Effects on sleep disturbance of changes in aircraft noise near three airports

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Field measurements were conducted of potential sleep disturbance associated with changes in nighttime aircraft noise exposure near three airports. One study was conducted near Stapleton International Airport (DEN) and Denver International Airport (DIA) in anticipation of the closure of the former and opening of the latter. Sleep behavior was monitored in 57 homes located near runway ends at the two airports. A second study was conducted in the vicinity of DeKalb-Peachtree Airport (PDK), a large general aviation airport that expected increased nighttime flight operations due to the Olympic Games in July and August of 1996. Similar methods of measuring nighttime noise levels and sleep disturbance in the two studies were maintained over the course of 2717 and 686 subject-nights of observations, respectively. No major differences in noise-induced sleep disturbance were observed as a function of changes in nighttime aircraft noise exposure. © *2000 Acoustical Society of America.* [S0001-4966(00)01005-5]

INTRODUCTION

The prevalence of aircraft noise-induced sleep disturbance in airport communities remains a matter of considerable interest to regulatory, advisory, and standards agencies, since a fully credible dosage-effect relationship useful for assessing nighttime aircraft noise effects on residential populations remains elusive. The findings of recent large-scale field studies (e.g., those of Ollerhead *et al.*, 1992; and of Fidell *et al.*, 1995a) cast doubt on the likelihood of adverse public health consequences of familiar nighttime aircraft noise exposure of adapted populations residing in airport neighborhoods. They also encourage controversy about definitions of sleep disturbance, data analysis methods, and the reconciliation of findings of laboratory and field measurements of noise-induced sleep disturbance.

Little of what is known about the prevalence of noise-induced sleep disturbance in airport neighborhoods (cf. Pearsons *et al.*, 1995) addresses the time course of response to changes in nighttime aircraft noise exposure. The recent studies of Ollerhead *et al.* (1992) and of Fidell *et al.* (1995a) were made under generally stable aircraft noise exposure conditions among airfield-vicinity residents familiar with both their sleeping quarters and routine neighborhood noise sources. The paucity of information about adaptation to changes in nighttime noise is due in large part to the rarity of appropriate settings for field study of habituation to major changes in aircraft noise-induced sleep disturbance.

The primary goal of the present studies was to document potential changes in sleep disturbance associated with changes in aircraft noise levels. The first study began in January 1994 in anticipation of changes in aircraft noise exposure associated with the (expected) imminent closure of Stapleton International Airport (DEN) and the opening of the newly constructed Denver International Airport (DIA). Sev-

eral postponements of the opening of DIA eventually led to four rounds of data collection. The second study was conducted over a 6-week period in residences near DeKalb-Peachtree Airport (PDK). Data collection took place during the 18 days prior to the Atlanta Olympic Games, the 17 days during the Olympics, and 1 week after the closing ceremonies.[1]

I. METHOD

Data collection methods for both studies were similar to those described by Fidell *et al.* (1995a). Except as otherwise noted below, instrumentation was employed as shown in Fig. 2 of Fidell *et al.* (1995a) to simultaneously monitor indoor and outdoor noise events. As described by Fidell *et al.* (1995a), 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 push button attached by a cable to a palmtop computer at bedside for behavioral confirmation of awakening. Test participants were instructed to push the button upon awakening for any reason whatsoever during the night.

A. Study 1: Observations of noise-induced sleep disturbance near Stapleton International and Denver International Airports

1. Study sites and data collection schedules

Observations of noise exposure and sleep disturbance were made in single-family detached homes near Stapleton International (DEN) and Denver International (DIA) during

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TABLE I. Summary of data collection conditions in studies 1 and 2.

Site	Data collection round	Number of homes	Number of test participants	Number of subject-nights of data collection
Study 1				
DEN	Before closure (February/March 1994)	15	30	677
DIA	Before opening (April/May 1994)	14	29	712
DIA	Spanning opening (February/March 1995)	13	30	848
DEN	After closure (April 1995)	15	28	480
	Total	57 (38 different homes)	117 (77 different people)	2717
Study 2				
PDK	Before Olympics (2–16 July 1996)			294
PDK	During Olympics (17 July–4 August 1996)	12	22	295
PDK	After Olympics (5–11 August 1996)			97
	Total	12	22	686

four rounds of data collection. Preference in selection of data collection sites was given, to the extent possible, to homes with greater proximity to runways.

The initial data collection plans were based on the announced closing of DEN in March 1994. Data collection began in two neighborhoods to the immediate south and east of DEN 2 weeks prior to the announced closing date. Data collection continued for an additional 2 weeks after the closing data had been postponed. Noise exposure and sleep disturbance were measured in 15 residences located across residential streets from the airport fence to the south and east of Runway 26 L.

A residential neighborhood as close as possible to DIA was selected for a second round of data collection after the opening date for DIA was first postponed. This neighborhood was located approximately 4 km from the north end of Runway 34.[2] Data collection began 3 weeks before the second announced opening data (15 May 1994) and continued for an additional 2 weeks after the opening was once again postponed. Noise exposure and sleep disturbance were measured in 14 test participants' homes near DIA. Test participants were paid adult volunteers in good health who responded to canvassing letters.

A third round of data collection was conducted in the same neighborhood as the second round of data collection shortly before the final announced opening date of DIA, 28 February 1995. Data were collected from a total of 30 test participants in 13 residences, including several new participants. A fourth round of data collection began during the first week of April 1995 at homes in two neighborhoods near DEN. Data were collected from a total of 15 residences and 28 participants for a period of 3 weeks.

2. Noise measurements

Indoor noise measurements were made continuously during the first two rounds of data collection for the 4-week data collection period. Noise-monitoring instrumentation[3] inside test participants' sleeping quarters in the first round of data collection recorded average sound levels[4] every 60 s, as well as 1-s time histories of noise events. Outdoor noise measurements were made with five unattended noise monitors in the vicinity of test participants' residences programmed with the same noise event classification parameters as indoor noise monitors. The noise-monitoring equipment was reprogrammed in the last two rounds of data collection to record average sound levels every 2 s.

3. Definition of noise events

An outdoor noise event in the first two rounds of data collection was considered to have occurred when the noise level exceeded 70 dB for at least 2 s. An indoor noise event was considered to have occurred when the noise level exceeded 60 dB for at least 2 s. During the last two rounds of data collection, an outdoor noise event was considered to have occurred when the noise level exceeded 60 dB for at least 2 s, whereas an indoor noise event was considered to have occurred when the noise level exceeded 50 dB for at least 2 s.

Since both indoor and outdoor noise levels were monitored by unattended instrumentation, their sources are not known with certainty. Outdoor microphones were located in such a manner, and noise event classification criteria were so set, however, that the great majority of outdoor noise events was almost certainly aircraft. Many of the indoor noise
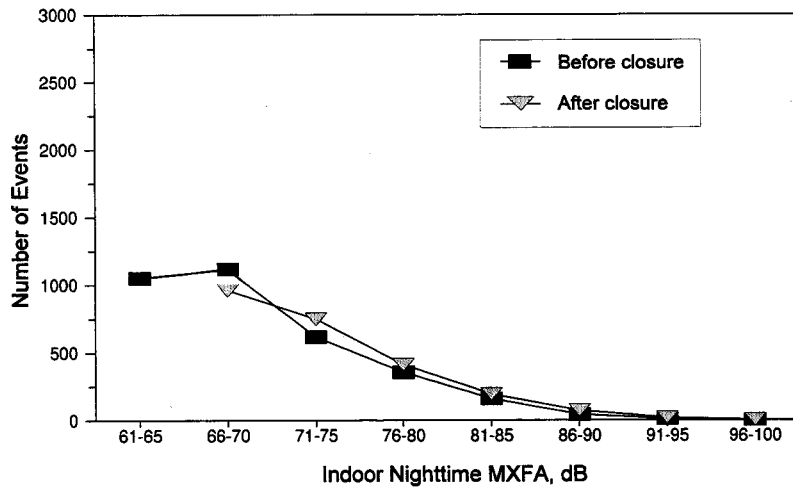
FIG. 1. Distribution of noise events recorded inside test participants' sleeping quarters at DEN from 2200 to 0700 hours.

events were attributable to aircraft, but some were created by other sources as well. In any event, indoor and outdoor levels were analyzed separately.

4. Response measurements

Nighttime motility was recorded with wrist-worn actimeters. All 30 test participants in the first round of data collection living near DEN were provided with the same (Gaehwiler) actimeters employed in the study of Ollerhead *et al.* (1992). In addition, six test participants wore actigraphs manufactured by Ambulatory Monitoring, Inc. (AMI).[5] The latter actigraphs were also used to measure motility in the homes of six test participants near DIA during the second round of data collection. All test participants in the third and fourth rounds of data collection were provided with AMI actigraphs to measure motility.

B. Study 2: Observations of noise-induced sleep disturbance near DeKalb-Peachtree Airport

1. Study sites and data-collection schedules

Observations of noise exposure and sleep disturbance were made in 12 single-family detached homes to the north of PDK. Data collection began on 2 July 1996, 15 days prior

to the opening ceremony of the Olympic Games, continued through the Games, and ended one week after their conclusion.

2. Test participants

Observations of sleep disturbance of a total of 25 different people were made in the course of this study. Procedures for recruiting test participants near PDK were similar to those of study 1.

3. Noise measurements

Unattended noise-monitoring instrumentation was configured in this study as in the latter rounds of data collection in study 1. Indoor noise measurements were made continuously for the 6 weeks. Continuous 2-s time histories were recorded, as were hourly average sound levels. Levels associated with noise events were stored in the noise monitors during the entire measurement period. Noise events were defined as a time series of noise levels that began when a preset threshold was exceeded for at least 10 s, and that continued as long as the level remained more than 2 dB below the preset threshold. The threshold for indoor locations in this study was an A-weighted sound level of 50 dB.
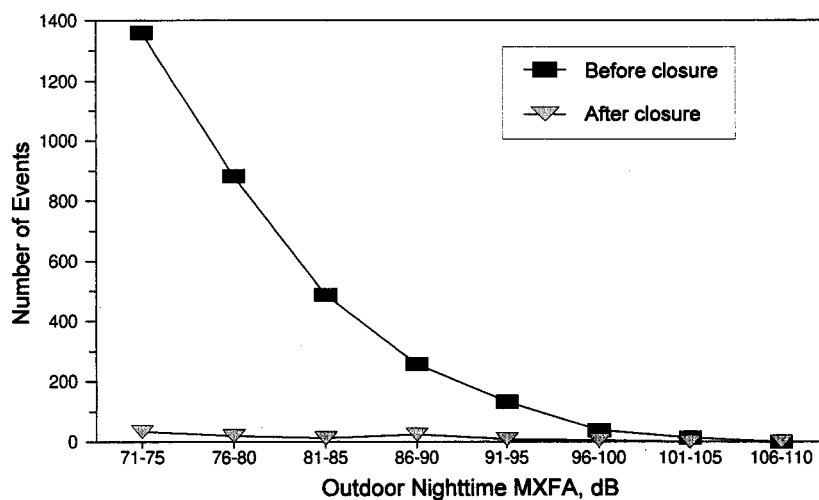

FIG. 2. Distribution of outdoor noise events at DEN between 2200 and 0700 hours.
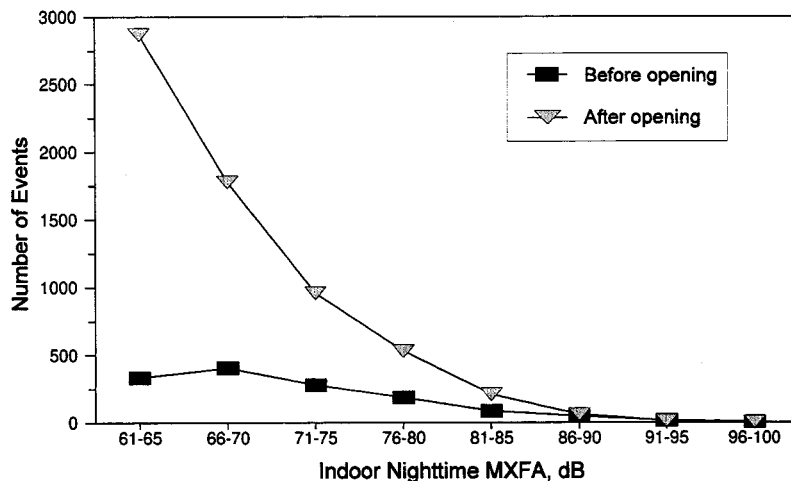
FIG. 3. Distribution of noise events recorded inside test participants' sleeping quarters at DIA from 2200 to 0700 hours.

Outdoor noise measurements were made in the vicinity of all test participants' homes with two Larson·Davis 820 noise monitors, with the same parameters used to collect indoor noise data. The outdoor noise-event threshold was set to an A-weighted level of 60 dB.

4. Response measurements

Sleep disturbance measurements in this study were identical to those of study 1. Recording accelerometers (AMI actigraphs) configured in the zero-crossing mode measured nighttime motility in 30-s epochs.

II. RESULTS

A. Study 1: Summary of noise measurements and sleep disturbance responses

Table I summarizes the conditions under which 2717 subject-nights of data were collected in the first study, and 686 subject-nights in the second study. Figures 1–4 summarize the distributions of indoor and outdoor nighttimes noise-event levels in each round of data collection. The noise levels are reported in terms of maximum sound level using fast response (125 ms) with A-weighting (MXFA). As expected, outdoor nighttime noise-event levels decreased after flight

operations ceased at DEN. Outdoor nighttime noise-event levels increased, although less dramatically, near test participants' homes after flight operations began at DIA. Note that no data are shown for the lowest indoor noise level interval for the "after closure" condition. Nonaircraft noise events in the homes of one or more test participants in this condition appear to have generated artifactual "intrusions." Indoor nighttime noise-event levels as measured in sleeping quarters were much less affected by the changes in aircraft operations at DEN. However, indoor noise events greatly increased after opening of DIA.

Figure 5 compares the average motility of individual test subjects attributable and unattributable to aircraft noise, while Fig. 6 compares the average rate of behavioral awakening responses attributable and unattributable to aircraft noise. The pattern of findings summarized in these figures indicates that motility and awakenings were little affected by the changes in nighttime aircraft flight operations.

Table II summarizes the number of awakenings confirmed by button pushes averaged over the two sites. Few of the responses were attributable to noise events.

B. Study 1: Inferential analysis

All dosage–response relationships were constructed from noise events occurring between 2200 and 0700 hours,
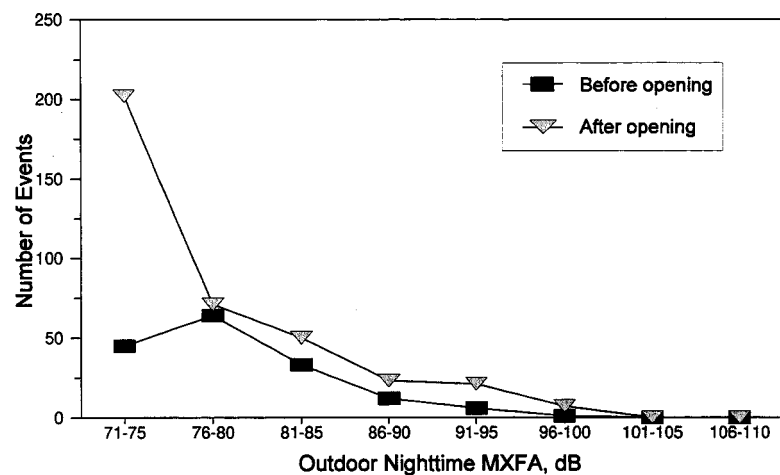

FIG. 4. Distribution of outdoor noise events at DIA between 2200 and 0700 hours.
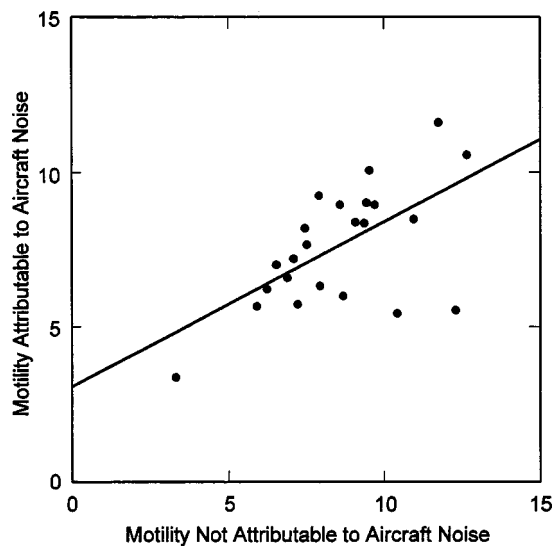
FIG. 5. Average motility in each 30-s epoch attributable to (ordinate) and not attributable to (abscissa) aircraft noise. Each data point represents responses of a single participant throughout study 1.

because earlier time periods in the evening and later time periods in the morning contained too high a density of (largely nonaircraft) noise events for reliable association with individual responses. Dosage–response relationships were constructed for five indicators of sleep disturbance:

(1) behavioral awakening responses (button pushes),
(2) arousals defined by Ollerhead *et al.* (1992)[6] criteria for the Gaehwiler actimetric data,
(3) arousals defined by Cole *et al.* (1992) criteria for the AMI actigraphic data,
(4) motility as recorded by the Gaehwiler actimeters, and
(5) motility as recorded by AMI actigraphs.

Analyses of awakenings associated with independently confirmed aircraft noise events at DIA were possible only for the month prior to opening and the month following the
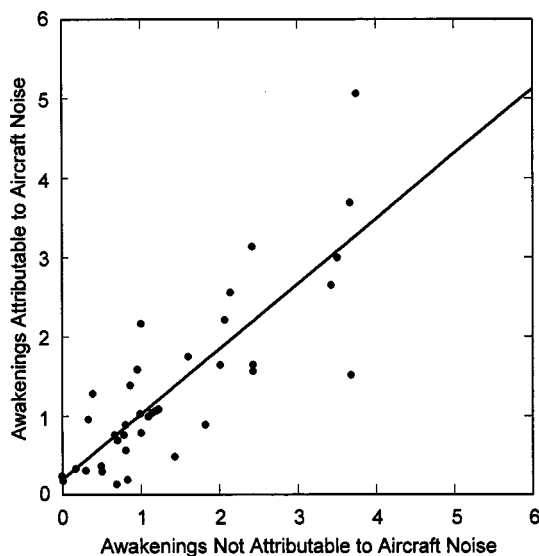

FIG. 6. Average number of behavioral awakening responses per night attributable to (ordinate) and not attributable to (abscissa) aircraft noise. Each data point represents responses of a single participant throughout study 1.

opening of the airport. The independent (predictor) variable for all dosage–response relationships was either indoor or outdoor sound-exposure levels (SEL), quantized in 3-dB intervals. Data points reflect the proportion of noise events in each noise level interval that produced a response. Data were combined for all test participants and all data collection sessions for behavioral awakening and AMI actigraph responses. Gaehwiler actimeter recordings were available only at DEN for the data collection session before airport closure. Table III shows the definitions of awakening, arousal, and motility adopted for the various data collection devices.

Correlations for the various dosage–response relationships are summarized in Table IV. Polynomial regressions revealed no higher-order relationships among noise metrics and any measures of sleep disturbance. Four of the dosage–response relationships, all based on SEL of noise events measured indoors, were statistically reliable. The SEL value of indoor noise events successfully predicted (1) behavioral awakening responses, (2) motility as recorded by the Gaehwiler actimeters, (3) motility as recorded by the AMI actigraphs, and (4) AMI actigraphic arousals as defined by Cole *et al.* (1992). None of the sleep disturbance measures varied reliably with SEL of noise events measured outdoors, nor did they vary reliably with SEL of confirmed aircraft noise events only.

Figure 7 shows that the probability of occurrence of at least one actimetric response recorded by a Gaehwiler actimeter within 5 minutes of the start of a noise event was strongly related to indoor SEL, $r(9) = 0.90$, $p < 0.001$. The data set in which this relationship was observed was composed of noise events recorded for the participants at DEN before airport closure. The slope of the regression equation shown in Fig. 7 is rather shallow: each 1-dB increase in SEL raised the probability of an actimetric blip (per the definition of Ollerhead *et al.*, 1992) by about 1.23%.

Figure 8 shows that the probability of occurrence of an average number of zero crossings greater than 0 as measured by the AMI actigraph also was reliably related to indoor SEL [$r(9) = 0.84$, $p < 0.025$]. The data set in which this relationship was observed was based on six participants in the first rounds of data collection at DEN and DIA, and all participants for remaining data collection periods. Each 1-dB increase in SEL raised the probability of occurrence of a motility indication by about 0.4%. The difference between correlations with SEL for the two actimetric criteria ($r = 0.84$ and 0.90) was not statistically reliable.

Figure 9 shows that the indoor SEL of noise events predicted behavioral awakening responses moderately well [$r(10) = 0.68$, $p < 0.025$]. The probability of awakening increased by about 0.25% for each 1-dB increase in SEL.

Arousals as scored by the Cole *et al.* (1992) actigraphic criterion also were predicted reasonably well by the indoor SEL of noise events [$r(9) = 0.62$, $p < 0.025$], as shown in Fig. 10. Motility measurements were collected from six participants in the first rounds of data collection at DEN and DIA, and from all participants during the remaining data collection periods. The probability of arousal increased about 0.28% for each 2-dB increase in SEL of indoor noise events.

TABLE II. Summary of behavioral awakening responses for all subject-nights at DEN and DIA.

	Variable		
	Average number of behaviorally confirmed awakenings per night	Average number of spontaneous awakenings per night	Average number of noise-related awakenings per night
Attributable to aircraft			
Mean	1.53	1.27	0.26
Standard deviation	1.99	1.80	0.59
Range	0–23	0–21	0–4
Not attributable to aircraft			
Mean	1.69	1.49	0.19
Standard deviation	2.12	1.98	0.56
Range	0–19	0–16	0–5
Averaged over all nights			
Mean	1.61	1.39	0.22
Standard deviation	2.06	1.90	0.57
Range	0–23	0–21	0–5

None of the correlations in Table IV differs reliably from the others ($p > 0.05$).

C. Study 2: Summary of noise measurements and sleep disturbance responses

Informed consent was obtained from 25 residents of 14 homes to participate in this study. Data screening reduced the number of participants considered in the data analyses to 22 residents of 12 homes. Indoor noise event levels were measured in sleeping quarters, while outdoor event levels were estimated from the measurements made at the closer of the two outdoor measurement locations to a participant's house. Table I (in Sec. II A) shows the numbers of subject-nights of observations made in the periods before, during, and after the Olympic Games.

Figures 11 and 12 show the distributions of maximum levels of noise events recorded between 2200 and 0700 hours indoors and outdoors near PDK before, during, and after the Olympics. The number of indoor noise events observed prior to the Olympics exceeded that observed during and after the Olympics, as shown in Fig. 11. The number of noise event levels in each 5-dB interval measured outdoors during Olympics was greater than that observed both before and after the Olympics, as shown in Fig. 12.

Table V summarizes the number of awakenings confirmed by button pushes. A total of 540 behavioral awakening responses (button pushes) was observed during the 294 subject-nights of data prior to the Olympics, for an average of 1.8 per night. During the Olympics, 370 behavioral awakenings were observed during the 295 subject-nights of data, for an average of 1.3 per night. After the Olympics, 98 behavioral awakening responses were observed during the 97 subject-nights of data, yielding an average of 1 per night.

D. Study 2: Inferential analyses

Three indicators of sleep disturbance were constructed for dosage–response analyses: behavioral awakening, motility, and arousal. The independent variable for all dosage–response analyses was either indoor or outdoor SEL, as in study 1.

Correlations for the various dosage–response relationships are summarized in Table VI. Polynomial regression failed to reveal any statistically reliable quadratic relationships. Two of the six dosage–response relationships were statistically reliable. The SEL value of indoor noise events successfully predicted arousals as defined by Cole *et al.* (1992), and the SEL value of outdoor noise events success-

TABLE III. Definitions of awakening and motility adopted for various data collection devices in study 1.

Indication of sleep disturbance	Recording device	Criterion of effect
Awakening	Push button	Occurrence of behavioral response within 5 minutes of start of noise event.
Arousal	Gaehwiler actimeter	Estimated awakening identical to that of Ollerhead *et al.* (1992).
Arousal	AMI actigraph	Estimated awakening as defined by Cole *et al.* (1992), using base algorithm without iteration.
Motility	Gaehwiler actimeter	Any activity occurring in any of the ten 30-s epochs following the start of a noise event.
Motility	AMI actigraph	Any activity occurring in any of the ten 30-s epochs following the start of a noise event.

TABLE IV. Summary of dosage–response correlations for events occurring between 2200 and 0700 hours. (Data aggregated over DEN and DIA for button-push responses and U.S.-made actigraph. Data available only at DEN for Swiss-made actimeter.)

Measure of sleep disturbance	Criterion for sleep disturbance	Number of indoor noise events	Number of outdoor noise events	Noise measurement type		
				Indoor criterion	Outdoor criterion	Outdoor confirmed aircraft
Motility	Gaehwiler actimeter (time above threshold)	1519	6915	0.90[a]	ns[b]	nd[c]
Arousal	AMI actigraph (zero crossings)	466	1535	0.84[a]	ns	ns
	Ollerhead (Gaehwiler actimeter)	1519	6915	ns	ns	nd
Awakening	Cole (AMI actigraph)	466	1535	0.62[a]	ns	ns
	Behavioral awakening response	2169	8572	0.68[a]	ns	ns

[a]$p < 0.025$, one-sided.
[b]ns: not significantly different from a correlation of 0.
[c]nd: no data.

fully predicted behavior awakenings as confirmed by button pushes. Reliable dosage–response relationships between indoor noise levels and behavioral awakening and motility could not be constructed from the data of this study.

Figure 13 shows that indoor SEL of noise events predicted arousal moderately well [$r(8) = 0.64$, $p = 0.033$]. The probability of arousal increased by about 5% for each 10-dB increase in SEL. Figure 14 shows that the outdoor SEL of noise events predicted behavioral awakening responses fairly well [$r(9) = 0.72$, $p = 0.013$]. The probability of awakening increased by about 1.3% for each 10-dB increase in SEL.

III. DISCUSSION

A. Relationship between outdoor and indoor aircraft noise-event levels

Observed changes in the outdoor aircraft noise environment were only loosely reflected in changes of nighttime
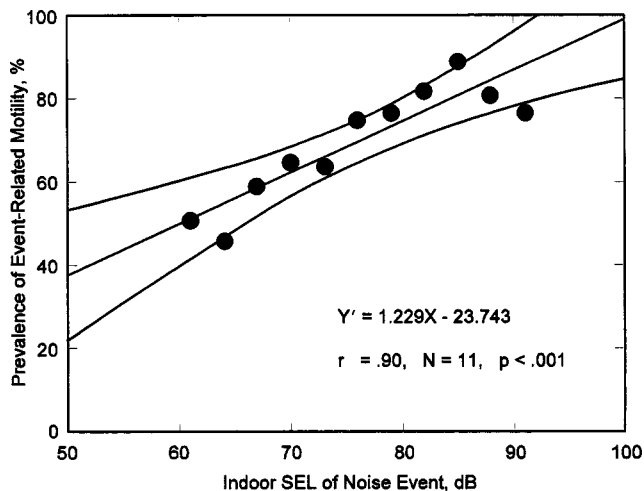

FIG. 7. Prevalence of actimetric blips (defined by Ollerhead's criterion) at DEN before airport closure, aggregated over test participants in 3-dB increments of indoor SEL values of noise events. Curved lines bound the 95%-confidence interval.
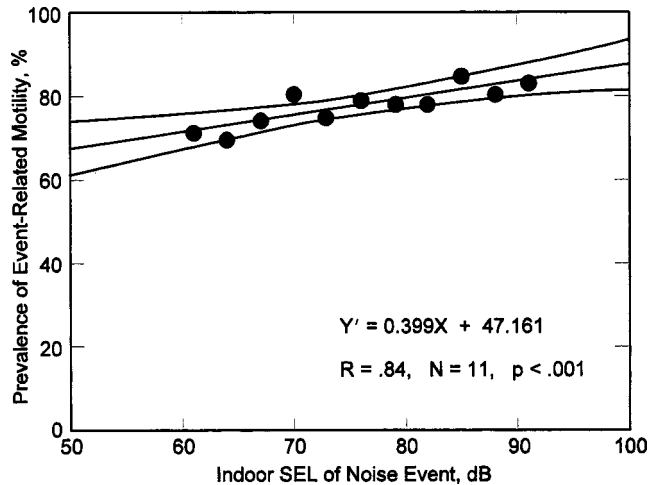
FIG. 8. Prevalence of actigraphic threshold crossings (defined by Cole's criterion) at DEN and DIA, aggregated over test participants in 3-dB increments of indoor SEL values of noise events. Curved lines bound the 95%-confidence interval.

$Y' = 1.229X - 23.743$

$r = .90$, $N = 11$, $p < .001$

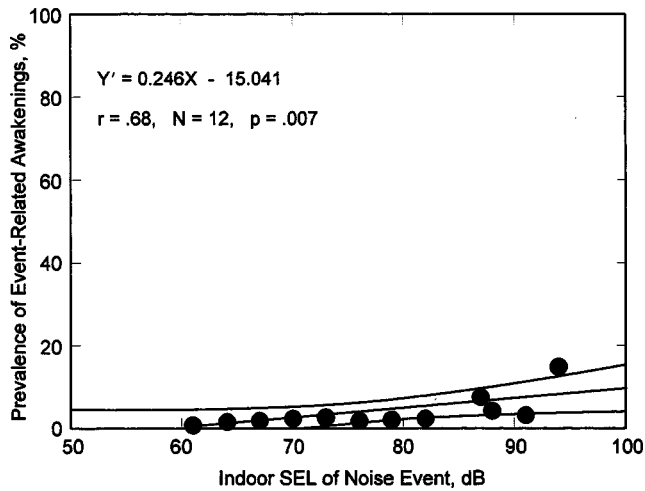$Y' = 0.399X + 47.161$

$R = .84$, $N = 11$, $p < .001$

FIG. 9. Prevalence of behavioral awakening responses at DEN and DIA aggregated over test participants in 3-dB increments of indoor noise measurements. Curved lines bound the 95%-confidence interval.

noise event levels as measured in sleeping quarters. This finding is consistent with Schultz's (1982) observations that differences between indoor and outdoor single-event levels ''typically fluctuate wildly over a range of as much as 30 dB,'' and that ''the outdoor noise stimulus may have little or nothing to do with the noise actually heard indoors.''

B. Dosage–respone analysis of five diverse field studies

Figure 15 plots the dosage–response relationship between SEL and behavioral awakenings inferred from the present data, along with data from six field studies reviewed by Pearsons *et al.* (1995), the data from Fidell *et al.* (1995a), and the data from Ollerhead *et al.* (1992).[7] The relationship shown for the combined data is reliable, but accounts for only about 20% of the variance in the data set. Each 10-dB increase in SEL increases the prevalence of awakening by only about 1.3%.

FIG. 10. Prevalence of arousal responses by U.S. actigraphic criterion at DEN and DIA aggregated over test participants in 3-dB increments of indoor noise measurements. Curved lines bound the 95%-confidence interval.
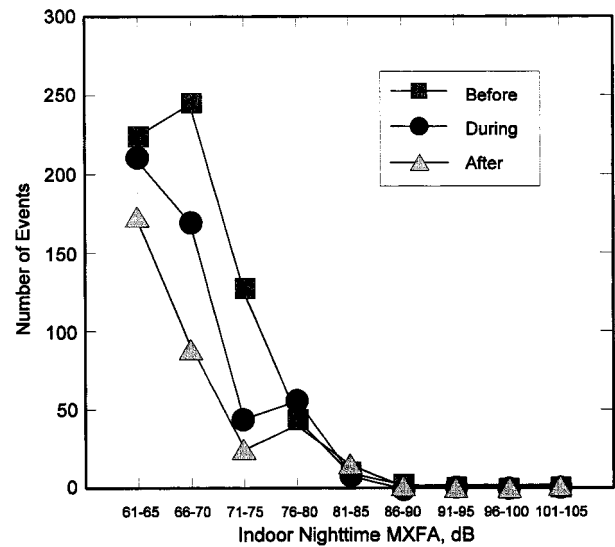

FIG. 11. Distribution of noise-event levels recorded inside test participants' sleeping quarters between 2200 and 0700 hours in three measurement periods.

The combined dosage–response relationship shows much greater variability at higher than at lower noise levels. For example, the range of prevalence of awakening at 60 dB is from 0% to about 2%. The range at 100 dB is from 0% to more than 20%. Even long-duration and/or high-level noise events sometimes failed to awaken test participants.

C. Dosage–response analysis of three similar field studies

The data of the studies described in this paper were combined with those of a prior study by Fidell *et al.* (1995a) in which similar definitions of noise events and of awakening were applied. Correlations for the six dosage–response relationships are summarized in Table VII. Four of the six dosage–reponse relationships were statistically reliable. The SEL value of indoor noise events successfully predicted behavioral awakenings as confirmed by button pushes.
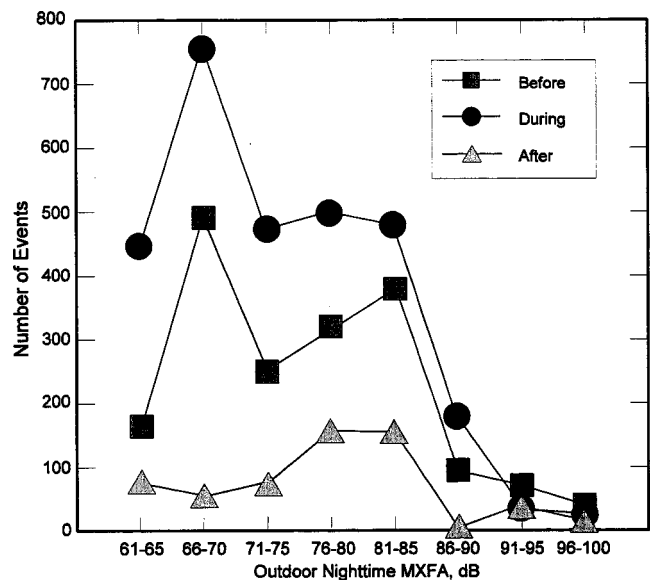

FIG. 12. Distribution of outdoor noise-event levels between 2200 and 0700 hours in three measurement periods.

TABLE V. Summary of behavioral awakening responses for all subject-nights during study 2.

Time frame	Average number of behaviorally confirmed awakenings per night	Average number of spontaneous awakenings per night	Average number of noise-related awakenings per night
		Variable	
Before and after Olympics			
Mean	1.63	1.20	0.43
Standard deviation	1.73	1.45	0.89
Range	0–10	0–8	0–7
During Olympics			
Mean	1.25	0.83	0.42
Standard deviation	1.40	1.05	0.86
Range	0–6	0–6	0–5
Averaged over all nights			
Mean	1.47	1.05	0.42
Standard deviation	1.61	1.31	0.88
Range	0–10	0–8	0–7

Figure 16 shows that indoor SEL of noise events predicted behavioral awakening moderately well [$r(15) = 0.75$, $p < 0.001$]. The probability of arousal increased by about 3% for each 10-dB increase in SEL. Polynomial regression revealed statistically reliable quadratic and cubic relationships ($p < 0.001$), with multiple R increasing to 0.89 with inclusion of the quadratic trend and to 0.96 with inclusion of the cubic trend. For convenience of comparison with other dosage–response relationships, however, only the linear fit is shown in the figure.

Figure 17 shows that indoor SEL of noise events predicted arousal moderately well [$r(11) = 0.66$, $p = 0.007$]. The probability of arousal increased by about 2% for each 10-dB increase in SEL. Figure 18 shows that indoor SEL of noise events predicted motility moderately well [$r(11) = 0.76$, $p = 0.001$]. The probability of arousal increased by about 4% for each 10-dB increase in SEL. Polynomial regression revealed no statistically reliable quadratic or cubic relationships in either of these predictive relationships with indoor SEL of noise events.

Figure 19 shows that outdoor SEL of noise events predicted behavioral awakening moderately well [$r(16) = 0.68$,

$p = 0.001$]. However, the probability of arousal increased by less than 1% for each 10-dB increase in SEL. Polynomial regression revealed statistically reliable quadratic and cubic relationships ($p < 0.005$), with multiple R increasing to 0.81 with inclusion of the quadratic trend and to 0.90 with inclusion of the cubic trend.

IV. SUMMARY OF FINDINGS

The present findings may appear counterintuitive, in that they suggest that the sleep of residents of neighborhoods near airports is not highly sensitive to nighttime disturbance by aircraft noise. Instead, the results indicate that relatively few nighttime noise intrusions disturb sleep, and that residential populations near airports seem well-adapted to nighttime noise intrusions. The general agreement among large-scale field studies of noise-induced sleep disturbance, involving thousands of subject-nights of observations, also suggests that further studies of a similar nature are likely to yield similar results.

The observed pattern of findings may be due in part to self-selection of airport vicinity residents for tolerance to

TABLE VI. Summary of dosage–response correlations for events occurring between 2200 and 0700 hours (data aggregated over all nights) for study 2.

Measure of sleep disturbance	Criterion for sleep disturbance	Number of indoor noise events	Number of outdoor noise events	Noise measurement type	
				Indoor criterion	Outdoor criterion
Motility	Actigraphic zero crossings	1487	5293	ns[b]	ns
Arousal	Cole *et al.*, 1992	1329	4693	0.64[a]	ns
Awakening	Behavioral awakening response	1487	5293	ns	0.77[a]

[a]$p < 0.025$, one-sided test.
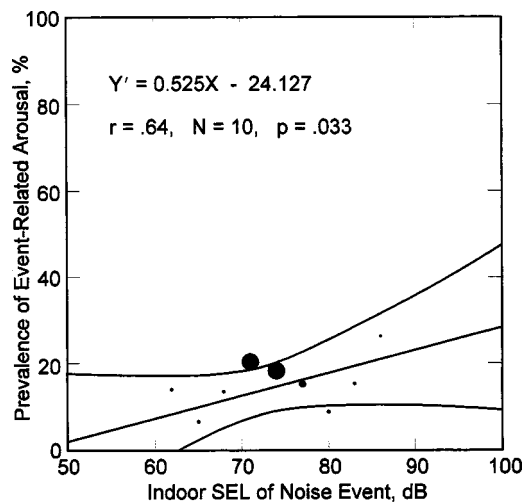[b]ns: Not significantly different from a correlation of 0.

FIG. 13. Prevalence of arousal aggregated by test participants in 3-dB intervals of indoor noise measurements (for study 2). Curved lines bound the 95%-confidence interval. Larger data points indicate relatively greater numbers of events.
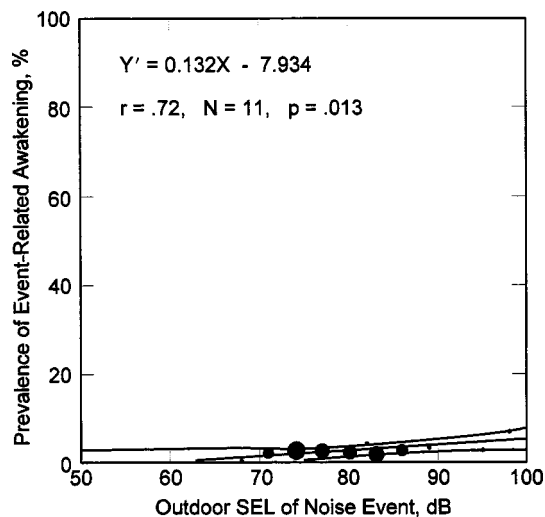

FIG. 14. Prevalence of behavioral awakening responses aggregated by test participants in 3-dB intervals of outdoor noise measurements (for study 2). Curved lines bound the 95%-confidence interval. Larger data points indicate relatively greater numbers of events.

nighttime noise intrusions, and in part to other nonacoustic factors, such as the meaning of the intruding noises. Those designing further field studies of sensitivity to noise-induced sleep disturbance may wish to consider controlled manipulations of such nonacoustic factors, including attitudinal factors and short-term habituation to novel (nonaircraft) noise sources.

V. CONCLUSIONS

Because no effort was made to rigorously define the complete population exposed to nighttime noise exposure, nor to obtain a representative sample of any wider population, conclusions drawn from the current studies apply strictly to observations made in the course of the present study only.

A. Study 1

The following are among the major findings of study 1:

(1) The current findings closely resemble those of prior field studies of noise-induced sleep disturbance.
(2) Numbers of outdoor nighttime noise events decreased greatly at DEN upon closure of the airport, but increased much less dramatically at DIA after opening of the airport.
(3) Numbers of indoor nighttime noise events varied much less at DEN before and after its closing, but indoor nighttime noise events increased greatly after opening of DIA.
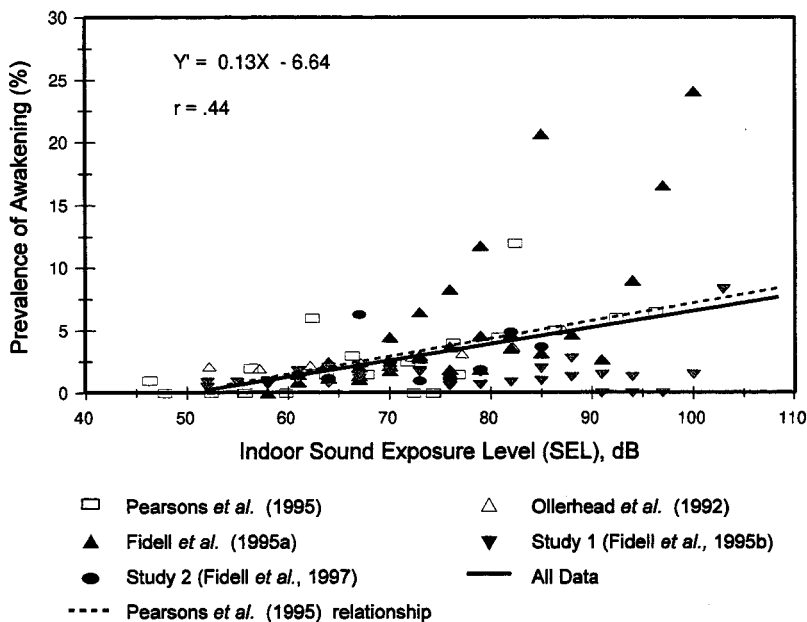(4) The average number of behavioral awakening responses per night was 1.8 at DEN and 1.5 at DIA. The number of

FIG. 15. Composite of data from current studies with findings of prior sleep disturbance field studies. (Data of Ollerhead et al., 1992 adjusted to reflect indoor noise measurements.)

TABLE VII. Summary of dosage–response correlations for events occurring between 2200 and 0700 hours. (Data aggregated over all nights.)

Measure of sleep disturbance	Criterion for sleep disturbance	Number of indoor noise events	Number of outdoor noise events	Noise measurement location	
				Indoor criterion, based on 19 158 events	Outdoor criterion, based on 24 543 events
Motility	Ollerhead et al., 1992 (zero crossings)	19 158	16 669	0.76[a]	ns[b]
Arousal	Cole et al., 1992 (time above threshold)	6 715	17 449	0.66[a]	ns
Awakening	Behavioral awakening response	8 892	24 543	0.75[a]	0.68[a]

[a]$p < 0.005$, one-sided test.
[b]ns: Not significantly different from a correlation of 0.

spontaneous behavioral awakening responses (unassociated with noise events) was 1.5 per night at DEN and 1.3 at DIA.

(5) Statistically reliable relationships were observed between sound exposure levels of individual noise intrusions as measured inside sleeping quarters and several measures of sleep disturbances. These were:

(i) SEL of individual noise intrusions accounted for about 81% of the variance in motility as measured by the Gaehwiler actimeter. The linear relationship between the percentage of test participants exhibiting motility following a noise event was % motility $= 1.23L_{AE} - 23.74$.[8]

(ii) SEL of individual noise intrusions accounted for about 71% of the variance in motility as measured by the AMI actigraph. The linear relationship between the percentage of test participants exhibiting motility following a noise event was % motility $= 0.4L_{AE} + 47.16$.

(iii) SEL of individual noise intrusions accounted for about 45% of the variance in behavioral awakening responses. The linear relationship between the percentage of test participants exhibiting a behavioral awakening response following a noise event was % noise-induced awakening $= 0.25L_{AE} - 15.04$.

(iv) SEL of individual noise intrusions accounted for about 38% of the variance in arousals as measured by the AMI actigraph and defined and processed in accordance with the criteria of Cole et al. (1992). The linear relationship between the percentage of test participants exhibiting arousal following a noise event was % arousal $= 0.28L_{AE} + 1.31$.
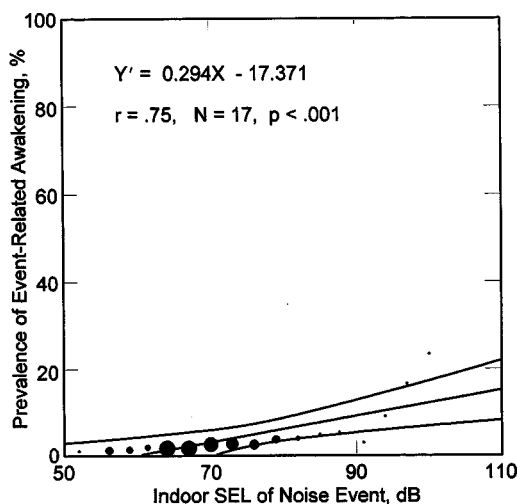

FIG. 16. Prevalence of behavioral awakening responses from three Fidell studies aggregated by test participants in 3-dB intervals of indoor noise measurements. Curved lines bound the 95%-confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.
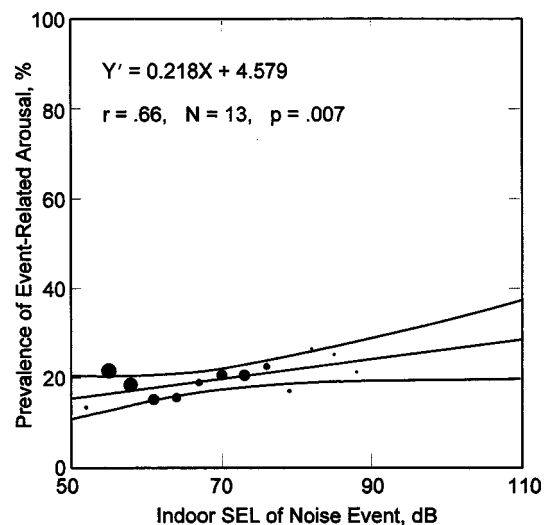
FIG. 17. Prevalence of arousal responses aggregated by test participants in 3-dB intervals of indoor noise measurements. Curved lines bound the 95%-confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.
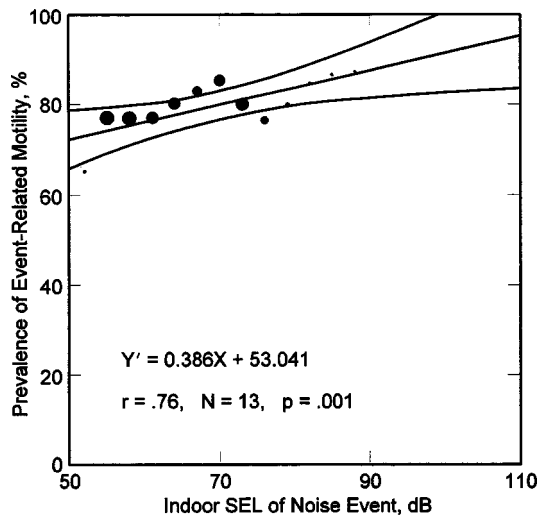
FIG. 18. Prevalence of motility responses aggregated by test participants in 3-dB intervals of indoor noise measurements. Curved lines bound the 95%-confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.

B. Study 2

Relationships between sleep disturbance and SEL values in the current findings are not fully comparable to those of prior studies. In prior studies (e.g., Fidell *et al.*, 1995a, 1995), a 2-s minimum was established for definition of a noise event. Minimum noise-event durations were set at 10 s in the current study to exclude more nonaircraft noise events. Since events with durations of less than 10 s were excluded, fewer total events were collected.

Likewise, the presence of masking by noise from mid-summer use of ventilating and air-conditioning systems in Atlanta may have been responsible for the failure to observe a reliable dosage–response relationship in the current data between awakening and indoor SEL levels, as in prior studies.

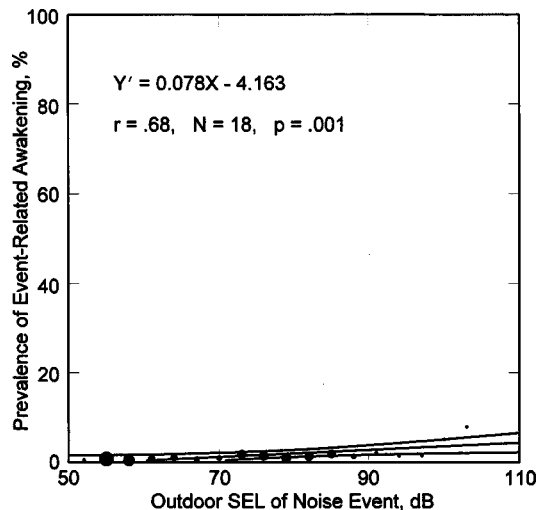Outdoor noise event levels, defined by a level threshold,

FIG. 19. Prevalence of behavioral awakening responses aggregated by test participants in 3-dB intervals of outdoor noise measurements. Curved lines bound the 95%-confidence interval for the linear fit. Larger data points indicate relatively greater numbers of events.

were reliably related to participants' behaviorally confirmed awakening as recorded by button pushes (% noise-induced awakening$=0.13L_{AE}-7.93$), but not to motility rates as measured actigraphically, or actigraphically defined arousal. This is only partially consistent with Ollerhead's (1992) finding of a dosage–response relationship between outdoor noise levels and motility. However, both the actigraphs used to measure motility in the current study and the noise measures employed were different from those used by Ollerhead.

A reliable dosage–response relationship was found between indoor SEL of noise events and arousal as determined by Cole *et al.*'s (1992) algorithm applied to the actigraph data (% arousal$=0.52L_{AE}-24.13$), but not between indoor SEL and behavioral awakening as recorded by button pushes or motility as measured actigraphically. This is not entirely consistent with prior findings of small but highly reliable relationships between SEL measured indoors and several indicators of sleep disturbance, including awakening and motility as well as arousal.

[1]Additional detail regarding data collection procedures, data reduction, and analyses of these two data sets is provided in Fidell *et al.* (1995b, 1998).

[2]Distances from runway ends to test participants' homes do not uniquely determine indoor single-event sound-exposure levels of aircraft operations. Many other factors also affect indoor aircraft noise-event levels, including differences in source levels, slant ranges to flight paths, types of operations, runway assignments, window size and opening, and so forth.

[3]Larson-Davis Model 820 and 870 noise monitors were used for unattended detection and recording of noise events.

[4]The abbreviations ''TAVA'' (or ''TAV'') and ''MXFA'' for time-averaged and maximum A-weighted, fast time sound levels follow the conventions of ANSI Standard S1.1 (1994), ''Acoustical Terminology for Levels of Acoustical Measures.''

[5]The Gaehwiler actimeter measures total time above an acceleration threshold, with a fixed sensitivity of 0.1 g over a bandwidth of 0.25 to 3 Hz. The AMI actimeter can measure both time above an acceleration threshold and the number of zero crossings (reversals of wrist movement directions). Its sensitivity is adjustable to 0.01 or 0.5 g over the range of 0.16 to 10 Hz.

[6] Ollerhead *et al.* (1992) define a motility ''blip'' as *any* nonzero value for the time above an acceleration threshold of wrist motion during a 30-s analysis epoch occurring after sleep onset, which was in turn defined as

starting 5 minutes into the first 7-minute-long movement-free period of the night. Cole's criterion for an awakening takes into account the duration of motility.

[7]The outdoor noise measurements reported by Ollerhead *et al.* (1992) are adjusted by 15 dB to represent them as indoor sound levels.

[8]The symbol for sound-exposure level in formulas is L_{AE} (see ANSI Standard S1.1-1994).

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