Field study of noise-induced sleep disturbance

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Behaviorally confirmed awakenings were recorded during nighttime hours for periods of approximately one month in 45 homes of 82 test participants. Measurements of awakening and of both indoor and outdoor noise exposure were made for a total of 632 subject nights near a military airfield, 783 subject nights near a civil airport, and 472 subject nights in neighborhoods with community noise exposure of nonaircraft origin. Sound exposure levels of individual noise intrusions were much more closely associated with awakenings than long-term noise exposure levels. The slope of the relationship between awakening and sound exposure level was rather shallow, however. Although the present findings do not resemble those of laboratory studies of noise-induced sleep interference, they are in good agreement with the results of other field studies. © *1995 Acoustical Society of America.*

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INTRODUCTION

A recent review of the quantitative literature on noise-induced sleep disturbance (Pearsons *et al.*, 1995) found major differences between the results of 16 laboratory and 5 field studies, as shown in Fig. 1. Pearsons *et al.* concluded from these differences that the results of laboratory studies of noise-induced sleep disturbance could not be generalized to predict the ability of familiar noises to disturb sleep in habituated residential populations. Results of a recent large scale field study of noise-induced sleep disturbance reported by Ollerhead *et al.* (1992) closely resemble those of the other field studies reviewed by Pearsons *et al.* The similarity of the findings of field studies to one another, as well as the marked difference between findings of field and laboratory studies, suggests that laboratory findings about noise-induced sleep disturbance do not suffice for reliable assessment of noise-induced sleep interference in communities. The present study, undertaken to produce information useful for environmental assessment purposes, focused on effects of relatively high level noise intrusions on sleep in adapted residential settings.

I. METHOD

Residential areas near Castle Air Force Base, near Los Angeles International Airport (LAX), and in sites lacking appreciable nighttime aircraft noise were purposively selected as test sites. Sites with aircraft noise exposure were selected near the ends of the main runway at Castle Air Force Base, and in an area north of runway 24R at LAX. Residences in suburban Los Angeles with negligible nighttime aircraft noise exposure were selected as control sites. Two of these residences were located adjacent to major freeways, three were located close to busy streets, and the remaining residences were in neighborhoods with lesser urban noise exposure.

Residents in areas immediately northwest and southeast of Castle AFB (27 people in 15 households) took part in the study. In areas near LAX, 35 people in 18 households were selected as test participants. An additional 23 people in 12 households that were not exposed to nighttime aircraft noise participated at other sites. Participants were paid a modest honorarium for their participation. In all, 38 men and 47 women, ranging in age from 19 to 79 yr (mean age=47 yr, standard deviation=18 yr), living in 45 homes, took part in the current study. The mean and standard deviations of test participants' duration of residence in their homes were both about 12 yr.

Figure 2 diagrams the instrumentation used to collect noise exposure information in test participants' homes. This equipment preserved time synchronization between time series of A-weighted sound-pressure measurements recorded indoors and awakening responses. Outdoor noise measurements were made in the vicinity of five residences near Castle Air Force Base and four residences near LAX. Instrumentation inside test participants' bedrooms recorded interior noise levels between 10:00 p.m. and 8:00 a.m. L_{eq} values were recorded every 2 s throughout the night. Half-second time histories of noise "events" were also recorded. A noise event was defined as a sequence of noise levels that began when an A-weighted threshold level was exceeded for at least 2 s and ended when the noise level dropped more than 2 dB below the threshold. The threshold was set on a site-specific basis to maximize collection of noise intrusions (primarily aircraft) in the presence of indoor ambient noise, without exhausting the storage capacity of the noise monitors too rapidly.

Each test participant used a palmtop computer at bedside to answer evening and morning questionnaire items. A push-button attached by a cable to this computer provided the behavioral confirmation of awakening during the night. The device also recorded the length of time spent in bed overnight. Evening questionnaire items sought ratings of tiredness during the day and information about consumption of

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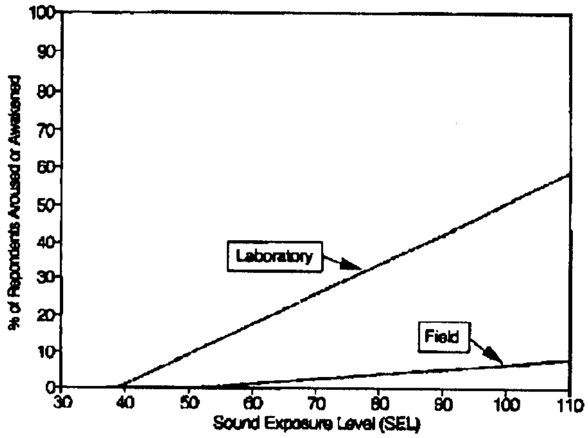

FIG. 1. Summary of dosage-response relationships developed by Pearsons *et al.* (1989) between awakenings or arousals and indoor sound exposure levels.

alcohol and drugs. Morning questionnaire items included judgments of overall sleep quality, feelings of tiredness, recall of numbers of awakenings during the night, and time to fall asleep.

II. RESULTS

Table I summarizes the data collection effort and provides additional site-specific information. The complete data set analyzed was composed of 1887 subject nights of observations: 632 at Castle Air Force Base, 783 at LAX, and 472 from nonaircraft sites. Average equivalent levels of 1-min

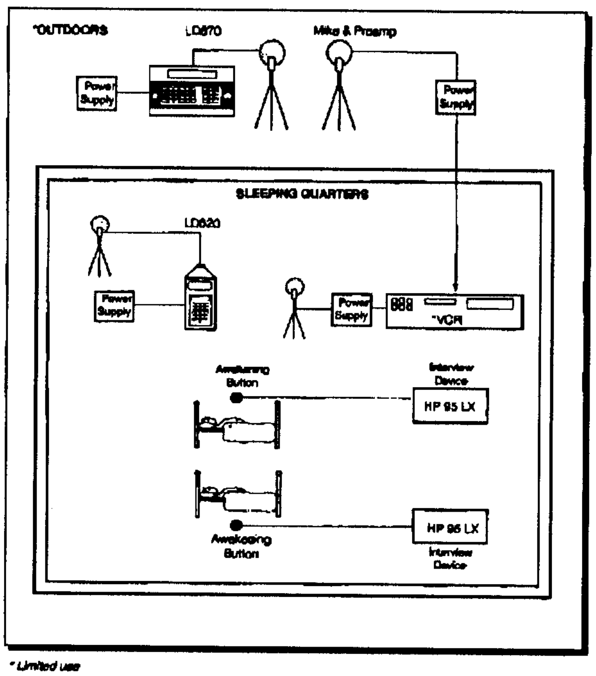

FIG. 2. Schematic diagram of field instrumentation.

TABLE I. Summary of field data collection, indoor measurement of equivalent levels, total numbers of events, and behavioral awakening responses at three study sites.

	Control sites	Castle AFB	LAX
Number of homes	12	15	18
Number of men	10	12	16
Number of women	13	15	19
Average age (in years)	33.9	43.9	52.2
Number of subject nights	472	632	783
Mean value of L_{eq} in 1-min epochs in sleeping quarters	37.8 dB	41.5 dB	39.5 dB
Number of noise events	7570	7646	18 950
Number of behavioral awakening responses	1043	1416	1993

indoor noise measurement epochs are summarized in Table I. Tables II and III summarize sound levels of noise events and of entire nights, respectively. Maximum A levels were measured with a "fast" sound level meter response. A-weighted signal-to-noise ratios were calculated by taking the difference between the maximum A level and the lowest level 5-min epoch level for the particular site and night containing the noise events. Sound exposure levels (SEL) were determined by summing 1-s pressure squared values for each event. Table II summarizes average levels of individual noise events as measured inside participants' sleeping quarters during the hours 10:00 p.m. and 8:00 a.m. throughout the entire study period.

Table III shows examples of all-night indoor noise metrics at the three sites. The levels were calculated from 2-s time history measures between the lesser of the subjects' longest sleep time or the hours from 10:00 p.m. and 8:00 a.m. The highest noise levels of both maximum L_{eq} and L_{eq} for the entire night were recorded at Castle AFB. The number of noise events was greatest at LAX, but the total duration of the nightly events was similar at Castle and LAX. The smallest numbers and shortest durations of events were observed at the nonaircraft sites.

Tables I and IV summarize the behavioral awakening

TABLE II. Summary of indoor measurements of individual noise events in sleeping quarters.

		Noise metrics (dB)			
Site	Statistic	Maximum A level	SEL	L_{eq}	A-weighted S/N ratio
Control	mean	67.3	69.4	63.0	29.4
	standard deviation	7.7	6.6	6.3	12.3
	range	43.2	42.9	33.6	56.9
Castle AFB	mean	76.6	81.0	72.3	39.5
	standard deviation	8.2	9.1	6.8	11.8
	range	65.7	61.0	56.1	84.7
LAX	mean	66.5	69.6	62.9	28.7
	standard deviation	4.4	4.8	3.2	12.1
	range	40.4	34.4	29.9	64.1

TABLE III. Summary of four measures of entire nights' noise exposure in sleeping quarters.

Statistic	Noise metrics			
	Maximum L_{eq}	Nightly L_{eq}	Number of events	Total duration of events (s)
Control (60-dB indoor threshold)				
mean	59.9 dB	44.5 dB	5.9	31.8
standard deviation	6.5	5.2	18.3	126.0
range	37.3	29.0	151	1419
Castle AFB (70-dB indoor threshold)				
mean	68.5	51.4	11.4	125.4
standard deviation	10.4	8.9	31.2	233.3
range	64.4	49.4	435	2620
LAX (60-dB indoor threshold)				
mean	60.8	45.9	20.5	126.2
standard deviation	5.6	5.5	45.7	275.5
range	36.8	30.4	279	1176

data. Table I shows the gross number of noise events and behavioral awakening responses. Figure 3 shows the distribution of the numbers of noise-event related behavioral awakening responses (i.e., those occurring within 5 min of a noise event). Figure 4 shows the distribution of numbers of non-noise related (spontaneous) behavioral awakening responses over subject nights. Awakenings associated with noise events were observed on only 16% of nights, while spontaneous awakenings occurred during 85% of the nights. Table IV shows the average numbers of events and behavioral awakening responses observed at the three study sites. (Note that few of the responses were associated with noise events.)

A. Screening of bivariate correlations between noise metrics and awakenings

Examination of correlations among noise metrics and awakening responses began with prioritization of metrics among the many that could be calculated from time series of A-weighted noise measurements. Table V shows the linear correlations among noise and prevalence of behavioral awakening responses within 1, 2, and 5 min of occurrence of noise events. The two statistically significant results, the correlation between SEL and awakening within 5 min ($r_{(30)}=0.56$, $\alpha=0.008$) and the correlation between SEL and awakening within 2 min ($r_{(30)}=0.49$, $\alpha=0.008$), were not reliably different from one another. Behavioral awakening within 5 min

TABLE IV. Summary of behavioral responses for all subject nights at all sites.

Variable	Mean	Standard deviation	Range
Average number of spontaneous awakenings per nights	2.07	1.50	0–9
Average number of noise related awakenings per night	0.24	0.67	0–7
Average sleep duration per night	469 min	67.10	126–624[a]

[a]For the 930 nights on which test participants retired after 10:00 p.m. and arose before 8:00 a.m.

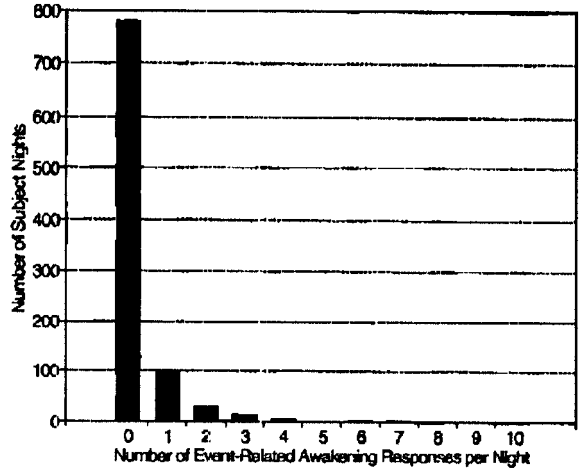

FIG. 3. Distribution of numbers of noise-event related behavioral awakening responses at all sites.

was selected as the more inclusive indication of awakening. SEL was selected as the preferred metric of noise exposure for more detailed analyses of the ability of noise events to disturb sleep.

Correlations between behavioral awakening responses and L_{eq} values of 1-, 2-, and 5-min epochs prior to button pushes may be seen in Table VI. Only the correlation between behavioral awakening and the L_{eq} in the preceding 1-min epoch ($r_{(40)}=0.43$, $\alpha=0.033$) was significantly different from zero.

Table VII displays correlations among four indices of noise exposure for entire nights with responses to eight questionnaire items and one behavioral variable. Seven correlations were statistically significant ($\alpha=0.003$) in this set, of which three were related to sleep disturbance. Report of awakenings by aircraft noise was weakly (but negatively) related to the two L_{eq} measures. The number of noise events was weakly related to sleep latency. The largest of these

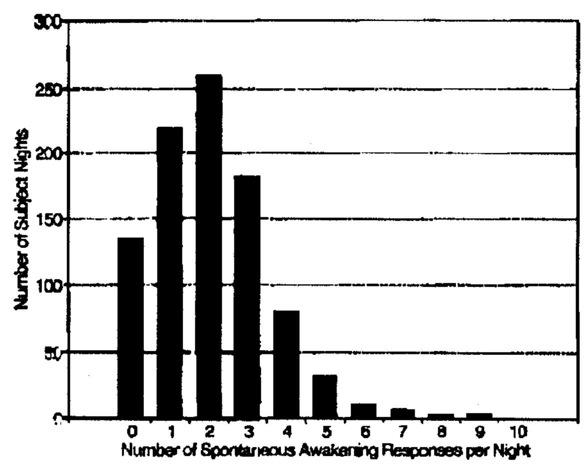

FIG. 4. Distribution of the numbers of non-noise related behavioral awakening responses over subject nights.

correlations accounted for no more than 2.5% of the variance in the data, however.

B. Dosage-response relationships for two measures of noise exposure

Figure 5 shows a dosage-response relationship derived from a linear regression of indoor SEL of noise events on the prevalence of behavioral awakenings occurring within 5 min at nonaircraft, moderate (LAX), and high aircraft noise exposure (Castle AFB) sites. The denominator for the prevalence calculation is the total number of noise events. The strengths of the relationships between the two predictor variables (SEL of events and L_{eq} of epochs) and the prevalence of awakenings did not differ significantly from one another ($p>0.05$).

C. Logistic regression analysis of predictability of behavioral awakening responses

A direct logistic regression analysis was performed on the occurrence of behavioral awakening responses occurring within 5 min of a noise event as the outcome variable. Several predictor variables were considered: indoor sound exposure levels of noise events, gender, age, duration of residence, sequential study night, L_{eq} of ambient noise in sleeping quarters, apparent event source (aircraft related or other), time since retiring, self-reported alcohol and drug consumption, tiredness before retiring, and spontaneous (nonevent related) awakenings. Responses of 81 test participants to a total of 10 096 events were analyzed. These included 326 noise events followed by awakening responses within 5 min and 9770 noise events unaccompanied by awakening responses within 5 min.

The predictive model of behavioral awakening derived from the logistic analysis was tested in two ways. First, the model containing all predictors was tested against a chance model—one which contained only the intercept. The statistically significant difference between the performance of the full and chance models, $\chi^2(12,\ N=10\,096)=376.07$, $p<0.001$, indicated that the performance of the full prediction model in predicting awakenings was better than would be expected by chance. A stronger test of the model evaluated how closely the behavioral awakening responses predicted by the model matched the observed awakenings. The lack of a significant discrepancy between the predicted and observed behavioral awakenings, Hosmer–Lemeshow $\chi^2(8,\ N=10\,096)=11.70$, $p=0.165$, revealed an adequate fit of the logistic regression model to the data.

TABLE V. Correlations between probability of awakening and individual noise event levels

Postevent interval	Maximum A level	SEL	L_{eq}	A-weighted S/N
Within 1 min	0.32	0.45	0.23	0.38
Within 2 min	0.35	0.49[a]	0.27	0.36
Within 5 min	0.42	0.56[a]	0.34	0.38

[a] $p<0.008$.

TABLE VI. Correlations between probability of awakening and noise levels in analysis epochs.

Epoch duration	L_{eq}
1 min	0.43[a]
2 min	0.29
5 min	−0.13

[a] $p<0.033$.

Table VIII shows regression coefficients, odds ratios, 95% confidence intervals for odds ratios, and the contribution of each of the predictors to the model. Regression coefficients (B) in this nonlinear analysis are useful primarily as indications of the direction of relationship of each predictor with the probability of awakening. Positive coefficients indicate that an increase in the value of the predictor results in an increase in the probability of awakening. The relative magnitudes of the coefficients do not indicate the relative strength of unique contributions to prediction of each variable, however, because variables are measured on different scales.

The odds ratio e^B is a more readily interpreted transformation of the regression coefficient B.[1] Regression coefficients and their associated odds ratios are estimated values, subject to sampling error. The 95% confidence limits bound the likely range of values (odds ratios) given the sample data. A variable significantly enhances prediction of awakening if the confidence limits about its associated odds ratio do not include 1.0.

The final column of Table VIII presents the results of a series of analyses in which regression models were formed with each predictor separately removed from the full model containing all predictors. The performance of the reduced model for each predictor was then compared with the full model. A statistically significant result indicates that the model without a given predictor yields significantly poorer prediction of awakening than one that includes the predictor, and thus serves as a test of the significance of prediction for that variable.

Seven variables successfully predicted behavioral awakenings associated with noise events in an analysis in which all predictors were statistically adjusted for all other predictors. Sound exposure levels of events were positively related to behavioral responses such that each 1-dB increase in SEL

TABLE VII. Correlations between independent (columns) and dependent (rows) variables based on entire night noise metrics.

	Maximum L_{eq}	Night L_{eq}	Number of events	Duration of events
Sleep latency (in minutes)	0.07	0.08	0.10[a]	0.10
Number of recalled awakenings	−0.04	−0.08	−0.06	−0.04
Awakened by aircraft noise	−0.16[a]	−0.16[a]	−0.01	−0.08
Sleep quality rating	−0.04	−0.05	0.10	0.07
Total sleep time	0.14	0.28	0.18	0.19
Annoyance rating	0.15[a]	0.17[a]	0.15[a]	0.18[a]
Tiredness rating	0.06	0.01	−0.16	−0.14
Reported time awake	0.00	0.04	0.03	0.03
Behavioral awakening responses	−0.08	−0.10	−0.11	−0.08

[a] $p<0.003$.

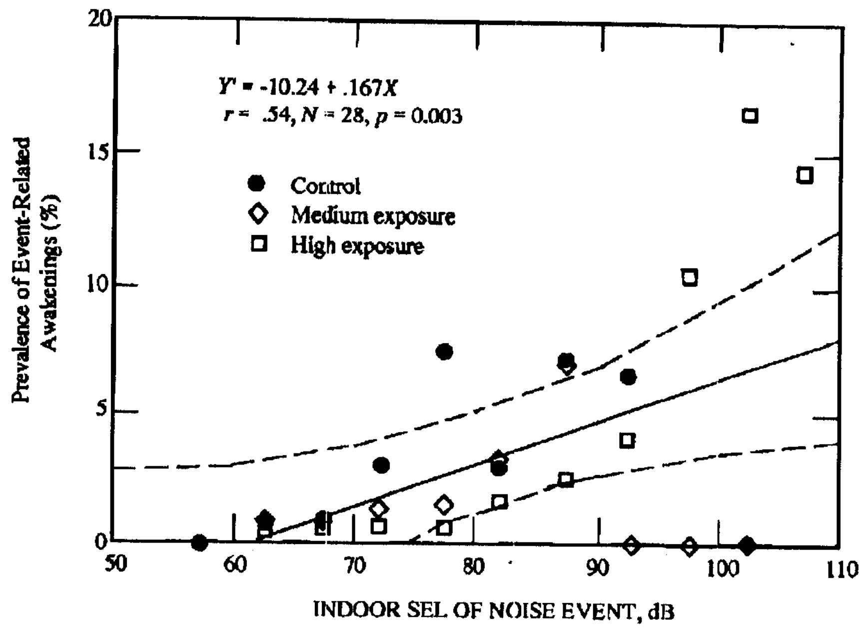

FIG. 5. Prevalence of behavioral awakening responses occurring within 5 min of noise events, aggregated by test participants within sites, in 5-dB increments. (Note exaggeration of vertical scale.)

increased the odds of awakening by a factor of 1.06. Time since retiring was also positively related to awakening: the longer the participant had slept, the greater the likelihood of awakening to a noise event. For each 15 min since retiring, the odds of awakening to a noise event increased by 1.06.

Time since retiring was the single strongest predictor of awakening in the presence of a noise event. Figure 6 plots behavioral awakening as a function of time since retiring. The probability of awakening (on the left ordinate) is represented by bars, whereas cumulative probability of awakening (on the right ordinate) is depicted by the curve.

Duration of residence (in months) was positively but trivially related to awakening, with an increase in odds ratio less than 0.01. Rating of tiredness in the evening interview

TABLE VIII. Regression coefficients, odds ratios with confidence intervals, and significance of removing predictor variables from a logistic regression model of event-based awakenings.

Variable (unit)	B	Odds ratio per unit	95% confidence interval for odds ratio: Lower	Upper	F to remove $df=1,10\,083$
Personal characteristics					
Number of spontaneous awakenings	−0.295	0.74	0.67	0.82	42.41[a]
Gender (category)	−0.048	0.95	0.75	1.21	0.19
Age (years)	−0.021	0.98	0.97	0.99	18.46[a]
Time-related characteristics					
Time since retiring (in 15-min increments)	0.059	1.06	1.05	1.07	167.39[a]
Duration of residence (months)	0.002	1.00	1.00	1.00	22.67[a]
Number of nights in study	0.008	1.01	0.99	1.02	1.47
Presleep characteristics					
Alcohol (category)	0.047	1.05	0.69	1.60	0.06
Medications (category)	−0.082	0.92	0.66	1.30	0.28
Tiredness on retiring (scale of 1–5)	0.233	1.26	1.13	1.43	16.72[a]
Noise characteristics					
Ambient level (dB)	−0.055	0.95	0.93	0.96	57.35[a]
Presumed noise source (category)	0.171	1.19	0.87	1.61	1.52
SEL (dB)	0.058	1.06	1.04	1.08	73.43

[a]$p<0.001$.

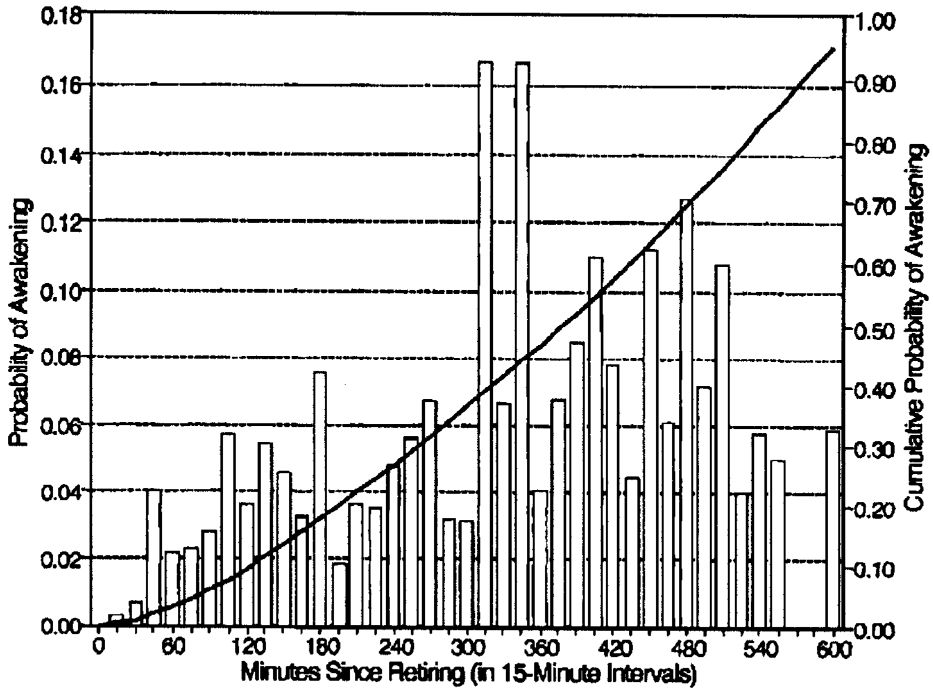

FIG. 6. Relationship between time since retiring and behavioral awakening in the presence of a noise event.

had a strong relationship with awakening to noise events, with an increase in odds of 1.26 for each one category increase in self-rating (ranging from 1=not at all tired to 5=extremely tired).

Ambient noise levels in sleeping quarters were inversely related to behavioral awakening. Each 1-dB increase in ambient noise level reduced the odds of awakening in the presence of a noise event by a factor of 0.05. The number of spontaneous awakenings for the night was also negatively related to awakening due to noise events. An increase of one spontaneous awakening lowered the odds of awakening to a noise event by a factor of 0.26. Age (or perhaps a correlate of age, such as hearing acuity) showed a small negative relationship with awakening in the presence of a noise event, with a factor-of-0.02 decrease in odds of awakening with each year of age.

Prediction based on SEL alone was meager, though statistically reliable. A logistic predictive model based on SEL alone accounted for only 5% of the variance in awakening.[2] That is, for 95% of the noise events that did awaken respondents, the model's predicted probability of awakening was less than 0.50; for only 5% of them was the predicted probability 0.50 or greater. A model based on SEL alone correctly predicted 97% of nonawakenings. That is, for 97% of the events that did not awaken participants, the model's predicted probability of awakening was less than 0.50; for 3% of the events that did not awaken participants, the predicted probability of awakening was 0.50 or greater.

Adding the set of covariate predictor variables to SEL significantly improved predictability, $\chi^2(11,\ N=10\,096)$, $p<0.001$. The model with all predictors included accounted for 13% of the variance in awakening. The correct predictions of nonawakening remained at 97%. However, the correct predictions of awakening rose from 5% to 8% with the addition of other predictors.

1. Relationship between behavioral responses and recalled awakenings

There was no significant difference between the number of awakenings recorded by button pushes and the number recalled the following morning. The two indicators of awakening were related, $r_{(928)}=0.69$, $p<0.001$, for the 930 subject nights on which test participants retired after 10:00 p.m. and arose before 8:00 a.m.

2. Relationship between cumulative nighttime noise exposure and annoyance

No statistically significant relationship was found between noise exposure of the entire night, as measured by L_{eq} in the time elapsed between retiring and the final behavioral awakening response, and the probability of consequential annoyance (self-descriptions as very or extremely annoyed).

3. Noise levels required to awaken

Two groups of events were formed on the basis of association with awakening. An analysis of variance on the SEL of indoor noise events revealed a small but statistically significant difference, $F(1,\ 10094)=167.78$, $p<0.001$,

$\eta^2=0.02$. On average, events that awakened test participants were higher in level (mean=80.6 dB) than were events that failed to awaken them (mean=74.1 dB).

4. Differences in responses among sites

A *post hoc* multiple discriminant function analysis was used to evaluate differences in ten response measures for an entire night among the three sites. The difference among the sites on the combined measures was statistically reliable, multivariate $F(20, 1836)=8.09$, $p<0.001$, $\eta^2=0.16$. No significant differences among sites were observed in behavioral awakening, sleep time, time since retiring, or numbers of noise-induced and spontaneous awakenings.

However, five of the self-report variables differed significantly across sites, after statistically adjusting for all other variables and setting $\alpha=0.001$ for multiple testing and *post hoc* analysis. Recalled number of awakenings was greatest at LAX (mean=2.59 per night) following by Castle AFB (mean =2.11), and nonaircraft sites (mean=2.04). Self-report of sleep quality also was greatest for LAX (mean=3.2 on a scale of 1–5), followed by Castle AFB (mean=2.94) and nonaircraft sties (2.86). Self-reports of time awake during the night were greatest at Castle AFB (2.02 on a scale of 1–5), followed by LAX (mean=1.96) and non-aircraft sites (mean =1.68). Tiredness the previous evening also was greatest at Castle AFB (mean=2.53 on a scale of 1–5), followed by nonaircraft sites (mean=2.38) and LAX (mean=2.24). Annoyance due to aircraft noise was greater at LAX (mean =1.49 on a scale of 0–5) and Castle AFB (mean=1.41) than for nonaircraft sites (mean=1.01).

5. Differences between weekend and midweek nights at Castle AFB

Nighttime training operations at Castle AFB occurred on weekdays only. Differences between weekday and weekend noise levels and responses were evaluated for 90 weekend subject nights and 258 midweek nights. Analysis of variance of indoor nighttime L_{eq} showed a small but significant difference between weekday and weekend nights, $F(1, 345)=25.65$, $p<0.001$. Average L_{eq} for midweek nights was 53.5 dB, while for weekend nights the average dropped to 47.7 dB. However, only 7% of the variance in sound level was associated with day of week, and behavioral awakening did not differ reliably by day of week.

III. DISCUSSION

Although many variables and combinations of variables were observed to be at least trivially associated with sleep disturbance (due in part to the relatively large sample size and the power of the statistical techniques), only a few of these findings are noteworthy for environmental assessment and other practical purposes.

A. Relationships between noise exposure metrics and behavioral awakening responses

The only reliable measure of the level of a noise event that predicted awakening within 2 and within 5 min of its occurrence was SEL. These relationships, although reliable, were not particularly strong. The larger accounted for about 30% of the variance in awakening within 5 min. A 10-dB increase in SEL was associated with an increase of only 1.6% in prevalence of awakening.

Only one of the three measures of noise levels within epochs reliably predicted behavioral awakening: L_{eq} in a 1-min epoch reliably predicted awakening, but accounted for less than 20% of the variance in behavioral awakening responses. A 10-dB increase in the L_{eq} value of an epoch preceding an awakening predicted an increase of 0.25% in prevalence of awakening.

B. Habituation to study participation

The possibility that the overall response rate varied systematically with duration of study participation was assessed by analyzing behavioral awakenings as a function of nights in the study. A small but reliable negative relationship was found, indicating that the number of button pushes declined slightly over the course of data collection. However, duration of participation accounted for less than 2% of the variance in behavioral awakening responses.

C. Implications for equal energy hypothesis

Only a slight association was observed between long-term noise exposure levels in sleeping quarters and sleep disturbance. The failure of analyses based on "entire night" noise measurements (that is, total noise exposure from retiring to last awakening) to account for appreciable variance in awakening data indicates that cumulative noise exposure metrics such as DNL are ill suited to prediction of noise-induced sleep disturbance.

The ability of sounds to awaken people is clearly sensitive to the temporal distribution of noise energy: small amounts of noise distributed over long periods of time are far less likely to awaken people than large amounts of noise energy concentrated within short periods of time (i.e., discrete noise events). The present findings do not support meaningful characterization of sleep interference in terms of DNL values of community noise environments.

The relationships observed in the present study between noise metrics and behavioral awakening responses suggest instead that noise-induced awakening may be usefully viewed as an event-detection process. Put another way, an awakening can be viewed as the outcome of a *de facto* decision that a change of sufficient import has occurred in the short-term noise environment to warrant a decision to awaken.

A subset of the present data contains information from which it is possible to make a gross estimate of the sensitivity of sleepers as detectors of noise intrusions. Analysis epochs may be viewed as "trials" (opportunities to make awakening decisions); behavioral awakening responses within 1 min of the time of occurrence of noise events may be viewed as hits, and behavioral awakening responses occurring at any other times may be defined as false alarms. The gross hit rate (as so defined) for all test participants in this subset of data was 4%, while the gross false alarm rate was 2.4%. Under conventional assumptions about the shapes and variances of

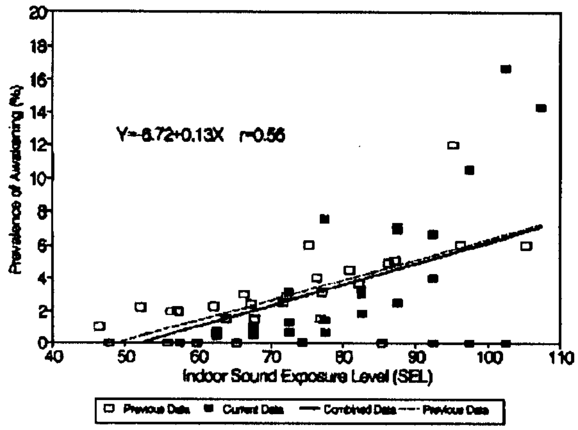

FIG. 7. Composite of data from current study with findings of prior sleep disturbance field studies. (Regression formula represents combined data.)

distributions of epochs with and without noise event signals (cf. Green and Swets, 1966), the value of the sensitivity index, d', which corresponds to this ratio of hits to false alarms is 0.23.

D. Relationship between findings of current and prior studies

Figure 7 plots data from the current study along with data from the six field studies reviewed by Pearsons *et al.* (1995) and the data reported by Ollerhead *et al.* (1992). The current findings are consistent with those of prior field studies. Sleep is a sufficiently complex physiological process that its properties can be measured in many ways, however, so that detailed comparisons of current and prior findings are sensitive to differences among studies in definitions of sleep disturbance, differences in noise measurement procedures, and differences in analytic approaches.

For example, Pearsons *et al.* (1974) reported an average of only three electroencephalographically defined awakenings per night in a small set of observations in the vicinity of Los Angeles International Airport. In an effort to relate actimetric observations of sleep disturbance to EEG-based observations, Ollerhead *et al.* (1992) adopted a definition of sleep disturbance that was sensitive both to shifts from deeper to lighter sleep states and to momentary awakenings. Thus Ollerhead *et al.* observed about 45 "awakenings or arousals" per night, of which 40% (18) were thought to be "awakenings." An awakening so defined may have persisted for as little as 10 s. Such brief departures from light sleep, even if electroencephalographically detectable, are unlikely to be recalled in the morning. The large nightly numbers of actimetrically defined awakenings described by Ollerhead *et al.* are thus not directly comparable with the smaller numbers of behaviorally confirmed awakenings observed in the current study.

A somewhat more direct comparison can be made between self-reported awakening rates observed by Ollerhead *et al.* and in the current study. Test participants in the study of Ollerhead *et al.* recalled a total of 7262 awakenings during 5742 subject nights of data collection, for a gross average of 1.3 recalled awakenings per night. No awakenings at all were recalled on 57% of the nights, however, so that the average awakening rate for the 43% of the nights on which any awakenings were recalled was 2.9 per night. The average rate of behaviorally confirmed awakenings in the current study was slightly more than two per night. Since the number of behaviorally confirmed awakenings did not differ significantly from the number of recalled awakenings in the present study, the current findings and those reported by Ollerhead *et al.* are at least roughly comparable.

IV. CONCLUSIONS

To the extent that generalizations are made from data collected from a purposive sample of test participants, they should be restricted to the effects of noise on the sleep of long-term residents of areas with stable nighttime noise exposure. The following are among the major findings of the present study:

(1) A statistically reliable direct relationship was observed between sound exposure levels of individual noise intrusions occurring in familiar sleeping quarters and behaviorally confirmed awakening within 5 min of their occurrence. This relationship accounted for less than a third of the variance in the awakening data, however, and had a very shallow slope, indicative of a relatively low probability that even high level noise events lead to awakenings.

(2) Longer term noise exposure metrics, such as DNL, showed no predictively useful association with sleep disturbance.

(3) The average spontaneous (non-noise event related) awakening rate among test participants at all sites was about two per night. This figure did not differ significantly across sites with widely varying levels of nighttime noise exposure.

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[1]An odds ratio greater than one indicates not only that the likelihood of awakening increases with increasing magnitude of the predictor, but also the extent of increase in likelihood. For example, an odds ratio of 2 indicates that as the predictor increases by one unit, the odds in favor of awakening doubles.

[2]Logistic regression analysis tends to underestimate variance accounted for in this application. For example, bivariate regression of SEL on probability

of awakening yields about 30% of the variance in awakening accounted for by SEL. The underestimate is probably due to the greater variability inherent in dealing with individual events rather than aggregations of events.

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