, to predict the frequency of No Sleep Disruption as a result of noise, we should take the duration of the noise into account, and use EdBA, EPNdB, and SENEL as predictors. In addition, there is somewhat greater predictive accuracy if EPNdB, rather than SENEL, is used as the unit of noise intensity.*

In comparing the two response measures, we find that frequency of No Sleep Disruption can be predicted more accurately than frequency of arousal or behavioral awakening if units of EdBA are used (No Sleep Disruption versus arousal or behavioral awakening† and units of EdBA--0.615 versus -0.789, t = 3.00, p = 0.005), but not if units of max dBA are used (units of max dBA--0.581 versus -0.692, t = 1.63, not significant). However, the generally larger magnitude of the coefficients found in the No Sleep Disruption section in Table 2 suggests that this

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*See J. S. Lukas, "Assessment of Noise Effects on Human Sleep," paper presented at the American Psychological Association Convention, Chicago, Illinois, 31 August 1975.

†The signs of the coefficients were not used in these calculations.

[37] H. M. Walker and J. Lev, Statistical Inference, p. 257 (Henry Holt & Co., New York, New York, 1953).

response can be predicted more accurately than the frequency of arousal and behavioral awakening.

The coefficient of correlation between the frequency of No Sleep Disruption and the frequency of arousal or behavioral awakening calculated across two age groups was -0.777. Thus, as might be expected, as the frequency of arousal or awakening increases, the simultaneous frequency of No Sleep Disruption decreases. This moderately high correlation indicates that our earlier suggestion[1] that No Sleep Disruption be used as a criterion measure against which to assess the effect of noise has merit because it is sensitive to both significant disruption in sleep pattern details and arousal and awakening.

Figures 1 and 2 permit a comparison of the distributions of No Sleep Disruption and of arousal or awakening in the two age groups caused by the same types of noise at various intensities. In Figure 1 it appears that Schneider's[30] data are deviant, that is, the sleep of her subjects was disrupted less than expected; in Figure 2 Schneider's subjects also showed a lower than expected frequency of arousal, as did the subjects of Osada et al.[27] However, Kramer's[36] and Zimmerman's[20] subjects were awakened much more frequently than expected. This high frequency of arousal was probably caused by increasing the intensity of the stimulus until an arousal was obtained. This procedure makes the subjects appear more sensitive than they would be if single noise bursts occurred at random intensities and intervals.[1] It is not immediately obvious why the subjects of Schneider and Osada et al. were aroused relatively infrequently. Perhaps in the experiments of Osada et al. the subjects did not "hear" the 20-s bursts of noise that occurred every 20 minutes until the noise attained levels the subjects could not "ignore." Consistent with this analysis is the report by Osada et al., that their subjects noted an increase (double or more) in the number of noises heard only when the highest noise levels (about 98 and 108 EPNdB) occurred.

Nevertheless, Figures 1 and 2 illustrate why, on the basis of available data, the frequency of No Sleep Disruption can be predicted more accurately than the frequency of arousal and behavioral awakening.

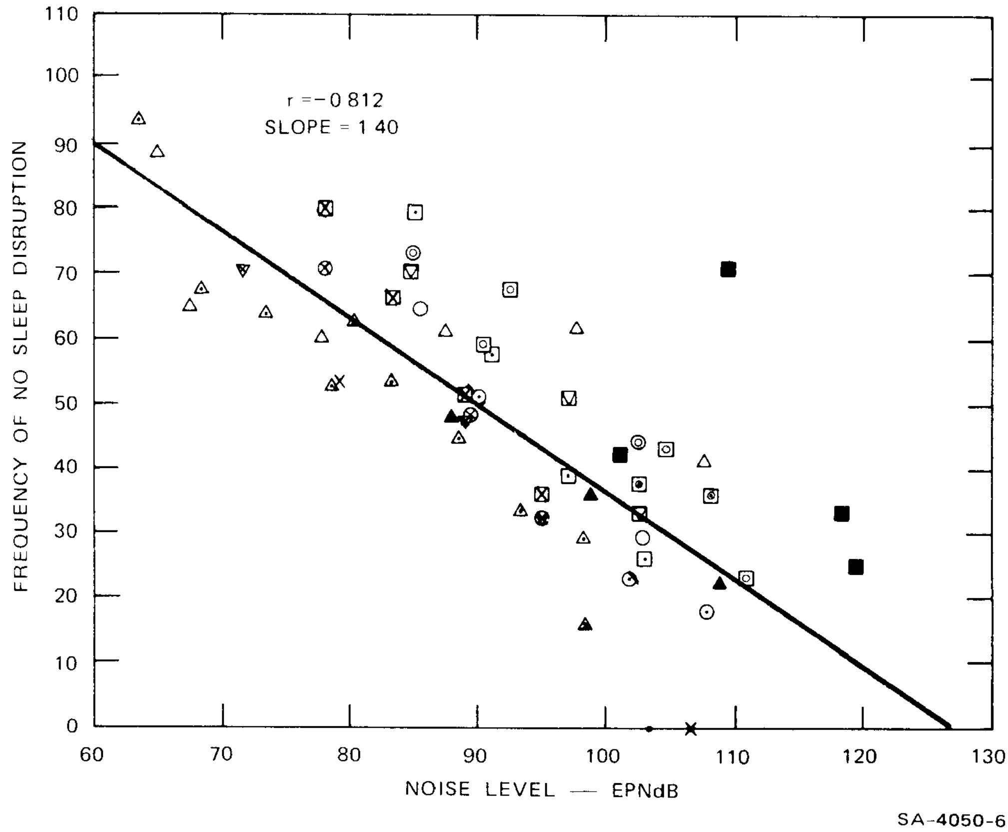

FIGURE 1 FREQUENCY OF NO SLEEP DISRUPTION AT VARIOUS NOISE LEVELS IN COLLEGE AND MIDDLE AGED MEN AND WOMEN (SEE TABLE 1 FOR STUDY AND STIMULUS CODE)

Predicting Sleep Quality

Schneider's[30] subjects filled out several questionnaires about the quality of their sleep, and their responses were analyzed to determine common factors. Three types of questions were found to be common and to explain about 77 percent of the total variance in the sleep quality data. The three factors, listed in order of relative importance, were: (1) feelings of well being on arousal, (2) feelings about the general

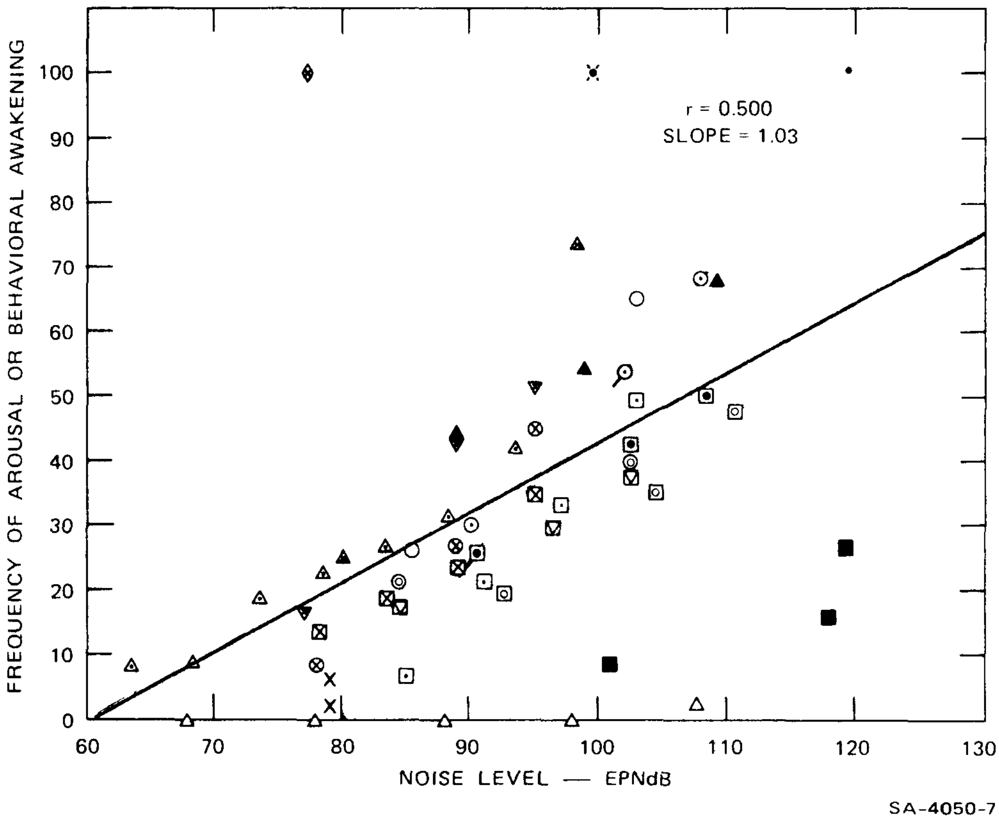

FIGURE 2 FREQUENCY OF AROUSAL OR AWAKENING FROM SLEEP IN COLLEGE AND MIDDLE AGED MEN AND WOMEN BY NOISE AT VARIOUS INTENSITIES (SEE TABLE 1 FOR THE STUDY AND STIMULUS CODE)

quality of sleep, and (3) an estimate of how long it took to fall asleep. Using these findings as a lead, studies of noise-disturbed sleep that included questions pertinent to all or some of the three factors were isolated. For each study a Composite Sleep Quality score was calculated* and the percentage of change in Composite Sleep Quality (relative to baseline or nights without noise) were correlated with the composite level of noise present during the noise nights.

Figures 3, 4, and 5 permit comparison of the distributions of changes in Composite Sleep Quality when the composite noise levels at night are calculated in units of CNR (Composite Noise Rating; Kryter),[39] $L_{eq(7.5)}$

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*In most of the studies the subjects marked a line indicating their position on each factor on a continuum ranging from good to bad, for example. The individual item score was the relative position of the subject's mark on the line. The Composite Sleep Quality score was simply the sum of the scores obtained on each question dealing with each factor. This procedure of summing permits questions with the greatest validity to contribute most weight to the composite score. Some studies included several questions about a single factor. In this case, an average score was calculated for each factor, and the averages were summed to obtain the composite score. Because investigators used different scales to assess quality (Schneider,[30] for example, used a scale of +60 to -60; Herbert[38] used a 10-cm line, where a score of 50 mm was analogous to a normal sleep night) and all did not include questions about each of the three factors, a percentage of change score calculated with respect to Composite Sleep Quality on a night (or nights) without noise was used in our analysis.

[38] M. Herbert and R. T. Wilkinson, "The Effects of Noise-Disturbed Sleep on Subsequent Performance," in Proceedings International Congress on Noise as a Public Health Problem, W. D. Ward, ed., pp. 527-539 (U.S. EPA No. 550/9-73-008, 1973); and M. Herbert, "Some Determinants of Subjectively Rated Sleep Quality," Brit. J. Psychol. (1975), in press.

[39] K. D. Kryter, The Effects of Noise on Man, pp. 484-485 (Academic Press, New York, New York, 1970).

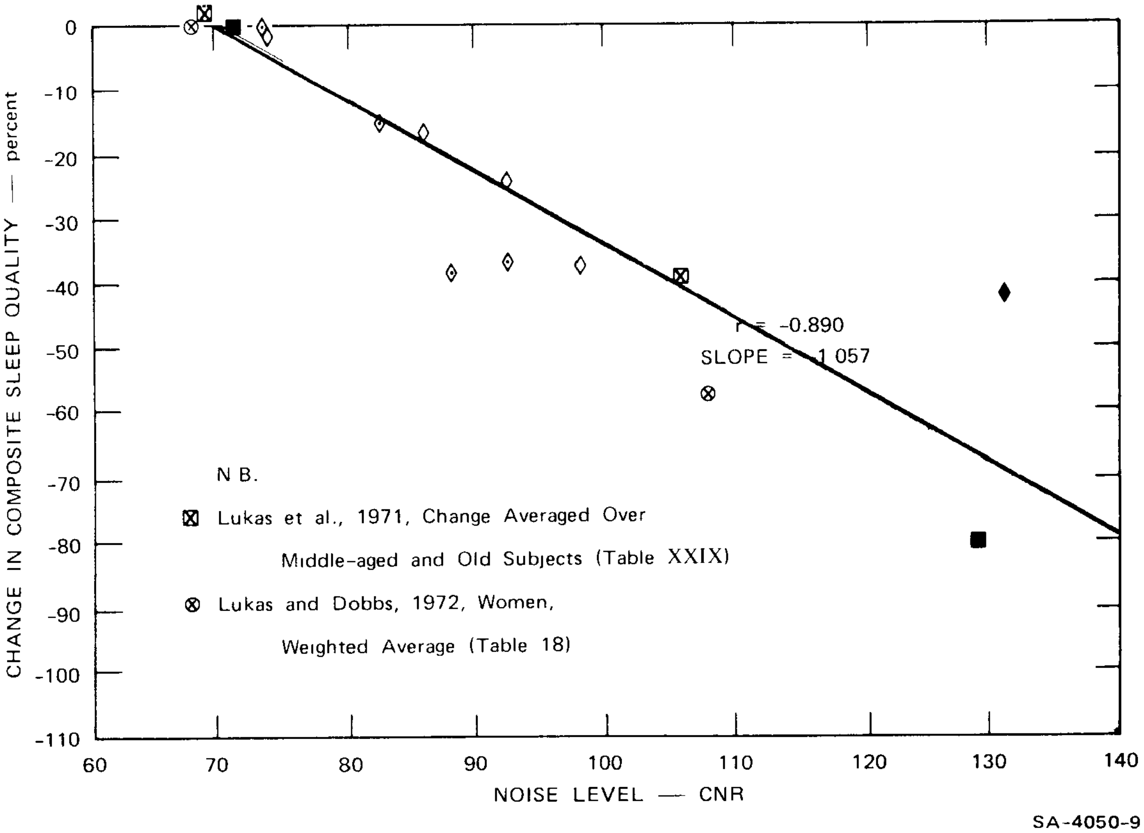

FIGURE 3 RELATIVE SUBJECTIVE DISTURBANCE OF SLEEP AT VARIOUS TOTAL NIGHTTIME NOISE LEVELS CALCULATED IN UNITS OF CNR (SEE TABLE 1 FOR STUDY AND STIMULUS CODE)

(Equivalent Level; EPA),[40] and NNI (Noise Number Index; Burns),[41] respectively. A reasonably systematic relationship is apparent for both the CNR and NNI measures and the change in Composite Sleep Quality, but is less apparent for the L_{eq} measure, although the coefficient associated with this measure is high (0.899). As illustrated in Figure 4, large

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[40] U.S. EPA, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," pp. A-12 and A-16 (EPA No. 550/9-74-004, 1974).

[41] W. Burns, Noise and Man, pp. 225-226 (John Murray, London, 1968).

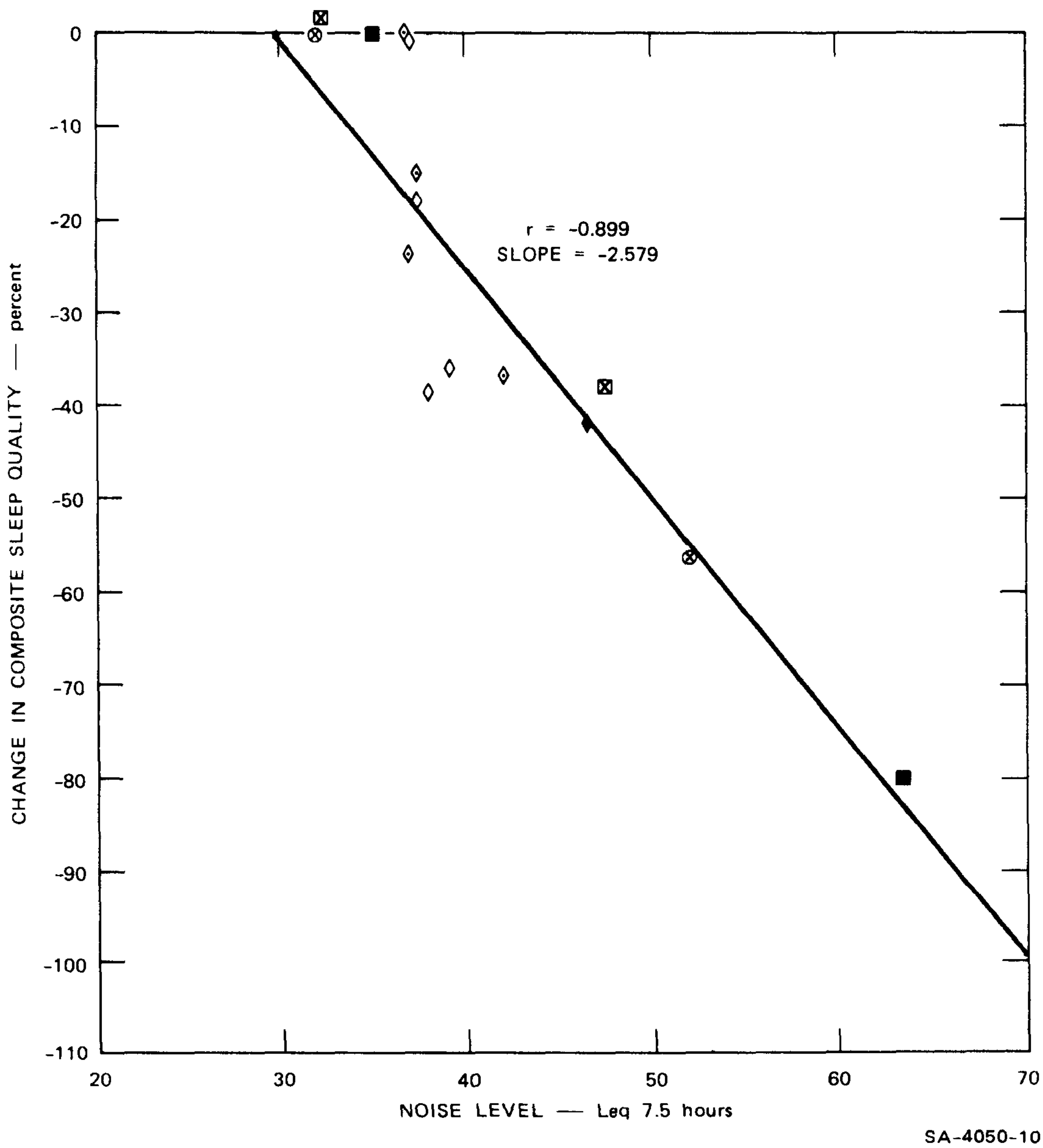

FIGURE 4 RELATIVE SUBJECTIVE DISTURBANCE OF SLEEP AT VARIOUS TOTAL NIGHTTIME NOISE LEVELS CALCULATED IN UNITS OF L_{eq} (SEE TABLE 1 FOR STUDY AND STIMULUS CODE)

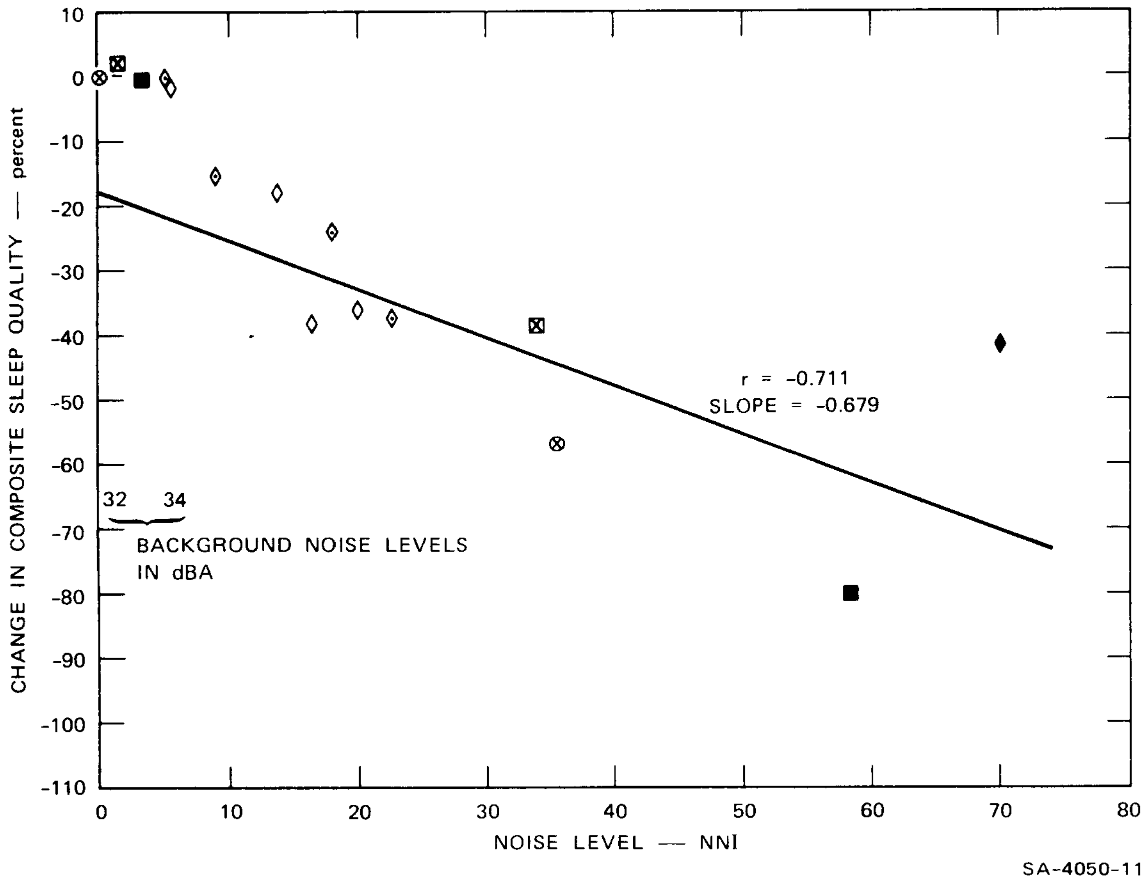

FIGURE 5 RELATIVE SUBJECTIVE DISTURBANCE OF SLEEP AT VARIOUS TOTAL NIGHTTIME NOISE LEVELS CALCULATED IN UNITS OF NNI (SEE TABLE 1 FOR STUDY AND STIMULUS CODE)

decreases in subjective sleep quality occurred at low (compared to the background) noise levels. The inconsistency between subjective sleep quality and composite noise levels in units of L_{eq} is due to the fact that the stimuli used had very short durations (see Table 1) compared with the total time (7.5 hours in our calculations) during the night. Therefore, in calculating L_{eq},* large negative values were subtracted from L_{max} levels, resulting in L_{eq} levels below background level. To correct this situation, the background level was assumed to be L_{max}, and present for approximately 7.5 hours, and the stimuli added only slightly to the L_{eq}. For example, in the Ludlow and Morgan[42] studies the background level was about 37 dBA (or L_{eq} = 37 dBA), and the eight simulated sonic booms of 62.5 dBA--each with a duration of about 0.5 s--contributed only 0.2 to total nighttime $L_{eq(7.5)}$ (37.2 dBA); booms 10 dBA higher (72.5 dBA) resulted in a $L_{eq(7.5)}$ = 38.8 dBA. Thus, it appears, on the basis of evidence presently available, that L_{eq} may not be useful in predicting Composite Sleep Quality when noise levels are low and of short duration compared to the background level.

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*The formulas were

(1) $L_{eq} = L_{max} + 10 \log_{10} \frac{nt}{2.3T}$, and

(2) $L_{eq} = L_{max} + 10 \log_{10} \frac{nt}{T}$.

Formula (1) was used if the noise had a triangular shape and formula (2) was used if the noise was a square pulse. t/T is the fraction of time the noise was present, T = 7.5 hours, n is the number of noise bursts, L_{max} is maximum noise level in dBA, and noise duration -t- is the time between the 10 dB downpoints.

[42] J. E. Ludlow and P. A. Morgan, "Behavioral Awakening and Subjective Reactions to Indoor Sonic Booms," J. Sound and Vibration, Vol. 25, pp. 479-495 (1972).

NNI* has deficiencies similar to those of L_{eq}. The original NNI technique specifies that units of maximum PNdB be used in the calculations; in other words, the durations of the noises are suggested to be of little importance. The data presented herein suggest that if EPNdB units were used to calculate NNI, better predictions of sleep disturbance should result. However, under certain noise conditions, if EPNdB or EdBA are used to calculate NNI, the NNI for the noise may be less than the NNI for the background. For example, presume ten noise bursts of 63 PNdB (50 dBA) each, and each burst of 10-s duration (between the 10 dB downpoints). The NNI is about 15 (in units of EPNdB) for a background level of 48 PNdB (35 dBA), whereas 10 bursts of noise are equivalent to a NNI of 10.8 (in EPNdB units). Twenty noise bursts, each of 50 dBA, or 5 bursts, each of 60 dBA, are required to produce a NNI equivalent to that of the background. Because of this inconsistency, the background noise levels in Figure 5 are shown in units of dBA, not in NNI units.

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*NNI (Noise and Number Index) = average peak noise level + 15 $\log_{10}$ N - 80, where average peak noise level is the logarithmic average.

$$\text{Logarithmic average peak noise level} = 10 \log_{10} \frac{1}{N} \sum_{1}^{N} 10^{\frac{L}{10}} ,$$

where L = peak noise level of each noise, and N = number of noises (after Burns, 1968, pp. 225-226). EPNdB levels were used to calculate CNR and NNI. Because L_{eq} specifies that duration between the 10-dB downpoints be used to determine t (the time the noise was on) particularly when the noises are more than 10 dB above background noise levels, a duration correction was not needed.

In contrast, Kryter's Formula 8 (p. 484)[39] for computing CNR was found to be a reasonable metric for calculating background levels, and his Formula 7* (p. 484) was a compatible technique for calculating night-time noise exposure.

A technique for calculating a composite of the background noise and randomly occurring noise peaks is needed because laboratory experience indicates that subjects adapt to fairly low levels (below about 40 dBA) of constant background noise and, after adaptation, sleep "normally." Normality is defined as the usual sleep pattern for any particular subject, and for healthy subjects their sleep patterns can be compared and assessed with respect to the patterns of normative samples.[43,44,45]

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*CNR (Composite Noise Rating) = $[(EPNL + 10 \log_{10} O_1) + \ldots (EPNL_n + 10 \log_{10} O_n)] - 2$, where EPNL = frequency weighted spectrum and duration of the noises 1 through n, EPNdB calculated using 0.5 sec as the reference duration, and O_1 through O_n are the number of occurrences of each noise (Kryter, Formula 7, p. 484).

[43] I. Feinberg, "Effects of Age on Human Sleep Patterns," in Sleep: Physiology and Pathology, A. Kales, ed., pp. 39-52 (J. B. Lippincott Co., Philadelphia, Pennsylvania, 1969).

[44] W. B. Webb, "Twenty-Four-Hour Sleep Cycling," in ibid., pp. 53-65.

[45] W. B. Webb, "Sleep Behavior as a Biorhythm," in Biological Rhythms and Human Performance, W. P. Calquhoun, ed., pp. 149-177 (Academic Press, New York, New York, 1971).

IV CONCLUSIONS AND RECOMMENDATIONS

(1) In a broad sample of the population, available evidence indicates that units of EdBA, EPNdB, and SENEL can predict the frequency or probability of No Sleep Disturbance to nighttime noise with nearly equivalent accuracies. EPNdB appears to be slightly more accurate than EdBA and more accurate than SENEL. Units that do not account for stimulus duration, such as maximum dBA or PNdB, are far less accurate than those that do.

(2) Although we are able to predict the frequency of behavioral awakening or arousal in middle-aged populations with reasonable accuracy if stimulus duration and intensity are accounted for, these predictions are far less accurate for college-aged populations. Across the two age groups the accuracy of predicting arousal or awakening is generally poor, and units such as maximum dBA are no more accurate than units such as EdBA.

(3) There is evidence that questionnaires about subjective sleep quality should include items about the subject's (a) feelings of well-being on arousal, (b) feelings of general sleep quality, and (c) an estimate of how long it took to fall asleep, The answers to these questions should permit the subject to mark his response on a continuum ranging from, for example, good to bad, or better (longer) than normal to far worse (shorter) than normal. The quality of sleep for each item may then be proportional to the distance from some neutral point along the continuum. A simple sum of the scores on each item can be used as a measure of Composite Sleep Quality.

(4) Although the available evidence is limited, Composite Sleep Quality apparently can be predicted with reasonable accuracy from measures of nightly composite noise levels. Among the three composite noise measures calculated, it appears at this time that CNR is best able to predict changes in Composite Sleep Quality, when CNR is calculated using EdBA or EPNdB as the basic unit of noise measurement.

(5) Additional studies of the reliability of the Composite Sleep Quality measure, and of the relationship of subjective sleep quality measure to composite noise level measures are recommended.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

A review of domestic and foreign scientific literature on the effects of noise on human sleep indicates that no sleep disruption can be predicted with good accuracy (correlation coefficients of about 0.80) if the noise descriptor accounts for the frequency-weighted spectrum and the duration of the noise. Units such as EdBA, EPNdB, and SENEL are better predictors than a unit such as maximum dBA. Furthermore, no sleep disruption can be predicted more accurately than arousal or behavioral awakening responses.

Some evidence suggests that questionnaires about subjective sleep quality should contain items dealing with the subject's (a) sense of well being on arising, (b) sense of the general quality of his sleep, and (c) estimates of how long it took to fall asleep. Scores on these items can be summed to develop a Composite Sleep Quality measure. Although the amount of evidence is limited, such Composite Sleep Quality is correlated highly (about 0.90) with Composite Noise Rating (CNR) when units of EPNdB or EdBA are used to calculate CNR. Other techniques for calculating the total nighttime noise environment, such as L_{eq} and NNI, have some shortcomings with respect to their ability to predict Composite Sleep Quality.

17. KEY WORDS AND DOCUMENT ANALYSIS

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